DYNAMIC ROVER SIMULATION FOR TELEOPERATIONS IN PLANETARY SURFACE EXPLORATION

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Abstract

Advanced Simulation Techniques (AST) combine interactive technologies like Virtual Environments (VEs), Augmented Reality (AR) and real-time simulation, and finds potential space applications. One of these applications is the exploration of a planetary surface by teleoperated rovers.
This paper presents the Smart Teleoperations Workstation (STW). As an initial result of the research into advanced simulation techniques applied to planetary surface explorations, the STW will be used as a tool for further research. An introduction to telepresence exploration and dynamic rover simulation are given, together with design considerations of the workstation and results achieved. The paper is completed with a discussion and preliminary conclusions, stating that Virtual Environments and Augmented Reality may give the operator an enhanced situational awareness and tools for planning safe trajectories on the basis of numerical simulations rather than trial and error.

1. Introduction

In July 1994, ESA started an in-house study addressing the technical contents for a "LUNAR European Demonstration Approach" (LEDA) [1]. ESA's Lunar Study Steering Group has recently concluded a study to determine Europe's potential role in the future exploration and utilisation of the Moon [2,3]. The permanent robotic presence on the Lunar surface and the demonstration of the capabilities to operate a rover system under a wide range of surface conditions and distance are a challenge, e.g., operating in the shadow of local structures and permanently dark areas, and even in radiographic dark areas. Such a rover must also be able to detect and avoid obstacles autonomously. The rover and most of its equipment should be remotely controlled from a ground control station on earth.
Teleoperations is the technique to control a remote robot platform. Operators controlling the manipulators usually perform their task by indirect manipulation, i.e., pushing of buttons and pulling of levers. In so-called "operator-in-the-loop" situations, the task of the operator is even more difficult to accomplish. The operator has to evaluate sensor information and has to generate the right control signals. This is a very complex process, especially when there is a marked delay between a command, the resulting action, and the (visual) feed-back of the result of the action. This problem becomes actual in the control of planetary rover vehicles and the manipulation of robot extensions, when control signal round-trip delay can be in order of seconds in the case of Lunar exploration, to tens of minutes for rovers on Mars. In order to overcome the above mentioned difficulties, a new generation of tele-robotics control systems is subject of study and prototype development. It is envisioned that this system will to a large extent be based on the emerging technology known as Virtual Reality (VR) or Virtual Environments (VEs). The situational awareness of the operator can be significantly enhanced, allowing more efficient, effective and safer control of the remote mobile platform and robot extensions by placing the operator in a VE. This VE is an 'exact' copy of the rover's actual environment. The operator is now able to survey the environment. This technique is known as: *telepresence exploration*.
The VE is initially constructed with a priori geometrical data obtained from satellite photo's and/or previous missions. An on-board sensor system surveys the

environment for enhancing and updating the VE (e.g. [4], [5], [6]). Depending on the kind of sensors that are used, the sensor system produces geometrical and visual information on the environment.
Besides surveying, the operator may specify the rover's actions by performing simulation and direct manipulation in the VE. A *simulation model* of the rover should be used, based on a mathematical model of the rover's kinematic and dynamic properties.
The survey and simulation options are necessary to detect zones in the environment which are accessible for the rover and which are not.
The TNO-Physics and Electronics Laboratory (TNO-FEL) developed a prototype Smart Teleoperations Workstation (STW) to verify and test the concept of performing teleoperated task making use of a dynamic rover simulation model within a Virtual Environment.
This paper provides a view on the functionality of the workstation. Chapter 2 describes the workstation. Section 2.1 discusses the design concept of the STW. The design considerations of the station are discussed in section 2.2. Section 2.3 briefly describes operation modes. Chapter 2 is closed with a discussion of the dynamic rover simulation module. Chapter 3 discusses the STW applied to telepresence exploration. Special attention is directed towards the telepresence control modes for a wide range of time delays (Section 3.1). The section is closed with a description of equipment and infrastructure needed for testing and demonstrating the STW. The paper is concluded with a discussion and conclusions in Chapter 4.

2. Smart Teleoperations Workstation

2.1 Design concept

Advanced Simulation Techniques for planetary exploration bring together the fields of computer vision, sensor-based environment modelling, telecommunications, command and control, VE, robotics, and human-machine interfacing. These fields allows the operator, at least in principle, to control a remote robot platform and monitor the state of the platform and its environment.

Figure 1 shows a set-up for a telepresence surface exploration system. This set-up consists of five parts:
1. a robot platform (= rover);
2. a planetary control platform;
3. a data transmission system;
4. a Smart Teleoperations Workstation (STW);
5. an operator.

While traversing through a terrain, sensor data and rover status information are sent via the planetary control platform to the STW. The measurement systems on the rover can be controlled locally or remotely, depending on de complexity of the control process. For example the generation of a rover control program can be achieved by the STW, while obstacle detection can be achieved on-board the rover and/or its control platform. However, large (Moon) to extremely large (Mars) communication distances, result in long delays between the STW and the rover. These long delays are inadmissible for operator-in-the-loop situations: the operator does not see immediately the results on his actions. This means that the process is not controllable. Further, the operator has to be sure that each taken action can be fulfilled without losing contact with the rover and without causing damage to the rover and its equipment (there is no way back).

A solution for these two problems is found in splitting the control loop up in two loops: one loop between the STW and the rover (the actual rover control-loop) and the other between the operator and the STW (the rover simulator control-loop). The essence of these two loops will be made clear on the basis of the functional architecture as shown in Figure 2.

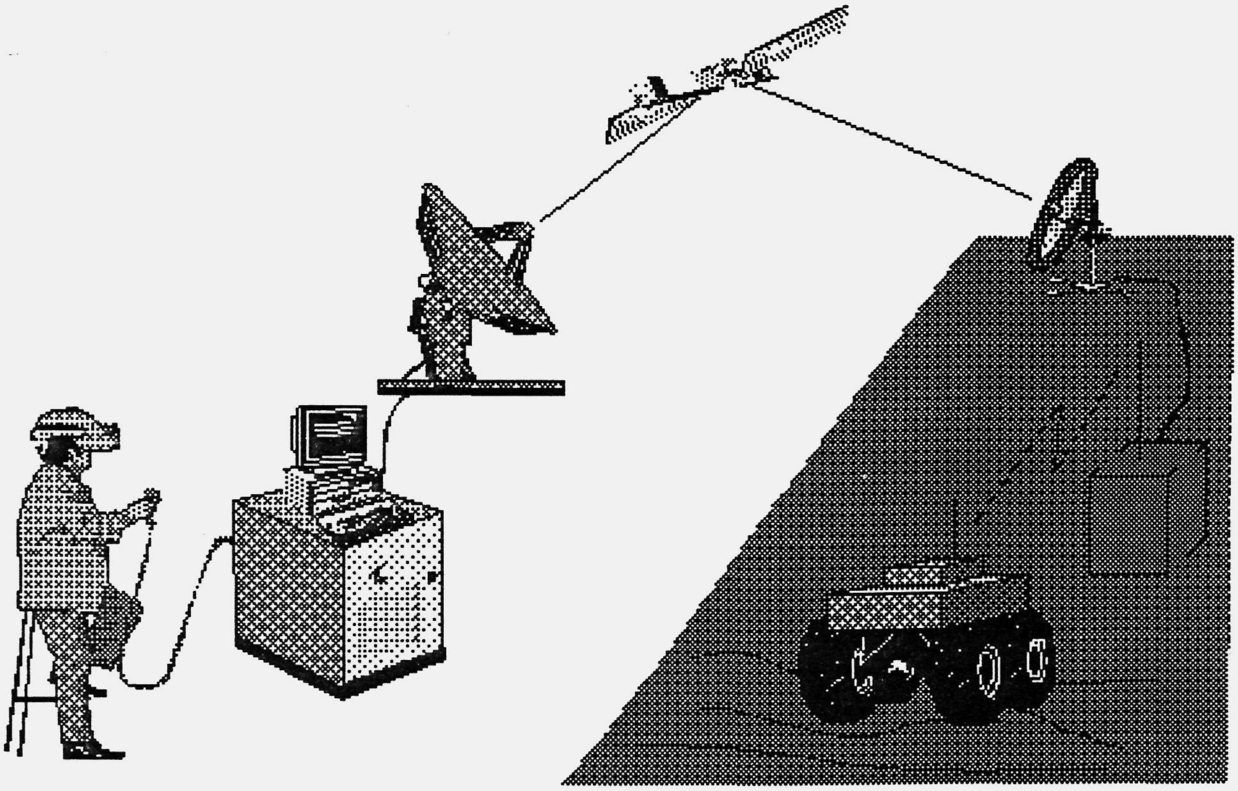


Figure 1: Telepresence surface exploration with Advanced Simulation Techniques.

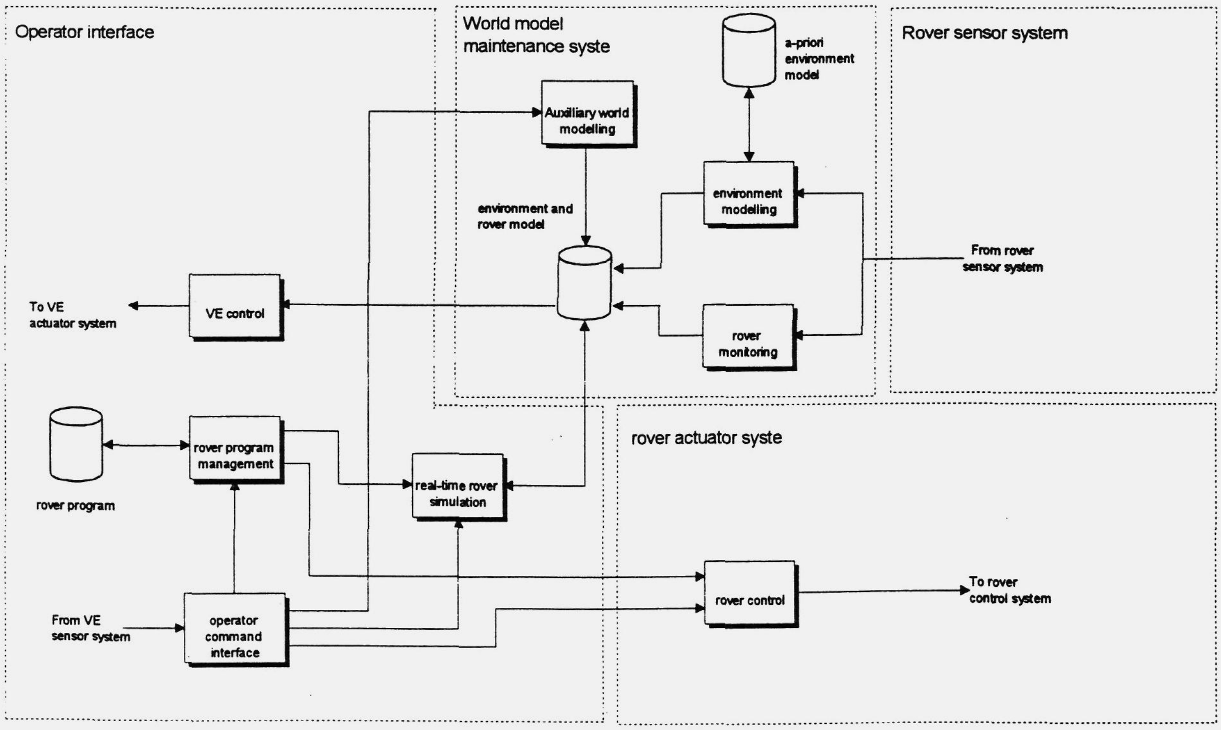


Figure 2: Functional architecture of the STW.

The actual rover control-loop consists of :

- rover sensor system;
- world model maintenance system;
- the store 'rover programs', and
- the rover actuator system.

The heart of this control-loop is a data store that represents all current knowledge on the real and simulated world ("the environment and rover model store" in Figure 2).
With the data, the virtual environment control module generates the user feedback to enhance the situational awareness. This visual feedback can be a copy of the available video images of the remote site, or it may consist of 3D graphics images generated from a synthetic model of the environment. In an optimal situation, an a priori environment is available.
The use of an a priori environment model can be restricted in two ways:

1. The a priori environment will become invalid if the environment changes during the teleoperation;
2. The resolution of the a priori environment model is too low, and/or it is impossible to create a model for certain locations due to the lack of information of the environment.

The environment modelling unit takes sensor data as input from the rover's site and processes this data to either update/refine a given a priori environment model or create a completely new environment model.
The rover monitoring module acquires the state of the rover and all its subsystems. This information is used to align the state of the real-time rover simulation module with the state of the real rover. This alignment ensures that the simulated rover displayed in the VE correctly represents the real rover. The monitoring module can also be used for monitoring state information like battery power state.

The rover simulator control-loop consists of four functional units and two stores:

- a rover program management unit;
- a real-time rover simulation unit;
- an operator command interface unit;
- a virtual environment control unit;
- an environment and rover model store, and
- a rover programs store.

The operator command interface module interprets the user commands from the VE sensor data. This can be, e.g., data from head-tracking sensors, and/or from other VE peripheral devices like a 3D mouse and data gloves. Interpreted commands are sent both to the rover control module and to the rover simulation module (to simulate the effects of the commands).

The rover program management module, allows the creation and evaluation of the rover programs to plan effective, efficient and safe trajectories.
A rover program is a stored sequence of control commands. Programs can be created by controlling the simulated rover (while the rover program management module samples the commands and stores them in a program), and evaluated by replaying the program via the simulated rover. Finally, a rover program is brought into the actual rover control-loop to send it to the rover control unit.

2.2 Design considerations

The architectural design process of the Smart Teleoperations Workstation was guided by four important rules:

1. design to maximum performance;
2. design to minimal latency;
3. design to modularity;
4. design to maintainability.

Obviously, performance should be optimal. To achieve this, the design must exploit multiprocessing whenever possible. As long as CPU data processing is a bottleneck, it should be possible to improve the system performance by adding a CPU to the system.
System latency is a critical issue for a number of functions within the STW. In order for the system to be an effective tool for the operator, the command interpretation, rover simulation and feedback generation loop must be very efficient. Both the rate and the latency of this loop are of crucial importance for the system effectiveness.
The third rule takes the research character of the system into account so that later modifications and extensions can be made easily. For example, the dynamic rover simulation module can be replaced with a module representing a rover of a different kind.
The last rule considers the system's maintainability. Specific operational conditions can be added, removed, or changed without modifying the software but by modifying run-time configuration files. For example, modifications are directed towards:

- display devices (shutter glasses, HMD, etc.);
- input devices (keyboard, 3D-mouse, joysticks, etc.);
- etc.

Through these configuration means, the STW can always be configured to obtain the best possible performance from the hardware available.

2.3 Operational modes

For any teleoperation mission four general requirements may be distinguished, that are essential for the operator to accomplish a task remotely. These requirements for the operator are:

1. obtain a thorough, as complete as possible, situational awareness;
2. get a clear impression of what to do and insight in how to do it;
3. command what has to be done and define how it has to be done;
4. perceive the effects of the actions that have been carried out.

Considering the situational awareness of the operator, the information source, modality of information, and combination of information are of interest for the perception of the environmental status. The operator must have a clear idea of the goal and end status into which he wants to manoeuvre the rover or robot extension (global awareness). The same aspects as apply to the situational awareness apply to monitoring whether the actual end status matches the desired end status.
Interactive control of the movement through the environment is essential to be able to define and verify a route by piloting the simulated rover in its virtual environment. The control of the visualisation parameters is required to be able to adapt the information presented to the task to be performed. The most essential parameters in this respect are the point of view and the viewing direction.
Planning and preparation of operations requires 3D landmarks and waypoints to be assigned by the operator. Also, interesting areas like sampling sites and danger zones, surveyed zones (safe zones) and individual samples like rocks can be indicated within the 3D virtual environment.
The 3D trajectory of the rover (or the robot arm) should be specified by indicating 3D intermediary position stages. For the realistic rendering of the remote site in the VE, the combination of a priori information and (incoming) sensor data is desirable. The integration may be limited to texturing the a priori model database with sensor data derived textures to increase visual realism.
The operator shall be able to pilot the simulated rover across the virtual terrain, where actions and responses of the simulated rover will mirror the actual rover at the same time. These actions and responses are derived from dynamics simulations, and are essential for the operator to judge whether intended operations are feasible or not. Simulation results are available via computer generated imagery indicating the dynamics behaviour of the rover and in a simulation run history log for re-evaluation of the simulation program.
The four requirements are implemented within the STW in four operation modes:
1. Survey mode,
2. World modelling mode,
3. Rover control mode, and
4. History playback mode.

Survey mode
This mode provides the operator tools to survey the (unknown) environment. The operator takes interactively new view points which might be constrained by height to suggest that the operator walks across the terrain or unconstrained to suggest that the operator flies above the terrain. The operator viewpoint can also be linked to the rover's position and orientation (see figure 2). The type of information that is displayed visually can be controlled by the operator. Via menus, the operator can request visual feedback on the environment model, the real environment (direct display of sensor data), the status of status of both the actual and simulated rover, and auxilliary information (e.g. the planned trajectory, danger zones).

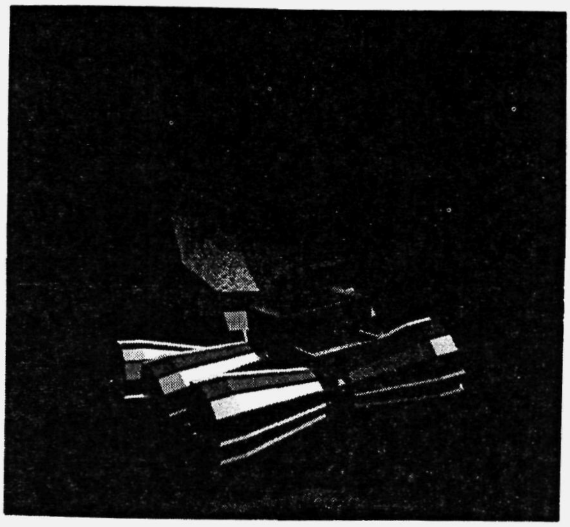
World modelling mode
The world modelling mode provides the operator tools to maintain the environment model and, to add, remove and edit auxiliary information to the VE.
The operator is able to load an a priori environment file that is obtained during previous missions. This environment model can be improved by updating the environment model with new received sensor data.
The auxiliary information can be composed of four types of elements:
- geometries;
- trajectories;
- dead zones, and
- safe zones.

A geometry is used for marking locations to carry out special tasks. For example, the location for sampling the soil can be marked with a spade.

A trajectory visualises the planned path to be traversed by the rover. Within the VE a path can be visualised with a tunnel. This tunnel can be used as a guide while driving through the terrain.
In most of the cases the terrain is not completely accessible. These locations can be allocated as dead zones. Entering these zones can cause damage to the rover and/or its equipment, or the rover can be locked between, e.g., rocks. These dead zones can be marked with railings, or walls.
On the other hand, some areas might have been explored with a high level of detail. This means that it is not necessary for the rover to turn on all survey sensors for traversal purposes. This might be important at times of energy-famines.
Further, the operator gets a good impression of which part of the terrain is explored and which is not. Leaving a safe zone requires that all necessary sensor systems are turned on. As dead zones, these areas are marked with, e.g., railings.

Auxiliary world modelling information can be presented in a number of layers. These layers can be visualised, manipulated and visualised independently from each other.

Rover control mode
The rover control mode supports the operator in interactive control of both the actual (see figure 4)



Figu re 3: The simulated rover in action.

and the simulated (figure 3) rover. The simulated rover can be controlled in preparation and execution mode and the actual rover is controlled in execution mode. The preparation mode provides the operator with tools to plan a safe and efficient trajectory for the rover. The key tool for this purpose is a fully dynamic simulation of the actual rover with real-time performance.
The position and the orientation of the actual and the simulated rover can be visualised simultaneously in both preparation and the execution mode to enable the operator to get a complete overview of any diversion of the intended trajectory and the actual trajectory. The position and orientation of both the actual and the simulated rover are stored in a history store.

History playback mode
The history playback mode supports the playback and examination of an earlier recorded history file of the actual or the simulated rover. The loaded history record can be played both forwards and backwards at different speeds.

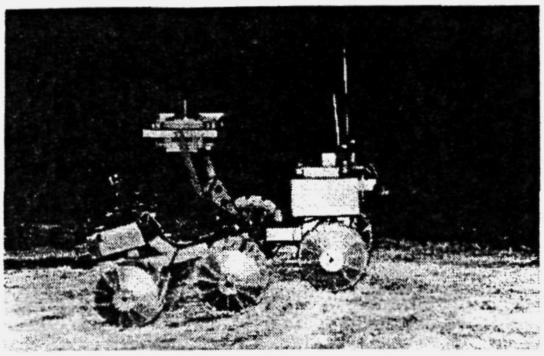


Figure 4: The actual rover in action..[1]

2.4 Dynamic rover simulation

The dynamic rover simulation is based on BAMMS (Bondgraph-based Algorithm for Modelling Multibody System) [7]. BAMMS is a multi-body modelling and research environment by TNO Road-Vehicle Research Institute to simulate the dynamics of vehicles. Models of dynamical systems in BAMMS are stored symbolically. The advantage of symbolical multi-body codes is that the resulting representations of model behaviour is stored in program code. Thus, generated simulation models can be compiled and linked with other software. This means also, that for adding new features to the construction of the rover model, software has to be compiled again. The software does not need to be compiled again, in cases of adapting model parameters like gravity, geometry and inertia data, stiffness and damping ratios, friction, etc.

BAMMS uses so-called Newton-Euler equations to describe the dynamic behaviour of bodies in space. All degrees of freedom are absolute and with respect to a fixed reference frame. The gravity acceleration itself is a model parameter and can be set to any value, e.g., the gravity value of Mars or Moon.
The model of the rover contains three 3D bodies: front body centre body and the rear body. A number of components define one extra rotational degree of freedom for the centre body, the front and rear axle levers and for each of the 6 wheels on the vehicle.

A BAMMS body module in 3D space introduces 6 degrees of freedom. These degrees of freedom are:
- The three components of the velocity of the centre of gravity parallel to the global frame;
- The three components of the angular velocity of the body module. Angular velocities are described parallel to the body fixed frame of the body.

[1] A demonstration by ESA of teleoperating a TNO-rover at the ESA stand during the Lre Bourget international air- and space show in 1995

In BAMMS, typically the bodies in a system are connected using a library of connection elements. Most of the available connection elements do not introduce extra mass. Depending on the selected type of connection, a number of degrees of freedom of a model are removed. Some of the available connection elements introduce force elements (like linear or non-linear spring dampers) that still allow some deformation in the system. Different connection elements are available for introduction of point connections, line connections and/or beam connections. In the rover model, the different body components are connected using two point connections. An overview of the model components are presented in figure 5

The complete rover model consists of 13 degrees of freedom. Rotation of the 6 wheels and the front and rear lever are defined as externally driven motors. The input for these motors is controlled in the STW system (i.e. by the operator).

The lateral contact between wheels and the environment model is defined by friction laws. An advanced contact point algorithm is implemented to allow real-time simulation over an unlimited range of articulated road surfaces.

3. STW applied to telepresence exploration

3.1 STW control modes

The smart teleoperations workstation supports the operator in controlling the rover in a wide range of time delays:

- A neglectible time delay ($\Delta t \approx 0$ s) ;
- A small but not neglectible time delay ($\Delta t \approx 1$ s) ;
- Large time delays ($\Delta t \gg 1$ s) ;

A rover control system without any time delay is the most simply way of controlling a rover. The operator has direct control over the rover, and all rover actions are directly visualised to the operator, e.g., by passing stereo images from the rover to the operator. The awareness can be increased further by using a pan and tilt stereo camera platform to follow the head movements of the operator.

In case of small but not neglectible time delays, actual sensor and rover actions are visualised to the operator after a while. Usage of only a sensor control system will result in a unstable control system. In this case the STW has to be supported with a rover simulator to predict rover states for a short period of time. These predicted states give the operator a first feedback on the taken actions. The real rover state data will be monitored to the operator as soon as real sensor data becomes available from the actual rover. In case of driving a rover, the predictived rover position will be visualized as a graphical overlay on the most actual images of the environment (Augmented Reality). In practice, an acceleration of the rover leads to an increase of distance between the operator and the virtual rover model. The virtual rover comes closer at a decreasing acceleration and shall coincide with the actual rover model if the rover comes to a standstill. The position of the simulated rover is equal to the position of the actual rover

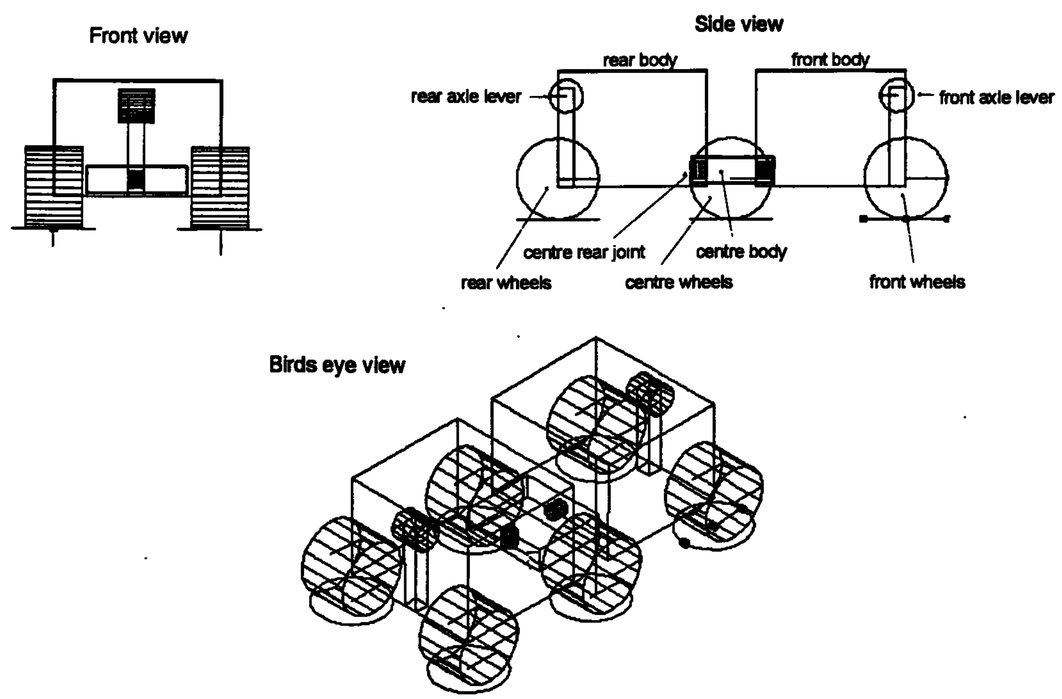


Figure 5: Views on the rover model

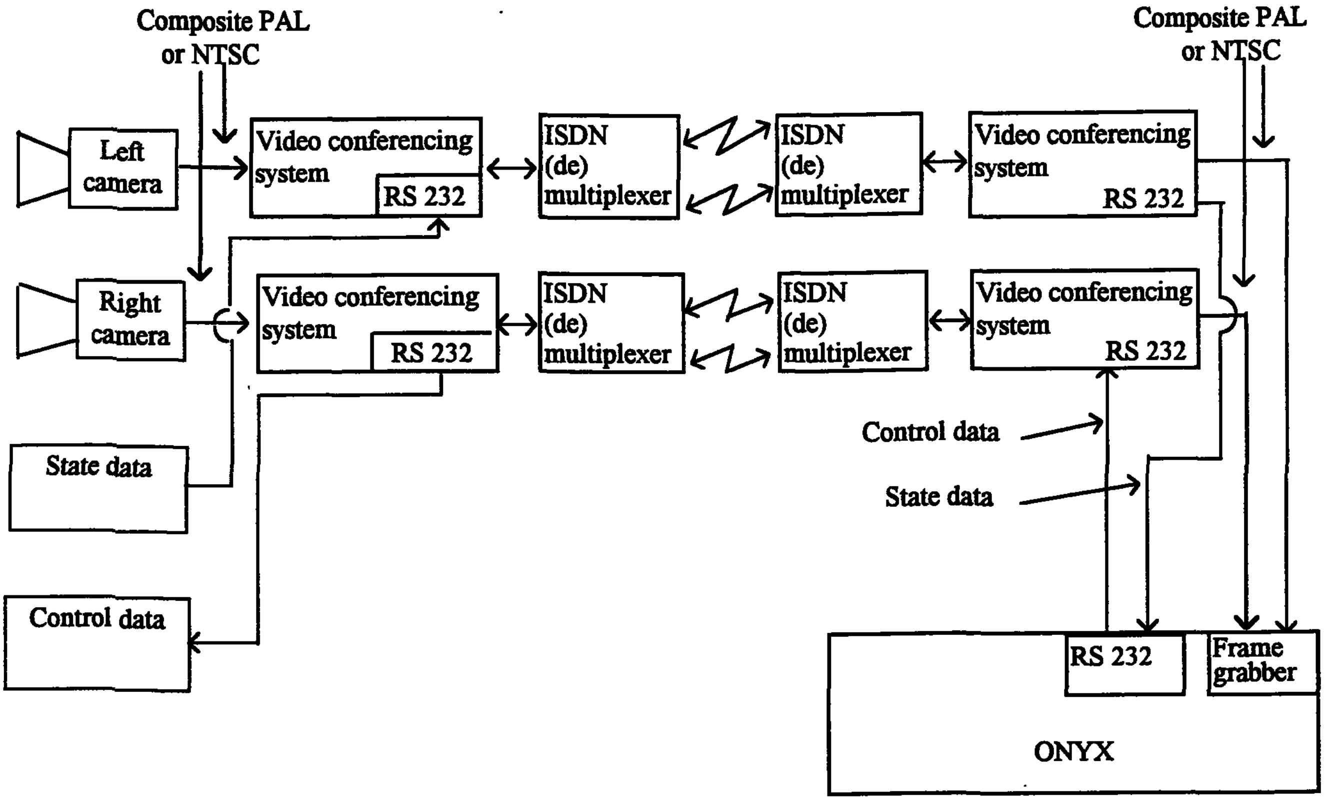


Figure 6: Telecommunications infrastructure of the STW test site

Large delay times can only be handled with a sophisticated control system that simulates all rover actions within a virtual environment. Due to the large time delays, the rover states have to be simulated over a large time domain. Therefore, the simulations have to be more accurate than in the predictive mode.

<u>3.2 STW test and demonstration</u>

The following infrastucture and equipment are essential for testing and demonstrating the STW:

- a rover;
- a test site;
- a telecommunications infrastructure.

Rover
A six-wheel rover has been developed by TNO (see figure 4). Although it has a space-look, the rover is not space proof and is intentionally designed for Earth-based use on rough terrain. This rover was used by ESA for demonstration purposes at the air- and space show "Le Bourget '95", where a laser positioning system[1] was used to determine and to monitor the global (actual) position of the rover in the terrain. The rover is provided with a stereo imaging system. Stereo images and rover position data are sent, for example via a ISDN connection, to the STW.

Test site
A terrain can be used as test site for the STW if it fulfils several requirements. The test site must have enough structure to test and determine the performance of the rover and the STW. A Digital Elevation Map (DEM) of the test site has to be available for reconstructing the VE and to simulate the behaviour of the actual rover. Although it is not required, a Moon- or Mars-like terrain is preferable.

Telecommunications infrastructure
Integrated Services Digital Network (ISDN) is a full digital public network for telecommunications purposes matching multimedia needs. It combines public networks and provides high speed data exchange and high reliability. The technology of video-conferencing provides an infrastructure for demonstrating the Smart Teleoperations Workstation on earth.
There are two ways to get access to ISDN, firstly, ISDN-2 utilising two independent telecommunications 'B' channels with a capacity of 64 kbps and one 16 kbps 'D' channel for signalling, secondly, ISDN-30

[1] CAPSY by TNO-bouw

utilising thirty independent 64 kbps 'B' channels (also known as Primary Rate Access or PRA) and one channel with a capacity of 16 kbps for control purposes.
Point to point access can be reached within 2 seconds. Communicating two uncompressed video signals requires at least 120 Mbps channel capacity. This capacity can be reached with 64 channels with PRA. Each PRA is composed of 30 channels with a single channel capacity of 64 kbps. To reduce the number of PRA channels, data compression is necessary. For that purpose CCITT H.261[2] coding (also known as p×64 algorithm) will be used resulting in an image resolution of 352×288 pixels at 15 images per second (Full Common Intermediate Format FCIP), or an image resolution of 176×144 pixels at 15 images per second (Quarter Common Intermediate Format QCIF).
Figure 6 shows a design of a telecommunications infrasrtructure for the STW. Two complete video-conferencing systems are needed for stereoscopic vision. Multiplexing and demultiplexing of video signals are necessary if more than one ISDN channel is used per image frame. The exchange of state and control data takes place via a RS-232 port on the video-conferencing system and provides a maximum data rate of 19,2 kbps.

4. Discussion and Conclusions

4.1 Discussion

The Smart Teleoperations Workstation was developed to assess insight in the feasibility of the usage of augmented reality, virtual environments and teleoperations for explorations of planetary surfaces. The system combines a virtual environment and a dynamic simulation of a robotic platform into a teleoperations system to overcome problems related to telecommunications time delays and the unstructured nature of the remote environment.
The mode mission preparation is introduced within the rover control operation mode to become familiar with the dynamical behaviour of the (virtual) rover and its interaction with the environment and get insight in the limits of the rover system.
After defining the ultimate rover program, the operator switches to the execution mode and runs this rover program. Within this mode control signals are sent both to the simulated and the actual rover. Differences in position between the actual and the simulated rover are eliminated by an alignment of the simulated rover to the actual rover. Differences in target positions of the simulated and actual rover occurs if the parameters of the simulated rover do not corresponds very well with the real rover and/or the virtual environment does not correspond very well with the actual environment.

The spin-off from this study can be found in each part of the STW. Example applications in the space domain can be found in design and design evaluation, training, and teleoperations:

- future scenarios and related systems for planetary surface explorations;
- ergonomic human-computer interfaces;
- rover/manipulator concepts;
- sensor systems;
- Distributed Interactive Simulation (DIS) concepts for teleoperations simulation;

Training of:

- assessment of sensor-based situational awareness;
- rover/manipulator control.

Teleoperations of:

- rover for various purposes;
- manipulators for various purposes.

The STW can be used as a platform for evaluating topics concerning human behaviour like:

- mastering (large) time delays and jitters in time and/or space while avoiding unstable performance;
- mastering nonanthropomorphic tele-robots;
- sensorimotor performance (e.g., haptic feedback from the dynamic simulator to the control joystick);

4.2 Preliminary conclusions

In conclusion, the development of the "smart teleoperations" workstation based on the utilisation of virtual reality technologies and real-time dynamic rover simulations to control an existing rover is feasible to overcome problems related to telecommunications time. However, the usability of such a system remains to be demonstrated. The prototype STW developed by TNO is that generic in nature that it can be adapted to teleoperations applications in domains including transport, nuclear, defence, nautical, health and agriculture.

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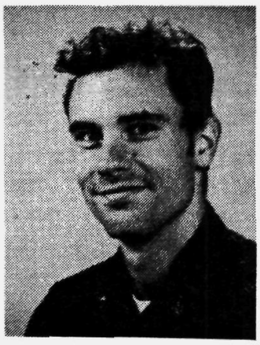
About the author



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About TNO-Physics and Electronics Laboratory

The TNO-Physics and Electronics Laboratory (TNO-FEL) is a contract research organisation operating in the field of Command & Control, Communications and Information Technology. Expertise in the field of (distributed interactive) simulators is based on a thorough understanding of interactive multimedia including Virtual Environments, distributed computing, computer-generated imagery, and information technology.

About TNO Road-Vehicles Research Institute

The TNO Road-Vehicles Research Institute is a contract research organisation operating in the field of small, medium-size and heavy road vehicles. The institute is constituted of four departments: Internal Combustion Engines, Crash and Injury Prevention, Homologation, and Vehicle Dynamics.
Key activities of the Vehicle Dynamics Department are:

- Vehicle-driver dynamics and criteria for stability and manoeuvrability of single and double-tracked vehicles.
- Determination of dynamic behaviour of on-road and off-road vehicles by means of experimental research, linear and non-linear mathematical modelling and simulation.
- Optimisation of vehicle design properties.
- Quality aspects of small vehicles and vehicles for handicapped people.

Voordracht gehouden tijdens de 453e werkvergadering