PROJECTIVE VIRTUAL REALITY: A NOVEL PARADIGM FOR THE COMMANDING AND SUPERVISION OF ROBOTS AND AUTOMATION COMPONENTS IN SPACE

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Abstract

Smart man machine interfaces turn out to be a key technology for service robots, for automation applications in industrial environments as well as in future scenarios for applications in space. Experience at the Institute of Robotics Research in this field showed that intuitively operable man machine interfaces can be developed most efficiently, if a twofold approach is taken. On the one hand the capabilities of the automation system is enhanced in a way that they can act and react more autonomously, but on the other hand, the development of an intuitively operable virtual reality based man-machine interface is pushed further to be able to command and to keep control over the system. Latest results gained from the realization of the ground control station for the Japanese space robot ERA proved impressively, that the realization of a man machine interface based on modern virtual reality (VR) techniques is a promising approach for a new command and supervision interface that is intuitively operable. The general aim of the development which has been used for the ERA robot was to provide the general framework for „*Projective Virtual Reality*" which allows to „project" actions that are carried out by users in the virtual world into the real world with the help of robots and other means of automation.

1 Introduction

When autonomous systems with multiple agents are considered or when intuitive control of automation means over long distances is required, conventional control- and supervision technologies are often inadequate because the amount of information available is often presented in a way that the user is effectively overwhelmed by the displayed data. New virtual reality (VR) [1][7] techniques can help to cope with this problem, because VR offers the chance to convey information in an intuitive manner and can combine supervision capabilities and new, intuitive approaches to the control of autonomous systems. In the approach taken, control and supervision issues were equally stressed and finally led to the new ideas and the general framework for *Projective Virtual Reality*. The key idea of this new approach for an intuitively operable man machine interface for decentrally controlled multi-agent (= different robots and automation means) systems is to let the user act in the virtual world, detect the changes and have an action planning component automatically generate task descriptions for the agents involved to *project* actions that have been carried out by users in the virtual world into the physical world, e.g. with the help of robots. Thus the Projective Virtual Reality approach is to split the job between the *task deduction in the VR* and the *task "projection" onto the physical automation components* by the automatic action planning component [4] (see chapter 4). Furthermore, the presented new approach to virtual reality based man-machine interfaces for automation applications allows to present system status- and sensor information by means of intuitively comprehensible metaphors and visualization aids (chapter 5).

2 Applications of the Virtual Reality System

Practical experiences with the control of a multi-robot system showed, that with a new *task deduction* capability of the realized Virtual Reality system and the corresponding *action planning component* a new quality of intuitive controllability, observability and system safety can be provided. The methods and techniques described in this paper have been developed and tested for two space robotics applications and several industrial applications related to flexible assembly workcells. The two space robotics applications were most challenging in the way, that the new techniques of Projective Virtual Reality as a man machine interface have been applied in the most comprehensive manner.

Proc. Fifth International Symposium on Artificial Intelligence, Robotics and Automation in Space, 1-3 June 1999 (ESA SP-440)

2.1 Commanding the Japanese ERA Robot

Already in 1996, the Japanese Space Agency NASDA and the German Space Agency DLR agreed on a Memorandum of Understanding (MOU) in the field of space robotics. A major part of this agreement was related to the Japanese ETS-VII (Engineering Test Satellite) which has been developed by NASDA to perform Rendezvous & Docking (RVD) and Space Robotics (RBT) experiments.

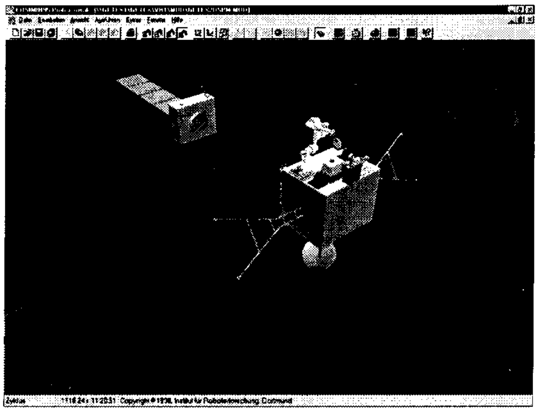

Fig. 1: Simulation of the Japanese ETS-VII Satellite

NASDA and the German Space Agency agreed on a cooperation project where the German side contributes the on-ground robot control and command station, which combines enhanced robot control and latest virtual reality techniques to provide intuitive control and supervision of the robot arm ERA onboard the ETS-VII. In April 1999, a team of the IRF traveled to Tsukuba, Japan, to install and run the ground control station based on the Projective Virtual Reality methods described in this paper.

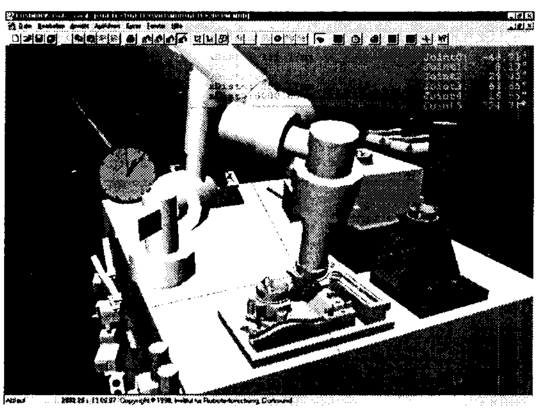

Fig. 2: View of the Projective Virtual Reality system to control and supervise the ERA robot

The mission in April 1999 was a great success. In five missions, different experiments were carried out which were safely commanded and supervised by the IRF ground station. The experiments ranged from simple routine tasks like gripper attachment and detachment over assembly benchmarks to manipulation tasks under force/torque control. (Details about the missions and the experiments can e.g. be found under http://www.irf.de/getex).

In cooperation with our Japanese colleagues, we even had a *world premiere*: For the first time, a space robot was commanded and supervised on-line by means of a "immersive virtual reality interface" based on helmet and dataglove — without previous off-line preparations and detailed pre-checks of the generated robot commands to be expected. Figure 3 shows Dr. Misushige Oda, Principal Investigator at NASDA, controlling the ERA robot by means of the IRF Projective Virtual Reality system. Dr. Oda successfully commanded a mission of the ERA robot after only 10 minutes of introductory training.

Fig. 3: Dr. Mitsushige Oda, Principal Investigator at NASDA, controls the first IRF experiment by means of a data-helmet and a data-glove.

The basic ideas of Projective Virtual Reality comprising task deduction, task "projection" and commanding and supervision metaphors that will be discussed below could fully be applied to the ERA application; this new paradigm proved to be very successful.

2.2 Applications in "Internal Space-Laboratory Servicing"

The very first and the still the most comprehensive application of Projective Virtual Reality was to provide the man machine interface for the multi-robot system in the CIROS-(Control of Intelligent Robots in Space) testbed (fig. 4), a multi-robot system developed for space-laboratory servicing. CIROS, as a multi-robot system, is more complex than a single-robot system like ERA and thus allows to demonstrate convincingly how to exploit the inherent flexibility of a multi-agent system automatically by means of the new Projective Virtual Reality system. Thus CIROS will serve as the main example in the further discussion.

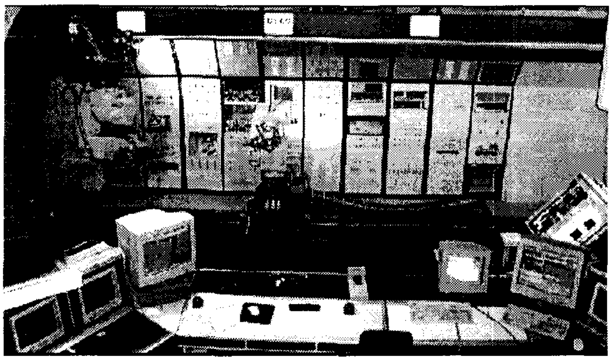

Fig. 4: The CIROS multi-robot testbed

The testbed developed in the CIROS project [3] is equipped with two redundant robots with 6 revolute and one prismatic axis each (fig. 4). The layout of the laboratory is similar to that of the Columbus Orbital Faciliy (COF), the European contribution to the International Space Station (ISS). Six racks, switches and other operating elements of the experiments were reproduced and arranged in order to be performing realistic operational sequences. A tool exchange capability and force/torque-sensors have been included to allow the robots to operate autonomously under the multi-robot-control IRCS developed at the Institute of Robotics Research.

The redundant two-armed robot configuration with the force/torque-sensors at the robots' wrists permit fully coordinated operation, similar to the cooperation capabilities of two human arms, as well as synchronized or independent action of the two robots, working together like a team. Furthermore, the robots are equipped with hand cameras and the whole laboratory can be supervised by a scene camera.

For this multi-robot-system, the VR-based man-machine interface allows the intuitive commanding of new tasks and permits the checking of status information and the intuitive „presentation" of warning messages as well as messages concerning the successful completion of tasks. While designing the virtual environment for the CIROS testbed, emphasis was laid on providing „a familiar environment" to an experimentator who conducts experiments in the space laboratory from ground with the help of the Projective VR system. In order to „immerse" into the virtual reality, the experimentator wears a head-mounted-display (HMD) and a data-glove. Both tools are equipped with position and orientation sensors, so that the location of the HMD and the data-glove are known to a graphics workstation which generates the virtual, graphical image of the environment with respect to the operators position and viewing direction. Furthermore, a graphical image of the operators hand is shown, which allows to operate in the virtual environment (Fig. 5). For cost-sensitive applications, a desktop VR version is available that works with shutter glasses to provide a stereoscopic view into the workcell.

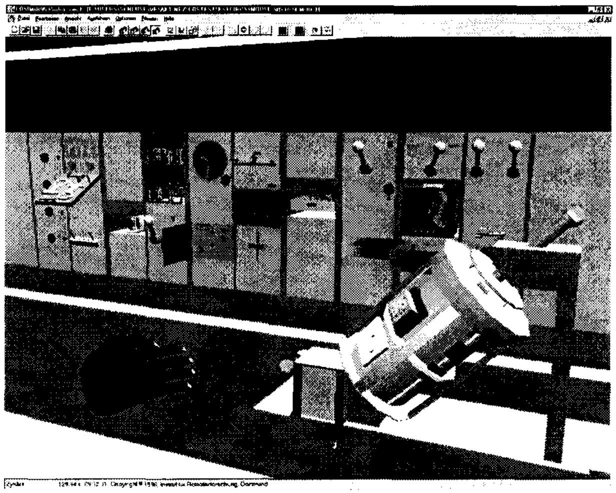

Fig. 5: The virtual laboratory

3 The Idea of Projective Virtual Reality Based Control

When we started to control the robots via VR, we immediately found that the standard teleoperation or "hand-tracking" approach would not work for most of our applications which contain assembly tasks [1][2]. The following problems arose:

- Time delays between the display of a robot's movement in the VR and its physical movements are critical for the stability of the process, because, similar to standard teleoperation approaches, the user is still "in a realtime control loop".
- The graphical model has to be very precise.
- The measurement of the position and orientation of the data-glove has to be very precise.
- Measures have to be taken to reduce "trembling" of the operators hand.
- A versatile sensor-control is necessary to compensate for unwanted tensions when objects are inserted into tight fittings.

To cope with the problems mentioned above, the previously mentioned *task deduction mode [5]* was developed. The solution was to enhance the VR-system in the way that while the user is working, the different subtasks that are carried out by him are recognized and task descriptions for the IRCS, the multi-robot control system of the CIROS environment are *deduced* (chapter 4). These task descriptions are then sent to the *action planning component* [5] of the IRCS. The action planning component can "understand" task descriptions on a high level of abstraction like "open drawer", "insert sample 1 into heater slot 1" etc. and thus is the ideal counterpart for the task deduction component of the VR-system. Using this task deduction mode is almost ideal, because:

- The required communication bandwidth is low, because only subtasks like "open flap", "move part A to location B" or "close drawer" are sent over the communication channel.

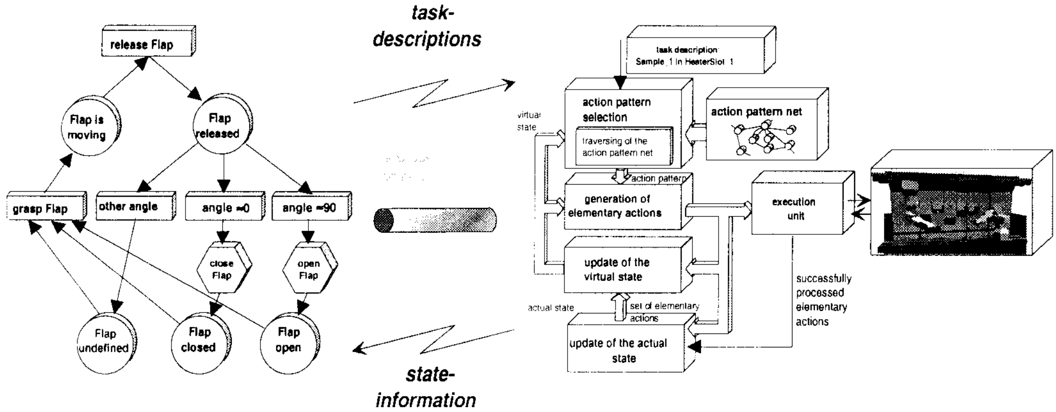

Fig. 6: Cooperation between the petri-nets for task-deduction and the action planning system

- The user is no longer in the "realtime feedback loop". Complete subtasks are recognized and carried out as a whole without the necessity for immediate feedback to the user.
- For assembly tasks, the accuracy of the environment model can be compensated for by automatic sensor-supported strategies.
- The accuracy of the data-glove tracking-device is not as important as for the direct tracking mode. The allowable tolerances when the user is gripping an object or inserting a peg into a hole can be adjusted in the VR-software.
- Different users working at different VR-systems can do different tasks that are sent to the planning component of the IRCS, which then can compute an adequate sequence of the tasks to be carried out, depending on the available resources. Thus one robotic system can serve e.g. multiple experimentators in a space laboratory environment.
- If the robot control is versatile enough, there is no longer a need to even show a robot in the virtual environment displayed to the user; so the user more and more gets the impression of carrying out a task "himself", which is the highest level of intuitivity that can be achieved.
- If the planning component is versatile enough, it cannot only control the robots, but also other kinds of automated devices. The action planning component in the CIROS environment "knows" that to open the leftmost one of the three drawers (fig. 4), it doesn't need to employ a robot. This drawer is equipped with a motor, so that it just has to control the motor to open this drawer. Robot-automated and hard-automated tasks are thus controlled under one unified framework.

In general terms, it is one of the key issues of Projective Virtual Reality is splitting the job between the *task deduction in the VR* and the task *"projection" onto the physical automation components* by the automatic action planning component. The necessary expertise to conduct an experiment in a space laboratory environment like **CIROS** is thus *shared* between the user with the necessary knowledge about the experiment and the robot-control with the necessary "knowledge" about how to control the robots.

4 Task Deduction in the VR-Environment

The task-deduction module relies on messages from inside the VR system. Messages are generated and are sent to the task-deduction module for example when an object was gripped by the user, when an object was released or when the user's dataglove enters a certain region of the environment displayed in the VR.

These messages are interpreted by means of finite-state machines which can be visualized as petri-net structures. These structures determine whether the actions can be combined to a task description for the robotic system. Fig. 1 shows an example of such a petri-net which allows to deduce tasks like "open Flap" or "close Flap" from the actions a user is performing in the VR. Fig. 1 gives a simple example of a task-deduction network which allows to detect whether the user wants to open a flap. As a starting point, the flap shall be closed, so that we have to imagine a mark in the state "Flap closed" in the lower left part of fig. 1. During run-time, the task-deduction component is notified of different events related to user actions in the virtual environment.

For these events, different classes are distinguished, e.g. those related to interactions between the user and the environment by means of the dataglove, events related to user movements and events related to communication between the multi-robot control system and the VR-system. If the user grasps the flap, the corresponding message is evaluated, the "grasp Flap" transition fires, and a state-change in the petri-net is carried out from "Flap Closed" to "Flap is moving" (fig. 1). If the flap is released again, the state changes to "Flap released". For the next transition, the actual angle of the flap's joint has to be evaluated. If, for example, the user opened the flap, the angle is approximately 90 degrees, so that the mark is to be moved to "Flap open". On the way from "Flap released" to "Flap open" in fig. 1, we passed the six-edged "communication-symbol", which indicates, that the task description "open Flap" is to be sent to the action planning component of the robot control system at this time to have the robot perform this task physically.

5 Control and Supervision Aids in the Virtual World

The previous chapters outlined the basic ideas of controlling an automated system by means of Projective Virtual Reality: The user just acts in the virtual world, a corresponding task description is derived automatically by the task deduction component. The automatic action planning component in turn generates programs and commands for the physical automation means in order to have them carry out the corresponding action in the physical world. Besides providing this new control approach, the Projective Virtual Reality system developed at the IRF also realizes new ideas related to supervision, teleoperation and object placement aids to make the work in the VR as effective and as intuitive as possible

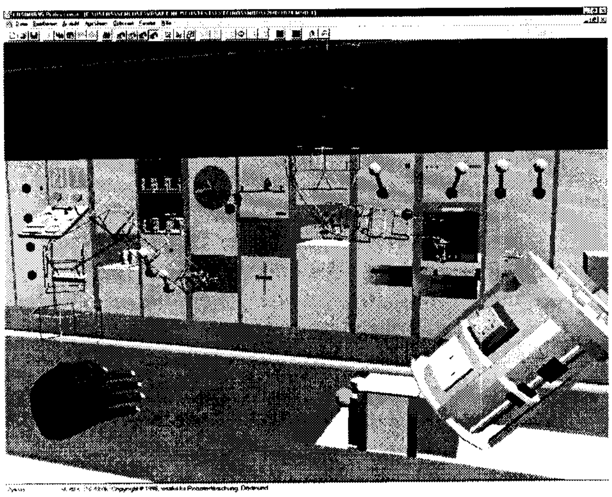

Fig. 7: The CIROS environment in supervision mode

As stated already in chapter 2.2, the virtual environment for the CIROS testbed was designed to provide „a familiar environment" to an experimentator who conducts experiments in the space laboratory from ground with the help of the CIROS-VR-system as shown in fig.5. Please note, that in fig. 5 the *robots are not shown* in order to not distract the experimentators from the experiment they are conducting. But, as our VR system allows to have different views into the same virtual world, the view of the system operator might be different from that of a "plain user", because the operator usually is interested very much in what the automation means are currently doing. So most of the time he will activate at least the simplest supervision aid provided: the image of the physical robots as wireframes (fig.7). The wireframe representation of the robots is only shown in "supervision mode", which can be switched on and off by the user through a simple gesture with the dataglove.

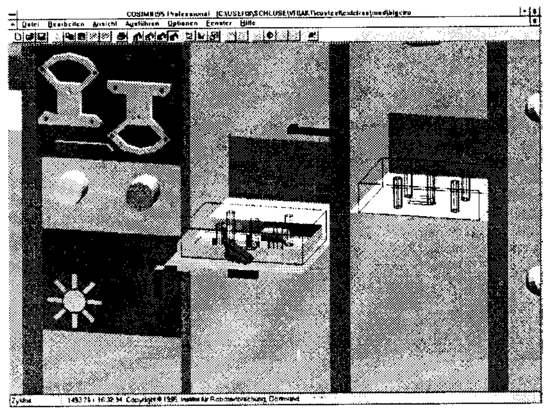

Fig. 8: Position and Placement Aids in the Virtual World.

Fig. 8 shows another two visual aids for the user in the virtual world; the image of the user's hand which has grasped an open sample container is displayed in the center of the left part of fig. 8. The first visual aid is the wireframe representation of the container displayed above the grasped container box. This wireframe — displayed in red on a color display — pops up in the virtual world, when the user approaches a sensible deposit for the object that is currently being grasped. The user may then release the object and it will snap to the wireframe position, so that minor trembling or errors of the dataglove position sensor can be compensated for automatically. The wireframe on the right of the container, the second type of visual aid, indicates the actual position of the physical container in the CIROS testbed which has not yet been moved by the robots. As soon as the robots start to move the physical container, this wireframe will move to the target position determined by the solid container and will vanish as soon as this position is reached thus indicating that the robots carried out the task successfully.

A last field where strong metaphors are necessary is the teleoperation and inspection support in virtual reality. Teleoperation in space applications mostly means, that a specialist at the ground station gets a video image from the robot system flying in space and he controls the robot by means of a joystick or a 6D space mouse. In order to also support teleoperation and video inspection by Projective Virtual Reality a first approach was to have a virtual camera that can be guided to the desired position. To do this, the user just grasps a virtual camera as a metaphor for teleoperation mode and positions it so that the desired object can be inspected. This action makes the action planning component switch the multi-robot control system to teleoperation mode and guide to the desired position a currently available robot that is equipped with a hand camera — as is depicted by the wireframe robot in fig. 9.

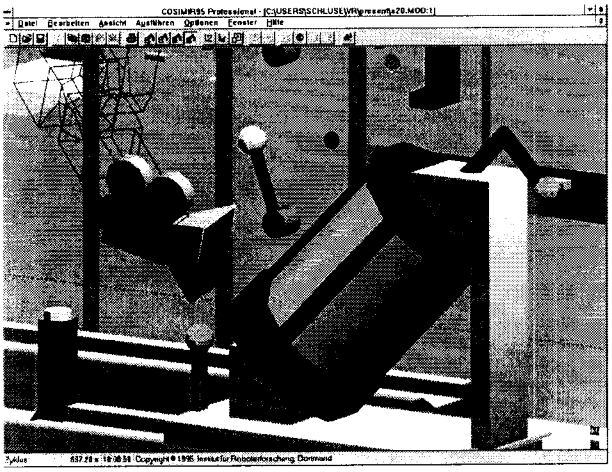

Fig. 9: Teleoperation commanded by the virtual camera

The deficiency of this idea is that the user, after having positioned the camera correctly in the virtual world, has to take off the head-mounted-display to watch the screen with the video image. This is an annoying procedure if applied practically, so that the metaphor of a "TV-View into Reality" was invented.

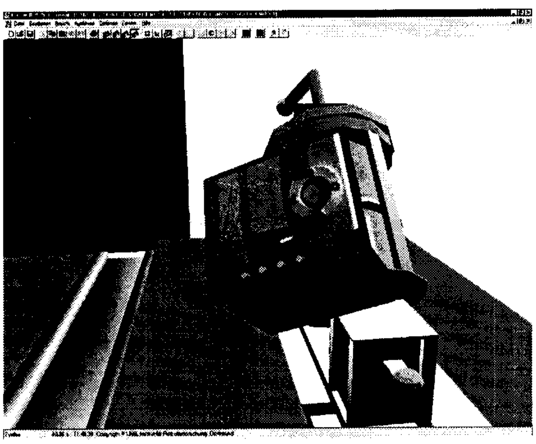

Fig. 10: Inspection with the help of the "TV-View into Reality" metaphor

Fig. 10 shows this new approach for inspection support. Instead of moving around a virtual camera to position the robot's hand camera, we replaced the virtual camera with a virtual TV and on the TV screen the actual video image is shown as a texture. Thus the user does not have to "leave" the virtual reality in order to get visual information about the physical environment. All he has to do is to "watch TV".

Apart from not having to leave the virtual world, this approach has another advantage over the first one: If the robot's hand cameras have to be turned and tilted to show a desired object, most users have difficulties imagining the current orientation of the camera, when they just look at the video screen. With the "TV-View into Reality"-approach, the user in the VR intuitively knows how the physical cameras are oriented by the orientation of the screen of the virtual TV. Most users that tested both methods preferred the virtual TV.

6 Conclusion

The given examples prove that Virtual Reality technology has developed the potential to become a key-technology for the design of modern man-machine interfaces not only for robotics in space environments. Whereas most VR-applications aim at the "plain VR", that is the improvement of the virtual worlds that are displayed to the user, this paper shows the application of new ideas related to *Projective Virtual Reality*, where the aim is to use VR-technology as an intuitively operable man-machine interface for robotic and automation systems. The presented new *task deduction approach* was developed to "project" virtual actions onto robotic systems, that is to make physical robots and other means of automation carry out the same tasks in the physical environment that have been carried out by the user in the virtual environment. Last but not least, the new metaphors to represent system states are a great help to be able to intuitively supervise complex automation systems.

This work was supported by the German Space Agency DARA/DLR under the Contracts No. 7984/40233, 50 TT 9434 and 6-056/0048

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