TELEROBOTICS FOR SPACE COLONIZATION AND INDUSTRIAL APPLICATIONS

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ZUSAMMENFASSUNG

Durch den früheren Entwurf, Forschung und Entwicklung (FuE), die Inbetriebnahme von Telerobotik-Bodenstationen in Raumfahrtzentren für bemannten Flug sowie letztlich ihren erfolgreichen Einsatz in geflogenen Raumfahrtmissionen, haben wir den Weg zur Anwendung der assoziierten Telerobotik-Technologien im Rahmen von Himmelskörper-Exploration und –Kolonisierung geebnet. Erhebliche Kosten- und Risiko-Reduktion bzw. –Vermeidung können bei der Verwendung von Telerobotik in der Missionsplannung eingeplant werden. Schlüsselreiche Konzepte, fortschrittliche Systeme, Astronauten-Robonauten-Zusammenarbeit sowie einige vorbereitende Massnahmen zur Exploration und Kolonisierung des Mondes und des Roten Planeten Mars unter Verwendung von Telerobotik mit besonderem Augenmerk auf Telerobotik-Konstruktion im Weltall werden dargestellt. Industrielle Anwendungen und vorgesehene Demonstrationen, die wir den U.S. amerikanischen Behörden des weißen Hauses, NASA, DoD, State Department und Homeland Security Department Anfang des Jahrhunderts mitgeteilt haben, werden zum ersten Mal hier veröffentlicht.

<u>Schlüsselworter</u>: Astronaut, Exploration, Kolonisierung, Konstruktion, Raumfahrt, Robonaut, Telerobotik, terrestrische Anwendungen.

ABSTRACT

Through the early design, research and development (R&D), deployment of telerobotics ground stations in space centers for manned spaceflight as well as finally, their successful application in flown space missions, we have paved the way for the utilization of the associated telerobotics technologies in the context of the exploration and colonization of celestial bodies. Substantial reduction and avoidance of costs and risks can be foreseen during mission planning, when telerobotics is incorporated. Key concepts, advanced systems, astronaut-robonaut cooperation as well as some preparing measures for utilizing telerobotics in the exploration and colonization of the Moon and the Red Planet Mars with particular focus on telerobotics construction are described. For the first time, industrial applications and foreseen demonstrations are mentioned in this paper, which at the beginning of this century, we have shared with the U.S. American government including the White House, NASA. DoD, the State Department, and the Homeland Security Department.

<u>Keywords</u>: Astronaut, Colonization, Construction, Exploration, Spaceflight, Robonaut, Telerobotics, terrestrial applications.

INTRODUCTION

Since the early 1980's it has been a pleasure to intensively work on conceiving and realizing several of the key space technologies that will allow us to settle and build new habitats for mankind in other celestial bodies starting with the Moon and Mars soon. Examples include the planning of entire interplanetary missions and design of advanced spacecraft avionics [1,2] for NASA as national award winner in the United States of America with my consortium, see Figure 1, as well as having co-elaborated with ESA some of the initial work for the first European mission to Mars [3,4], which is currently orbiting and mapping the Red Planet with algorithms that evolved from my world-wide pioneering work on real-time vision, telerobotics, and autonomous robotics for space exploration and colonization as well as terrestrial applications, see the left part of Figure 2. On the right, the Mars Express High Resolution Stereo Camera (HRSC) is shown.

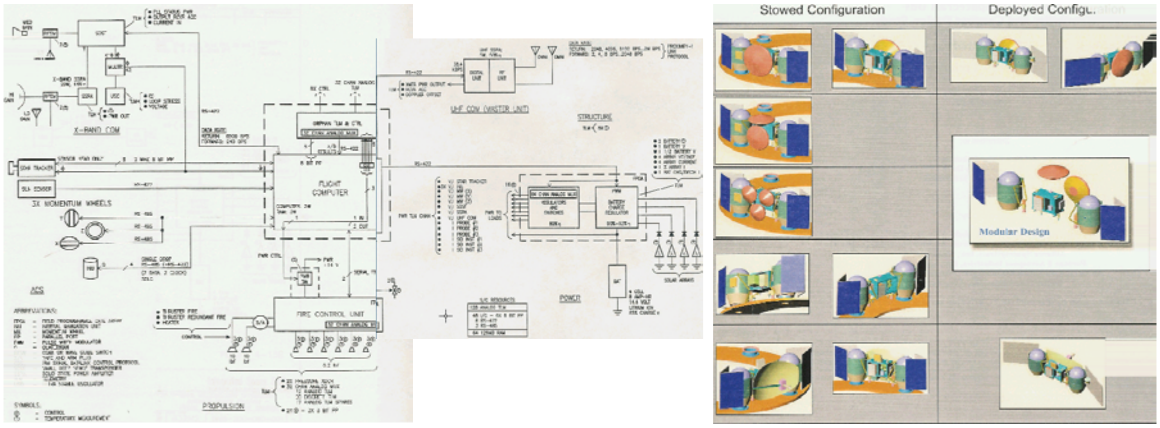

Figure 1. Spacecraft Avionics and Configurations for a Series of Mars Missions

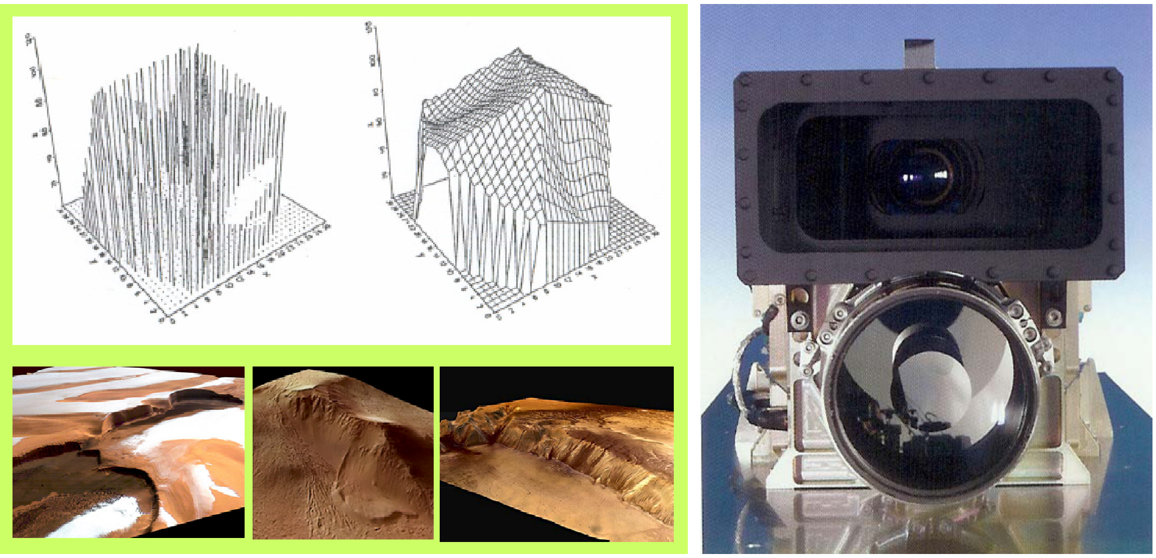

Figure 2. Real-Time 3-D Visual Surface Reconstruction [5,6] and Mapping the Surface of the Red Planet

Among others, my technology R&D work on spacecraft avionics, control and navigation, sensor systems, telecommunications, flight software, test strategies, and infrastructure building for manned and unmanned spaceflight has been very intensive over the years, in particular also for telerobotics and autonomous robotic systems for space exploration and colonization as well as terrestrial applications. Space-related and autonomy/intelligence R&D could be carried out with equal intensity. The combination of these two areas led to innovative concepts, designs, developments, missions, and strategies for advanced space exploration and colonization using autonomous robotic systems with or without human cooperation/interaction [7,8]. All perspectives of the study of intelligence were covered: artificial, behavioral, computational, and more recently biologically-inspired intelligence.

From the very beginning of history I was lucky enough to have been pioneering and leading these areas world-wide. Examples include my participation at the First International Conference on Telerobotics held at NASA JPL in Pasadena, California in 1988, where a potential DLR-NASA cooperation was explored. We finally demonstrated successfully telerobotics and autonomous robots during the DLR D2-space mission with NASA's Spaceshuttle Columbia (STS-55 flight), ESA's Spacelab, and DLR's space robot ROTEX in 1993. The spectacular results of those experiments utilizing a symbiotic cooperation between teleoperators, astronauts, and intelligent-autonomous robots I reported upon special invitation world-wide including at the main NASA and ESA centers. All those activities have built the foundations for more current efforts leading to the development of robonauts, the robotic-artificial version of (human) astronauts.

We focus in this paper on telerobotics, but there is a number of common topics with autonomous and semi-autonomous robotics. For example, Figure 3 shows some of the space exploration rovers for programs I was involved with. On the left is the first miniature rover we designed with ESA at the beginning of the European Mars program, which is currently with the Mars Express spacecraft orbiting and studying the Red Planet. In the middle is a future version of an advanced rover based on the original Marsokhod rover from the Russian space agency IKI, who we planned a cooperation with and for which some of the real-time vision systems I designed as space national lab civil servant in cooperation with the space industry, were conceived for, in addition to being utilized in telerobotics missions [9,10]. On the right, some of my work in advanced concepts and improvements, among others for autonomous flying and ground vehicles for space exploration is outlined [11-15]. To bring a subset of those concepts with realizations to solve terrestrial applications represents in itself a highly desirable goal.

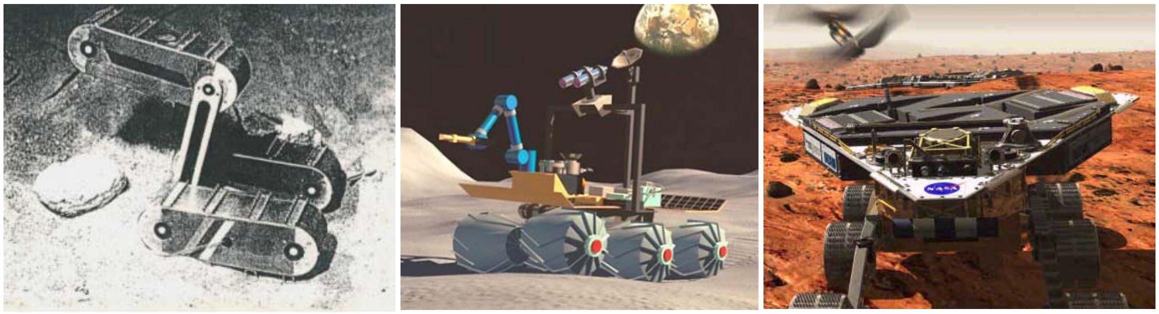

Figure 3. Space Autonomous Robotics Technologies

SPACE TELEROBOTICS CONCEPTS

Basic principles of telerobotics and space robotics can be consulted in [16-19]. To directly visualize some of the main space telerobotics concepts in a real spaceflight mission, we present some of the key aspects of a flown mission, the Robotics Technology Experiment (ROTEX). The space experiment was executed in one of the experiment racks of the Spacelab in connection with the DLR telerobotics ground station, which was originally built for its utilization with this experiment [20] as part of the D2 mission with ESA's space laboratory Spacelab [21-22] during the STS-55 flight on-board NASA's Spaceshuttle [23-24] Columbia in 1993.

Figure 4 shows left and right the start of NASA's Spaceshuttle and the structure of ESA's Spacelab respectively. The modular laboratory design consisted of experiment racks. In the middle, the open cargo bay of the Spaceshuttle with the Spacelab and the D2 payload on top is shown. Spacelab is a pressurized laboratory, which allows research under micro-gravity in Earth orbit. The main parameters of the Spacelab are a payload capacity of approximately 30 tones, a length of almost 25 meters, and a diameter of 5 meters.

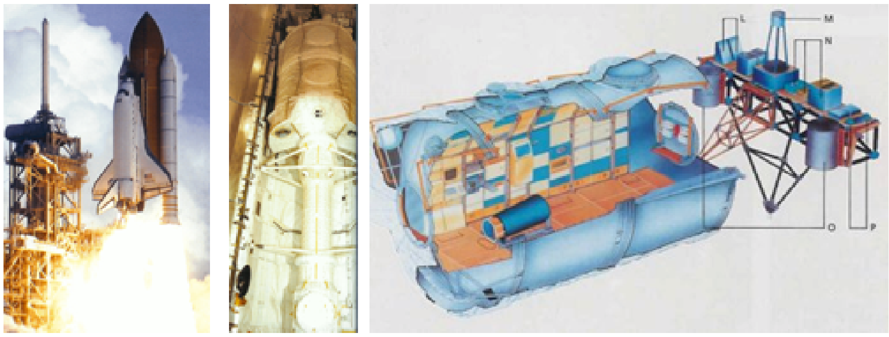

Figure 4. NASA's Spaceshuttle and ESA's Spacelab

Figure 5 shows the data communication channels between the U.S. American Johnson Space Center (JSC) in Houston, Texas and the German Space Operations Center. NASA's JSC controlled flight operations while all experiments were controlled from MSCC. Figure 6 outlines the control structures during the experiment execution with the participation of teleoperators on the ground and astronauts in the Spaceshuttle/Spacelab.

SPACE TELEROBOTICS TECHNOLOGIES AND SYSTEMS

Key technologies that needed to be conceived and developed, and have been successfully applied, cf. [25-26,10, 27-29, 9], include:

- Sensor-based teleoperation with local autonomy,
- Predictive three dimensional computer graphic simulation,
- Multisensory gripper technology, and
- real-time computer vision and result integration with real-time virtual reality environments.

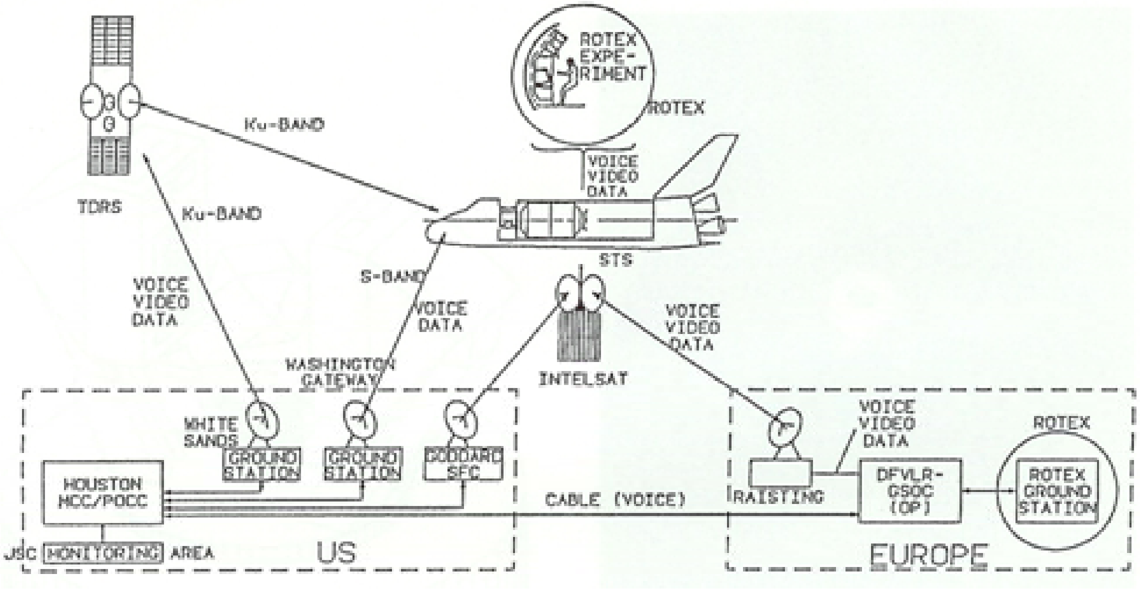

Figure 5. Telerobotics Data Communication Channels

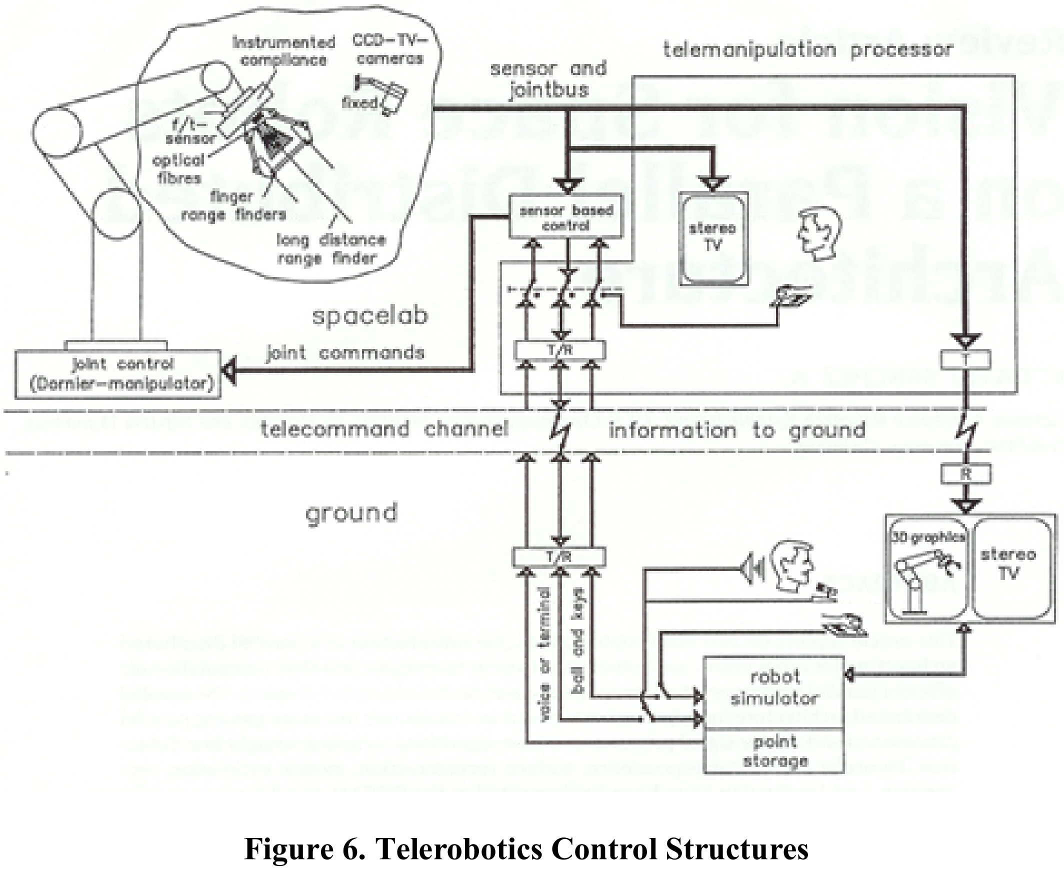

Figure 6. Telerobotics Control Structures

A vast number of trainings-instead-of-programming-oriented technologies have been investigated [30] since the early 1990's and before, e.g., among others in the areas of sensor calibration [31] and robotic control [32], and have been in the meantime also incorporated or are in that process.

We need to remain concise and a lot of details can be found in the provided references. To help visualize the systems involved, which I was fortunate enough to co-design and -build, Figure 7 shows in the left top part, the DLR telerobotics ground station with a substantial amount of graphics rendering of associated workcells in space. In the top right part, virtual reality devices and telecontrol are shown during a space robotic satellite service experiment flown. In the bottom left, the space teammates, astronaut and robonaut, are shown next to one another. In the bottom right, rendering animation of space tasks performing ahead and during the game are shown making use of computer graphics.

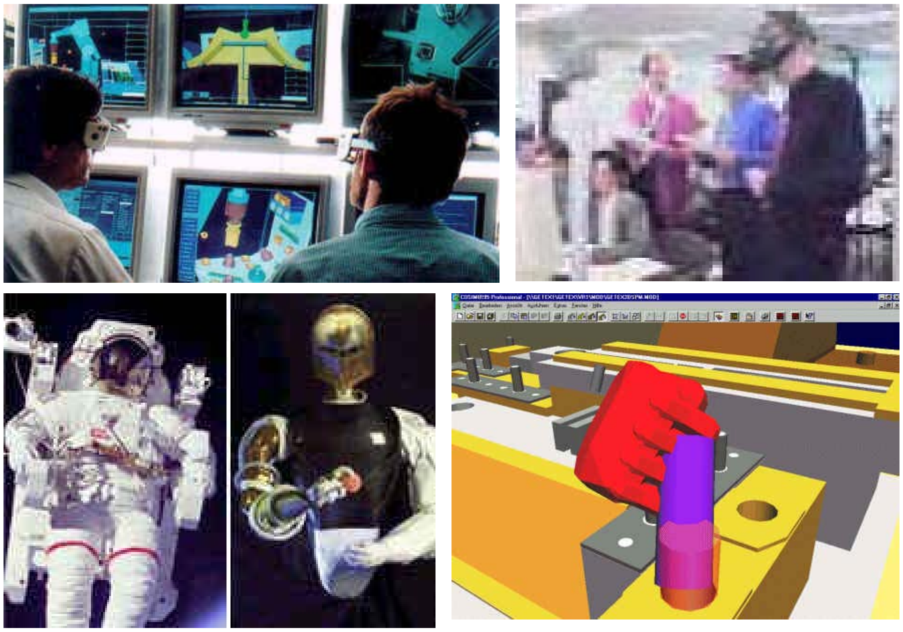

Figure 7. Space Telerobotics Technologies

One of the most difficult areas in telerobotics technology development is the utilization of vision and intelligent procedures. I was pleased to lead world-wide one of the first robot-vision system research, design, development, and actual spaceflight mission deployment efforts in history from my position of space national lab civil servant supervising the cooperation within my group as well as with industry and academia. Figure 8 shows my overall design in the top left part. In the right part, one of a series of prototypes with increasing complexity is shown, based on a scalable, parallel, distributed architecture of parallel, vector signal processors, and special hardware. In the bottom left part, one of two stereo images processed during the actual mission are shown, to the left from a fixed global stereo camera and to the right from a moving robotic-gripper-local stereo camera, which was the tiniest ever built at that point.

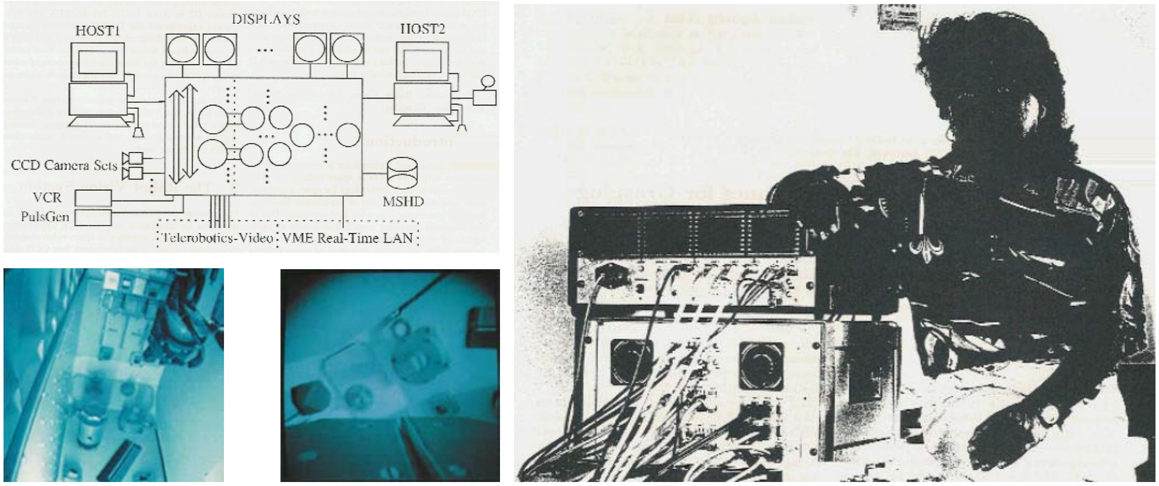

Figure 8. Space Telerobotics Image Processing and Understanding

TELEROBOTICS FOR INDUSTRIAL APPLICATIONS

Figure 9 shows two of several of the testing environments we needed to create to verify the diverse tasks and modes of operation during spaceflight. The shown environments are terrestrial, which link directly to the usage of space telerobotics systems for industrial applications, i.e., the terrestrial ones. Simulative add-on subsystems allowed testing of the spaceborne aspects.

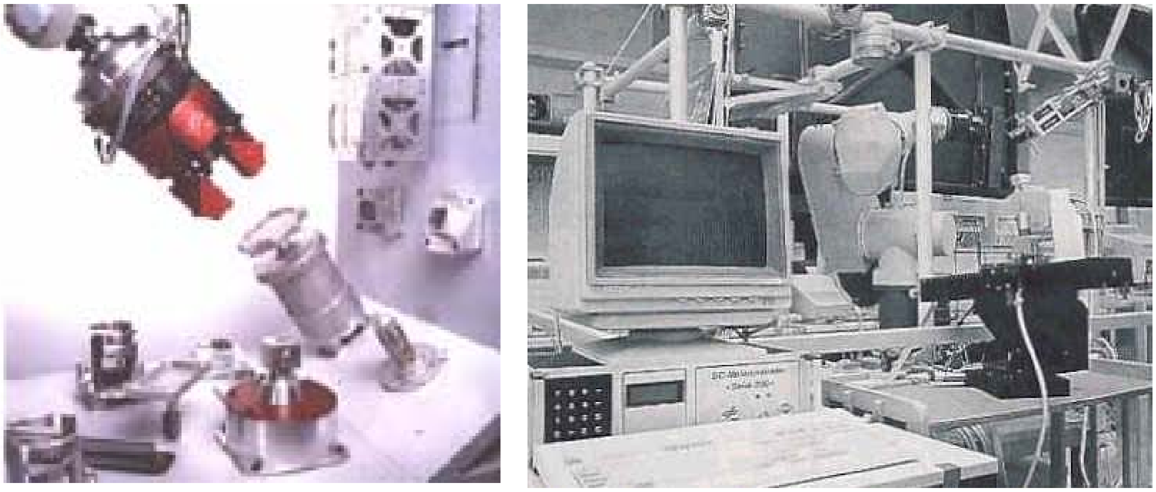

Figure 9. Space Telerobotics Testing Environments

One prominent example of a terrestrial application is telesurgery. A concrete system for this purpose consists of a surgery-specific robotic arm, a control device with kinesthetic feedback for the surgeon, and a stereoscopic laparoscope providing visual feedback. Figure 10 shows on the left an automatic laparoscope guidance system for minimally invasive surgery. The core technology is based on real-time color stereo segmentation and mark tracking in 3-D, the image processing results are used to servo the robotic arm camera. On the right, a future telesurgery system is depicted, which is universally applicable for e.g., heart, abdominal, gynecological, urological, craniofacial, maxillofacial, and spine surgery incorporating among others, enhanced sight, haptic feedback, redundant 7-dof light-weight robotic arms with an order of magnitude better weight to load ratio than the current state of the art.

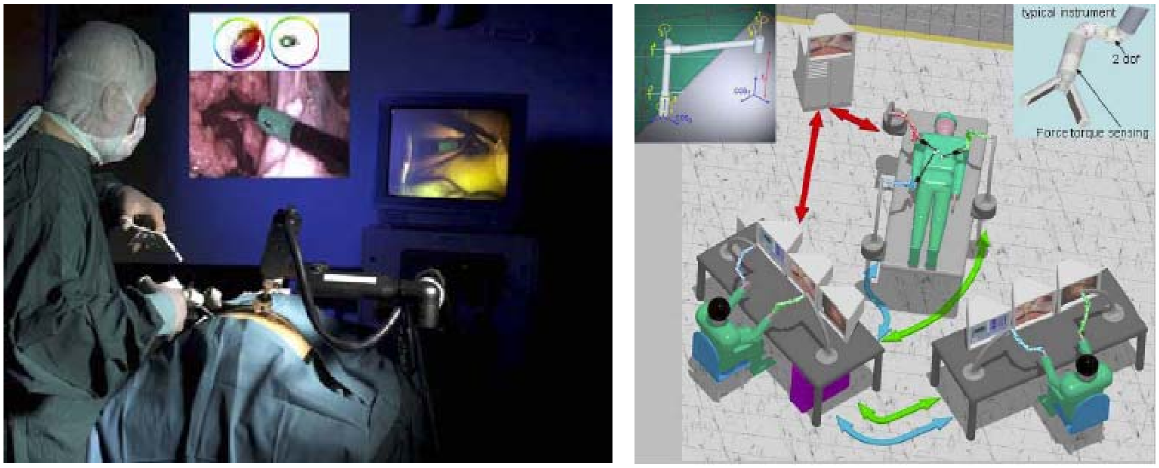

Figure 10. Telesurgery - Present and Future

Spaceborne telerobotics applications include remote capture of non-cooperative satellites as well as spacecraft service and repair. Key applications for the U.S. Homeland Security Department have been put together [33], here due to obvious reasons without further elaboration, among others in the area of expeditious and reliable port container inspection. Figure 11 in the top row shows two of the envisioned robonaut utilization concepts for spacecraft and satellite maintenance and repair (left and mid pictures) as well as to the right, one of the key forms of teleoperation being exercised in a test environment.

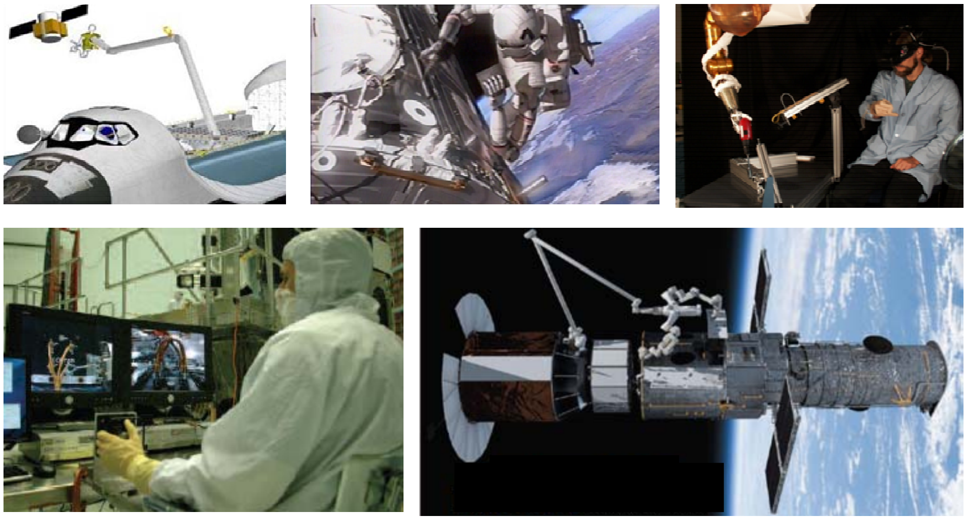

Figure 11. Spacecraft and Satellite Maintenance and Repair

The bottom row of the Figure shows a demonstration in 2004 of performing the necessary tasks for servicing the Hubble telescope robotically making use of the Special Purpose Dexterous Manipulator “Dextre”, a robot with two 7-dof arms, whether under human control with a joystick or operating in a fully automated, pre-programmed mode at NASA’s GSFC and remotely from NASA’s JSC. The other two candidates for robotic servicing are the robonaut and “Ranger”, but are not as ready.

TELEROBOTICS FOR SPACE COLONIZATION AND CONSTRUCTION

Telerobotic approaches for construction I was pleased to share with NASA HQ [34] at the beginning of the millenium. Figure 12 shows highly preliminary concepts now made available to the general public evolving from paper to simulative, graphical analysis, and leading to terrestrial test environments and deployment on celestial body surfaces starting with the Moon and Mars. An entire set of alternatives need to be further conceived and traded off utilizing one, a pair, and populations of cooperating construction robotic assistants working independently, together, with robonauts, and with human astronauts

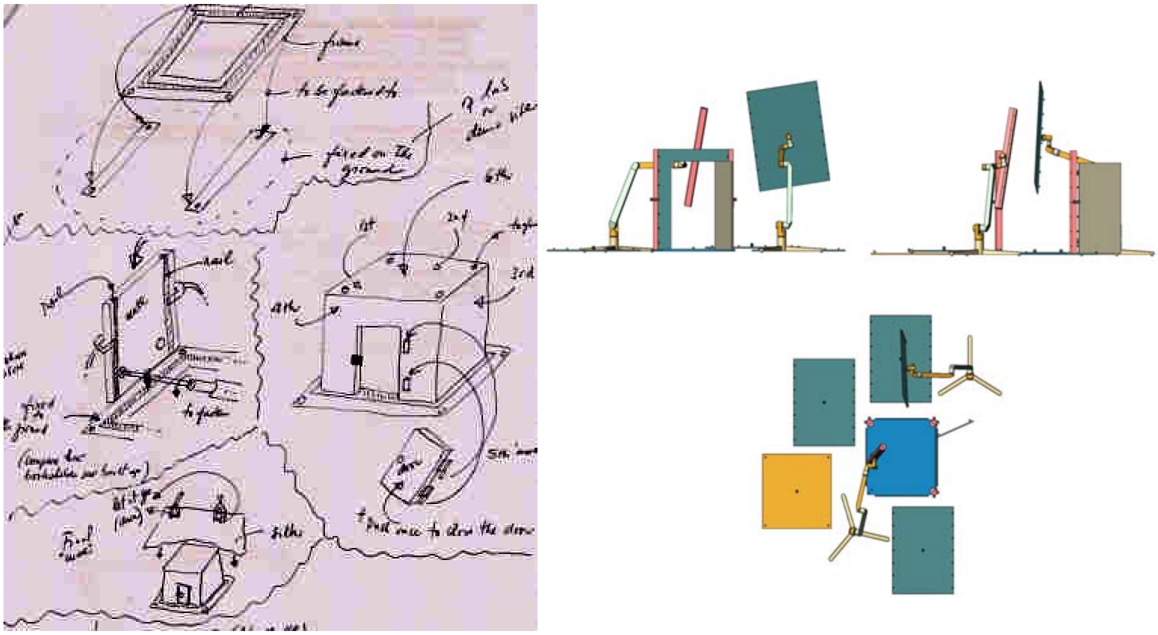

Figure 12. Space Telerobotic Construction Technologies

Figure 13 shows different control stations. On the left, a typical general-purpose ground station at the Manned Space Laboratories Control Center (MSCC) is shown, which I was honored to contribute building during its conception and first spaceflight mission. In the middle a custom telerobotics ground station used for satellite service spaceflight is shown, which is substantially smaller and needs to be connected to the overall general-purpose control station that is in charge of the spaceflight mission. Finally, on the left, another custom telerobotics ground station which I also was honored to co-build is depicted, which we used to train American (NASA) and European (ESA, DLR) astronauts to adequately cooperate with the telerobots while performing spaceflight tasks.

Figure 13. Space Telerobotics Control Stations

Major efforts are still needed at space and related national labs worldwide and innovative concepts, approaches, strategies, and technologies emanating from complementary sectors including academia and industry, hopefully further accentuated and motivated by the NASA's Centennial Challenges program office, which a few hours ago on December 2, 2005 announced the Telerobotic Construction Challenge to support enabling technologies that help robots to perform complex tasks with minimal human intervention. The event organization will be conducted by the Spaceward organization. According to the new priorities set, focused efforts are under way to bring humans back to the Moon as preparation for the first manned mission to Mars. In the framework of lunar exploration and colonization suggested in Figure 14 left and right respectively, it is and should be obvious for the educated expert that telerobotic construction can and should play a major role towards the reduction and avoidance of mission costs and risks.

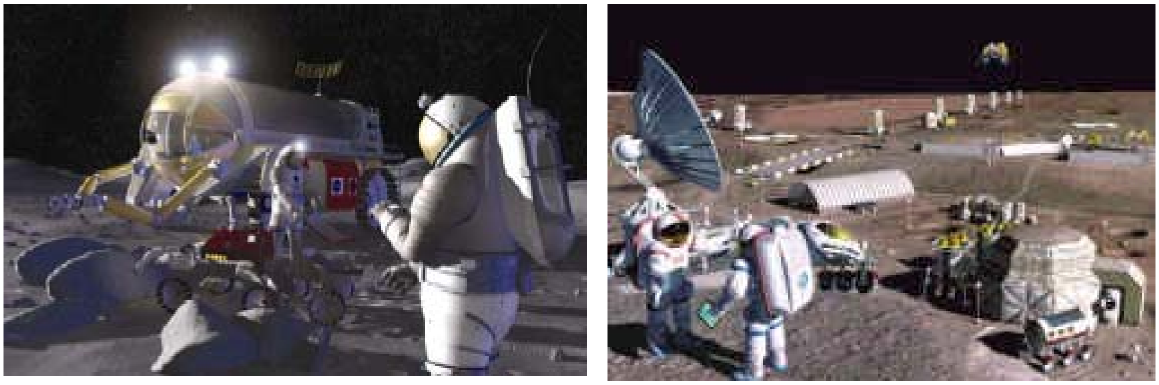

Figure 14. Lunar Exploration and Colonization

To make some of our visionary proposals, which are engineering-wise perfectly sound and will work, visible to a broad range of decision-makers within the U.S. government including the White House, NASA, DoD, the Homeland Security Department, and the State Department, we have proposed to build large telerobotics testbeds and demonstrate the technologies on Earth first, including symbolically having the U.S. President build a bridge in Irak from the White House via teleoperation, as a gesture of good will towards the reconstruction. In Europe and for ESA, DLR, we have during the last decade while conveying our message introduced the concept of a “Riesengründstück” (huge lot, that is Mars) and the “goal” of “building an Autobahn on Mars” using telerobotics, which have been clearly understood and have substantially contributed to build the intellectual basis for ESA's Aurora.

CONCLUSIONS

The main aspects of space telerobotics have been concisely presented providing specific examples for concepts, designs, systems, missions, and engineering-wise solid visions, which the author with colleagues have introduced and pursued for over two decades from within leading roles in the main space centers worldwide including NASA, ESA, DLR, and working closely together with the space and terrestrial industry as well as academia. In particular, attention has been for a while now focused on the utilization of the associated telerobotics technologies towards not only the exploration of other celestial bodies, but also their colonization, specifically the construction of infrastructure on alien surfaces using telerobotics, as well as a broad range of terrestrial applications. Building an intellectual, clearly understandable basis for making the right decisions at the government level, has been also a part of the work, which based on evolving facts, even when very slowly, shows that we are again moving in the right direction, back to the Moon on our way to the Red Planet Mars. In the U.S.A., we have been honored to closely work with the White House, NASA. DoD, the State Department, and the Homeland Security Department in those respects. A substantial amount of costs and risk reduction and mitigation can be expected for mission planning when incorporating telerobotics for our next manned spaceflight programs to the Moon and Mars.

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