Using Virtual Reality for Human-Assisted In-Space Robotic Assembly

Enrico Stoll, Markus Wilde, Christopher Pong

Abstract—**Telepresence systems are often used for terrestrial applications but they are not yet practically applied in space. The deployment of robots with visual as well as haptic feedback for servicing operations in space is a valuable addition to the existing autonomous systems since it will provide flexibility and robustness in mission operations. This is not only true for the robotic application itself but also for free-flying bases which can be used as the base of the robotic application as well as an independent inspector satellite. The operator on Earth will no longer be a pure observer but will have the capability of real-time interaction with the space environment. The use of virtual reality techniques will be of great benefit for the human operator on ground since it allows the implementation of means that help the operator in spatial orientation, navigation and control. For demonstrating the advantages of virtual reality in human-assisted in-space robotic assembly, a test environment is being developed at MIT Space Systems Laboratory, which is based on the SPHERES nano-satellite testbed.**

Index Terms — **telepresence, in-space robotic assembly, virtual reality, space robotics.**

I. INTRODUCTION

Telepresence systems enable a human operator to actively manipulate and intervene in a remote environment. The human operator can, in an ideal telepresence system, no longer differentiate between an interaction with a real environment and a technically mediated one. It is of great importance to provide the human operator with high-fidelity sensor feedback from the remote workspace.

In this regard, haptic devices enjoy a great popularity since they allow feeding forces back to the operator. They are used to measure the positions (or forces) of the human operator as shown in Figure 1. After being communicated via the communication channel, which bridges the barrier to the remote workspace, the values are used as set-points for the teleoperator position (or force). In this way, motions and manipulations are commanded from the operator site to the remote site. The resulting forces (or positions) within the remote environment are measured by sensors and fed back via the communication channel to the multimodal man-machine interface. Finally, diverse visual-acoustic displays provide feedback to the respective human sense and the haptic display lets the operator feel the contact situation[1] at the remote site.

The technology has been driven by applications in nuclear power plants [1] in order to enable a safe handling of hazardous material. In general, terrestrial applications can be differentiated by the type of the barrier between operator and the teleoperator. The handling of dangerous material as already mentioned demands *matter* as the barrier. If *scale* is the barrier, as it is the case in minimal invasive surgery [2], the telepresence system enables the human operator to carry out macro-sized procedures on the operator side, by scaling them down to micro-sized movements on the teleoperator side. Well understood terrestrial applications, in which

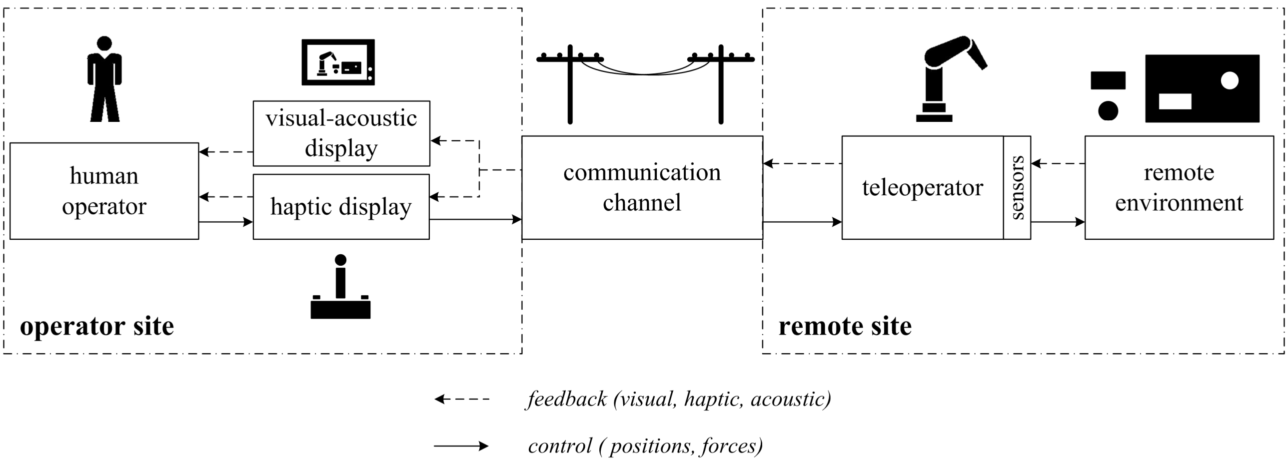

Figure 1: Block diagram of a multimodal telepresence system

Manuscript received July 25, 2009. This work was supported in part by post-doctoral fellowship programs of the German Academic Exchange Service (DAAD) and the German Research Foundation (DFG). Furthermore, it was supported by DFG within the Collaborative Research Centre SFB 453 on "High-Fidelity Telepresence and Teleaction".

E. Stoll is with the Space Systems Laboratory at Massachusetts Institute of Technology, Cambridge, MA 02139 USA (phone: 617.253.8207; e-mail: estoll@MIT.edu).

M. Wilde is with the Institute of Astronautics at Technische Universitaet Muenchen, 85748 Germany. (e-mail: m.wilde@lrt.mw.tum.de).

C. Pong is with the Space Systems Laboratory at Massachusetts Institute of Technology, Cambridge, MA 02139 USA (e-mail: cpong@MIT.edu).

[1] Walls at the remote site can for example be felt as rigid or appendages as flexible.

distance separates the operator from the teleoperator include the exploration and manipulation of deep underwater environments using so-called remotely operated vehicles (ROV) [3] and the use of unmanned aerial vehicles (UAV) in reconnaissance and combat.

Teleoperations in space are restricted by the computing power available on spacecraft and the roundtrip time delays of the long communication chains and research is still in an early stage, with most of the robotic missions being demonstrator technologies. Basically there are two distinguished types of robotic missions in space: *free flyers* and *robotic manipulators*.

The role of the free flyer is mostly concerned with proximity operations such as rendezvous and docking with the target satellite. It is also intended to be used for so called inspecting missions, in which the target satellite is monitored or on-orbit servicing (OOS) maneuvers are supported. The Autonomous Extra-vehicular Robotic Camera (AERCam Sprint) [4] for example was a remote inspections prototype, which was teleoperated by an astronaut inside the space shuttle cargo bay in 1997. The Experimental Satellite Systems 10 (XSS-10) and 11 (XSS-11) [5], [6] were launched in 2003 and 2005, respectively, and were intended to demonstrate key concepts and technologies relating autonomous satellite inspection operations. After separating from the launch vehicle, the respective rocket stages were used to simulate the spacecraft to be inspected utilizing autonomous navigation and proximity operations. The 2005 Demonstration of Autonomous Rendezvous Technology (DART) [7] mission was launched to verify hardware and autonomous software for rendezvous and proximity operations. However, due to a collision with the spacecraft to be inspected, it had to be prematurely retired.

The two Micro-Satellite Technology Experiment (MiTEx**)** spacecraft which were delivered into geostationary orbit in 2006 [8] reportedly demonstrated the first autonomous deep space inspection of a malfunctioning spacecraft by inspecting the out-of-control Defense Support Program (DSP 23) missile warning satellite in 2009.

Most of the OOS missions involving free flyers were applied in operations where the target (satellite) was known in detail. That way most of the missions were very successful by using an autonomous approach which had been monitored from ground.

In contrast, most of the missions that involved a robotic manipulator (on a free flying base) are utilizing some form of telepresence control. After the servicer satellite has docked with the target satellite, the objectives of robotic manipulators are to interact with the target and execute manipulations commanded from ground. This can either be executed autonomously with the human operator only observing and only giving high level commands (also called supervisory control) or teleoperated, with the human operator having an active role (telepresence). The first ground controlled robot in space, the Robot Technology Experiment (ROTEX) [9], consisted of a six degree-of-freedom (DOF) robot, featuring a multisensory gripper. Amongst other experiments, teleoperation by a human operator from ground, using predictive computer graphics, was performed which enabled the operator on ground to successfully complete complex tasks despite a round trip delay of six seconds. The Japanese Engineering Test Satellite ETS-VII [10], launched in 1997, used also so-called virtual telepresence using predictive displays to overcome round trip delays of six to seven seconds. The 6 DOF robotic arm on the servicer satellite was used to execute various OOS experiments with the target satellite in telemanipulation mode, pre-programmed execution mode, and the real-time execution mode with force feedback. The Robotic Component Verification aboard the ISS (Rokviss) [11] features a two joint robotic manipulator, controlled by a human operator via a direct radio link from a ground station. In contrast to ROTEX and ETS-VII, which have been controlled via geostationary satellites, typical round trip delays between operator action and Rokviss haptic-visual feedback are in the vicinity of 20 ms [12]. The DARPA Orbital Express mission validated software for autonomous mission planning, rendezvous, proximity operations, and docking, building on the experience of the DART mishap. Launched in 2007, it was the first time an autonomous spacecraft was robotically transferring propellant and a battery to a target satellite [13].

In summary, the benefits of a human in the loop were utilized in most of the missions involving robotic manipulators. It has repeatedly been shown that the human operator is capable of executing OOS maneuvers from ground. In contrast to autonomous missions, the telepresence approach requires a continuous communication link between the ground station and the servicer satellite with small communication delays. Therefore, acquisition times and round trip delays[2] play an important role in the mission design of an OOS mission. OOS experiments as ROTEX and ETS-VII applied predictive computer graphics to compensate for large round trip delays, which is in general not applicable if the remote environment is not known in detail. However, recent experiments [14] have shown that it is possible for a human operator to steer virtual as well as robotic applications with multimodal feedback via a geostationary satellite[3]. In the framework of the telepresence experiments, robotic manipulations could be executed with real-time feedback for the human operator and it was proven that telepresent OOS operations in Earth orbit are controllable by an operator on ground [15] with an acceptable amount of round trip delay.

This paper aims at emphasizing the advantages of virtual reality techniques for human assisted in-space robotic assembly. It underlines the capabilities of telepresently controlled servicer satellites in addition to autonomous control. Therefore, a test environment is currently being developed, which is outlined in section II. The tests and demonstrations which are envisaged with the test environment are the focus of section III.

II. The Spheres Test Environment

A. Baseline

The baseline of the test environment is the SPHERES (Synchronized Position Hold Engage Reorient Experimental

[2] The round trip delay is the time period between a telecommand sent and feedback received by an operator. It crucially influences the transparency of the system and thus the telepresence feeling.

3 The use of geostationary data relay satellites increases the acquisition time of a servicer satellite to a multiple and thus enables the execution of complex and time consuming servicing maneuvers in space, controlled from ground.

Satellites) hardware which was developed at MIT Space System Laboratory and consists of a testbed on Earth and a test facility aboard the International Space Station (ISS) [16].

SPHERES are nano-satellites, currently three each on the ISS (Figure 2) and on ground, which control their relative position using a cold gas system. The navigation system consists of a custom pseudo-GPS based on ultrasonic beacons and receivers. The ultrasound beacons are located at the borders of the respective test volumes such as the walls of the ISS nodes. This enables the SPHERES to perform relative state measurements.

Figure 2: SPHERES inside ISS

SPHERES are currently used to mature space technology. The ISS testbed features the possibility of easy abort–improve–repeat approaches since astronauts can assist with tests. In this way, SPHERES is a risk-tolerant testbed which can be modified for telepresence formation flight and docking algorithms. Before applying the telepresence control to space it will extensively be tested on ground. Thus, for initial ground tests, the SPHERES terrestrial 5-meter flat floor facility, a two-dimensional version of the same hardware used on the ISS, allows for initial testing and validation of the processes before attempting their implementation in the microgravity environment. This approach inherently reduces risk and allows for assessing repeatability while improving the reliability of the implemented process.

Figure 3: SPHERES with a docked flexible beam

Current work focuses on the assembly of a complex space structure with flexible dynamics. This so-called In-Space Robotic Assembly (ISRA) is tested via the SPHERES on an air carriage system, as shown in Figure 3.

B. *Test Environment*

The test environment which will be described in the framework of this paper will use a 3 DOF haptic feedback device [17]. These can be fed back to the human operator via the Novint Falcon, which can be seen in Figure 4. It features 3 DOF, which are of translational nature. Servo motors are used to feed forces in three degrees of freedom back to the user. Featuring a workspace of about 10 cm x 10 cm 10 cm, it reads positions in 3D with a resolution of about 400 dpi. This system has high utility for space applications since it allows the human operator to control the application in three dimensional space. The haptic device will control both the actual SPHERES hardware at the remote flat floor and a entity in a virtual reality (VR) environment, as shown in Figure 5. The latter is supposed to be implemented using Matlab/Simulink. For that purpose the position commands are processed by an estimator which has sufficient knowledge of the SPHERES physical parameters and a thruster model so it can estimate the dynamic feedback of the system. Using the VR toolbox of Simulink it is possible to create virtual objects with haptic properties and calculate the interaction forces of the controlled SPHERES with the environment.

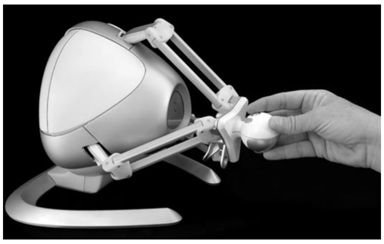

Figure 4: The Novint Falcon [17]

The position commands from the Novint Falcon, which are received at the remote side by the SPHERES communication system, will be executed in terms of controlled thrusts. Ultrasound beacons, which border the test volume yield distance information to the SPHERE as a pseudo–GPS. This, together with the onboard metrology system (cp. Figure 5), yields sufficient data for the position and attitude determination system to estimate the actual states, which are transmitted back to the operator site. They will be fed back into the VR environment and yield the operator a comparison between estimated states and actual states using a sufficient visual display[4]. This not only helps the operator in navigating through the remote scene but also benchmarks the estimator for initial implementation purposes.

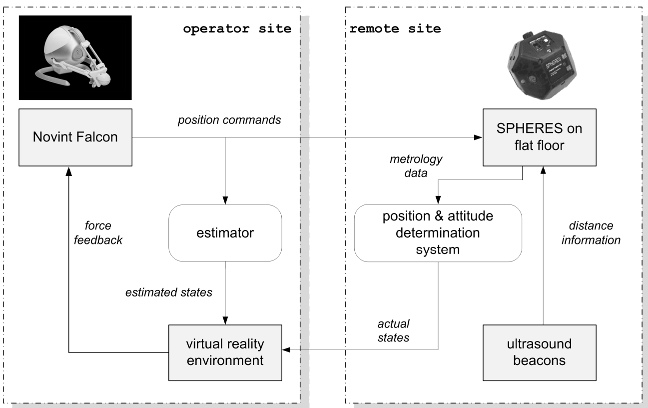

Figure 5: Block diagram of the test environment

[4] The human operator will receive visual information from both the hardware as well as the VR entity, while force feedback is only generated via the virtual entity and transmitted back to the operator.

III. Benefits of applying VR and TP

Telepresence allows the human operator to close the spacecraft's control loop. The system therefore makes use of the human visual, haptic and acoustic perceptional, data integration and model building capabilities. These have evolved over millions of years and are practiced and refined in daily life, whereas they need to be taught to autonomous systems by very complex software. Based on the sensory information, the human operators experience and decision-making process is introduced into the remote environment in real-time, thereby making the remote operation, e.g. manipulation or in this case maneuvering, more safe and efficient.

Since the quality of the human operator's mental model of the environment and thus also the decisions based on his/her situational awareness depend on the quantity and quality of available sensory information, the capabilities of force feedback and augmented reality systems greatly enhance the capabilities of the telepresent system. They therefore represent enabling technologies for telepresence operations in space.

A. Benefits of virtual reality techniques

The orbital environment shows characteristics that make the application of virtual reality technologies a quintessential part of telepresent operations. Space is a 6 DOF environment, which is governed by inertia instead of gravity and provides no natural references for relative positions and orientations. Moreover, all relative maneuvering on orbit occurs in an accelerated reference frame rotating around Earth at orbital velocities. This makes the trajectories resulting from control inputs highly unintuitive. It is therefore important to provide the operator with artificial reference information and orientation and navigation cues in order to make maneuvering during proximity operations both efficient and safe.

This can be achieved by using the spacecraft's attitude sensor information to provide an operator head-up display (HUD) displaying attitude, position and velocity cues. Attitude can thereby be provided by an azimuth and elevation grid such as commonly used in military and some commercial HUDs. Distances and velocities can be displayed by either graphical (e.g. velocity bars, numeric output, distance or velocity-based coloring of the display, etc.), acoustic (variable pitch of artificial background sound, simulated sonar-type signal in which frequency of pinging indicated distances) or haptic indicators (resistance force on the input device being inversely proportional to distance or velocity, erection of artificial walls enclosing target satellite and flight path). Many of these methods and technologies can be borrowed from other highly evolved man-machine interfaces, such as in aviation, underwater robotics or the automotive sector (such as the use of solutions for park distance controls and emergency braking assistants for distance and velocity displays and collision avoidance).

In addition to attitude and position information, the ground operator also requires references concerning safe and fuel efficient flight paths. As mentioned above maneuvering in space results in highly complex and unintuitive trajectories, which are described by the Clohessy-Wiltshire or Hill equations [18]. So will a single impulse in flight direction (along the so-called V-bar) not result in pure forward motion, but the spacecraft will first accelerate forward, but then upwards and finally fall behind (refer to Figure 6). Similarly, a pure "upwards" (meaning in radial direction away from Earth, or along the R-bar) impulse will have the spacecraft fly an elliptical trajectory until it reaches its starting point after one orbital revolution (Figure 7).

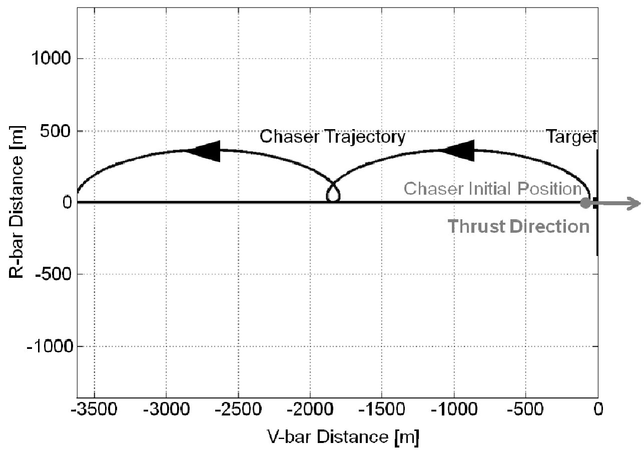

Figure 6: Orbital motion due to impulse in flight direction

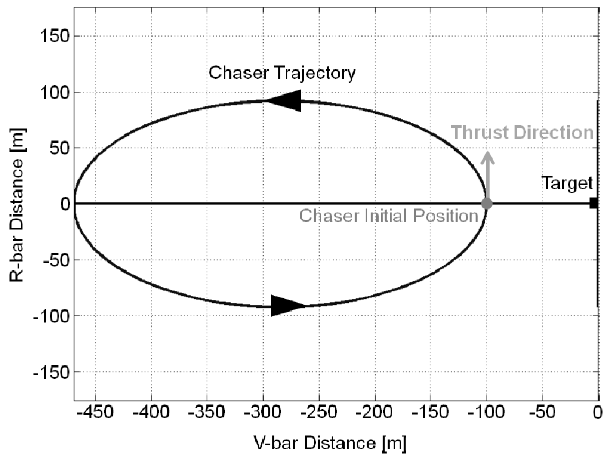

Figure 7: Orbital motion due to an impulse in radial direction

Since this behavior of the spacecraft is obviously not desirable while conducting maneuvers in close proximity to other objects in space, usually the approach of forced-translation is taken. In this, the natural motion of the spacecraft is compensated for by additional impulses, so that quasi-straight translational trajectories result. These match the movement of the spacecraft expected by the operator due to his control inputs, albeit at the cost of increased fuel usage. When maneuvering around the work site, the operator therefore needs computer assistance in determining the fuel-optimal flight path considering the high fuel expenditure required while countering natural motion. The solution is therefore to have the guidance computer perform real-time computations of the spacecraft's optimal trajectory based on actual position and control inputs. The resulting trajectories can then be displayed by a fuel optimal area, similar to a tunnel through which the operator must fly the spacecraft. An ambient damping force, as depicted in Figure 8, can be implemented, featuring a magnitude which is proportional to the deviation of the actual path from the fuel optimal trajectory and area, respectively.

Collision avoidance maneuvers for example can further be made visible and perceptible for the human operator, by placing virtual walls around other spacecraft as shown in Figure 8. Equipping these virtual walls with sufficient high stiffness means that the operator is not able to penetrate them by means of the haptic device, since it exerts to the operator a high resistance force. The distance between the virtual wall and the target satellite should increase with the uncertainty of the current environmental model or the time delay in the system.

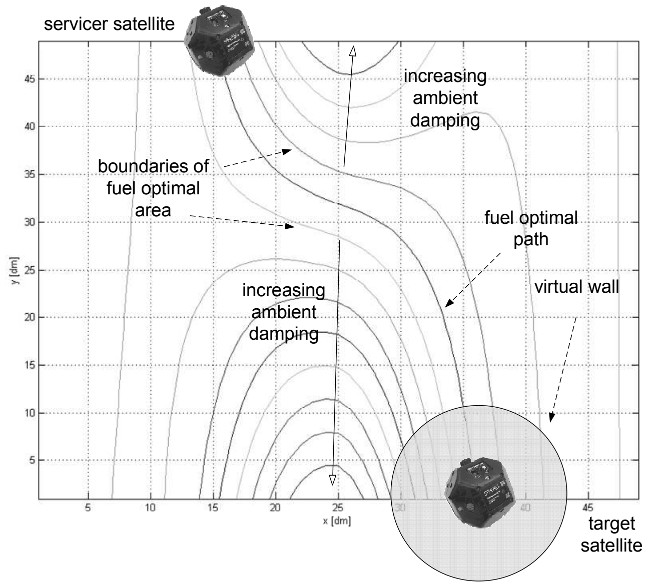

Figure 8: Using virtual boundaries for supporting the human operator

Docking maneuvers can be supported by virtual boundaries such as a haptic guiding cone and damping forces which are increasing with decreasing distance to the target. This will support the operator in a human assisted in-space robotic assembly scenario. The resistance forces, however, must be small enough for the operator to overcome in an emergency situation or whenever deemed necessary[5].

The applications mentioned above are but a few examples for the potential of augmented reality methods and technologies in robotic spaceflight.

B. Initial Experiments

A series of initial experiments are envisaged by using the developed test environment for proving the benefits of VR in human assisted in-space robotic assembly operations. A whole assembly mission can be stepwise demonstrated with the existing hardware.

The basic test is a three SPHERES scenario where one can be telepresently controlled at a time. Two of the SPHERES will fulfill an assembly scenario, where one is a servicer satellite and the second one the base of the spacecraft to be constructed. While these two executing proximity and docking maneuvers, the third SPHERE will be inspecting the procedures. That way either the inspector or the servicer satellite will be controlled by the Novint Falcon.

Proximity operations will be tested first for a telepresent inspector in the presence of virtual boundaries. The autonomous assembly procedure is inspected with virtual walls around the servicer and the spacecraft base. The second scenario will involve an autonomous inspector and a human-controlled servicer, which is docking to the spacecraft base. The collision avoidance approach and the fuel-optimal paths, described in the previous section can for example be tested in that way. In that connection efficient procedures have to be found for a fuel-optimal station keeping procedure of the human-controlled as well as autonomous inspector satellite.

A further aspect, that has to be taken into consideration, is the influence of the human in the loop on existing path planning algorithms. If a human operator is supporting autonomous OOS operations, the system has to take into account that the motions of the ground-controlled spacecraft are not as predictable as an autonomous spacecraft. Sudden changes in spacecraft direction, uncommon for an efficient autonomous path planner, can occur due to the human operator involved in the procedures.

The telepresence capability of the test environment has to eventually be evaluated by means of transparency measurements. This can either be executed by involving human participants for a qualitative measurement or by using quantitative measurements as e.g. the Z-width concept [19], which evaluates the accuracy in rendering the remote environment to the human operator. In an ideal case the human operator can no longer differentiate whether his interaction with the remote environment is immediate or mediated by technical means. The degree of transparency is usually very dependent on the control architecture of the teleoperation, since controllers cannot preserve stability and transparency of the system to the same degree at the same time. The more robust a controller is the less transparent the manipulation environment feels for a human operator. Time delayed teleoperations, for example, tend to affect the degree of transparency (cp. [15]).

IV. CONCLUSION

Telepresence control of in-space robotic assembly operations is a valuable addition to autonomous procedures. It enables the human operator on the ground to actively intervene in the remote environment and provides the possibility of instantaneous contingency operations[6]. This paper showed the benefits of introducing virtual reality techniques to assist the user in orientation, navigation, and control. The theoretical advantages of VR will be tested in a representative hardware environment and evaluated in detail in the future.

ACKNOWLEDGMENT

The authors would like to thank Prof. David W. Miller, Dr. Alvar Saenz-Otero, and Jacob Katz for collaboration on this research.

[5] A further approach for handling these situations is using an interface (as e.g. a button) to disable haptic feedback in certain situations.

[6] Except for the time delay in transmitting commands.

ISBN:978-988-18210-2-7

REFERENCES

[1] T. B. Sheridian, *Telerobotics, automation, and human supervisory control.* Cambridge, USA: MIT Press, 1992.
[2] T. Ortmaier et al., "Robot Assisted Force Feedback Surgery", in *Advances in Telerobotics,* Heidelberg, Germany: Springer, 2007.
[3] P. Ridao, M.Carreras, E. Hernandez, N. Palomeras, "Underwater Telerobotics for Collaborative Research", in *Advances in Telerobotics,* Heidelberg, Germany: Springer, 2007.
[4] Choset, H., and Kortenkamp, D., "Path Planning and Control for AERCam a Free-Flying Inspection Robot in Space", *Journal of Aerospace Engineering, 12*(2), 1999, 74–81.
[5] T.M. Davis, "XSS-10 Micro-Satellite Flight Demonstration", proc. of Georgia Institute of Technology Space Systems Engineering Conference, paper no. GT-SSEC.D.3, Nov. 2005.
[6] "XSS-11 micro satellite – fact sheet", Air Force Research Laboratory, Space Vehicles Directorate, doc. no. AFD-070404-108, Apr. 2007.
[7] T.E. Rumford, "Demonstration of Autonomous Rendezvous Technology (DART) Project Summary", proc. of Space Systems Technology and Operations Conference, Orlando, USA, Apr. 2003.
[8] Microsatellite Launch, *Crosslink- The Aerospace Corporation magazine of advances in aerospace technology*, *7*(2), 2006, 2
[9] G. Hirzinger, K. Landzettel, C. Fagerer, "Telerobotics with large time delays-the ROTEX experience", proc. of the IEEE/RSJ/GI International Conference on Intelligent Robots and Systems, Munich, Germany, Sep. 1994.
[10] T. Imaida, Y. Yokokohji, T. Doi, M. Oda, and T. Yoshikawa, "Ground-Space Bilateral Teleoperation Experiment Using ETS-VII Robot Arm with Direct Kinesthetic Coupling", proc. of IEEE International Conference on Robotics and Automation, Seoul, Korea, 2001.
[11] K. Landzettel et al., "Robotic On-Orbit Servicing – DLR's Experience and Perspective", proc. of. the 2006 IEEE/RSJ International Conference on Intelligent Robots and Systems, Beijing, China, Oct. 2006.
[12] C. Preusche, D. Reintsema, K. Landzettel, G. Hirzinger, "Robotics Component Verification on ISS ROKVISS – Preliminary Results for Telepresence", proc. of. the 2006 IEEE/RSJ International Conference on Intelligent Robots and Systems, Oct. 2006, Beijing, China
[13] J. Shoemaker, M. Wright, "Orbital Express Space Operations Architecture Program", Proceedings of SPIE Spacecraft Platforms and Infrastructure Symposium, Orlando, USA, 2004.
[14] E. Stoll, *Ground Verification of Telepresence for On-Orbit Servicing*, Dissertation, Lehrstuhl für Raumfahrttechnik, Technische Universität München, Munich, Germany: Verlag Dr. Hut 2008.
[15] E. Stoll et al., Ground Verification of the Feasibility of Telepresent On-Orbit Servicing, *Journal of Field Robotics, 26*(3),2009, 287–307.
[16] D.W.Miller, E.M.C. Kong, A. Saenz-Otero, "Overview of the SPHERES Autonomous Rendezvous & Docking Laboratory on the International Space Station", 26th Annual AAS Guidance & Control Conference, Breckenridge, CO, Feb, 2003.
[17] Novint Technologies, Inc., [online] www.novint.com, cited Jun. 2009.
[18] D.A. Vallado, *Fundamentals of Astrodynamics and Applications*. New York: McGraw-Hill, 1997, pp. 343-366
[19] K. Hashtrudi-Zaad, S.E. Salcudean, Transparency in Time-Delayed Systems and the Effect of Local Force Feedback for Transparent Teleoperation, *IEEE Transactions on Robotics and Automation*, *18*(4), Feb. 2002