A Brief History of DLR's Space Telerobotics and Force-Feedback Teleoperation

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Abstract: The DLR's Institute of Robotics and Mechatronics enjoys a unique history in space telerobotics that begins in 1993 with ROTEX, the first space telerobotics mission in history [1], and has been continuing to pave the way towards space telerobotics, on-orbit servicing and planetary exploration until the present. This paper reviews DLR's major telerobotics break-throughs during the last ten years, describing in particular requirements for space telerobotics, main mission challenges and robot control methods to allow one of the oldest yet still cutting-edge DLR's robotics vision: To extend the human arm into space, that is, space telepresence.

Our work has been massively inspired by the pioneering work of Tony Bejczy and his co-workers.

Keywords: Force-feedback; Teleoperation; Space Robotics; On-Orbit Servicing

1 Space Telerobotics

Telerobotics is one of the most succesful and versatile space technologies. In the last years there have been impressive space missions that involved the use of robots, showing their effectiveness in fields as diverse as Mars exploration, on-orbit servicing (OOS) or meteorite sample and return. The ROTEX mission, back in 1993, [1] [2] has been the major breakthrough in space robotics up to present since for the first time, a space robot was controlled from Earth. Apart from fundamental work of Tom Sheridan [3] our close contact to and many discussions with Tony Bejczy [4] were decisive for inspiring our courage to successfully perform, e.g. the catching of a free-floating object and force controlled assembly of a bajonet closure with roundtrip delays between 5 and 7 seconds. Predictive simulation [5] the only proved method for compensating delays of this nature and shared compliance control [6] were the techniques we have applied in these situations. Tony Bejczy had performed impressive work in the field of bilateral force reflection handcontrollers in the late eighties. His big hope was to fly his handcontroller - kinematically different from any teleoperated robot - during this ROTEX experiment, we seek to test and find out how force reflection works under zero gravity. Unfortunately he did not get the necessary support from NASA for this space experiment.

In general, the goal of a space telerobot is to perform some sort of telemanipulation of a spacecraft, an orbital object or a planet surface with more or less degree of autonomy. However, robotics hasn't yet shown its full potential in missions that require high dexterity levels. The ISS is still fully maintained by astronauts; four manned servicing missions on the Hubble Space Telescope raised original costs of \$2.5B to \$10B as of 2010 [7]. Robots are undeniable safer and more cost effective compared to on-site astronautic operations, though arguably, much more limited in terms of cognitive and manipulation abilities. Real-time teleoperation and force feedback are appealing technologies in these scenarios as they combine robotic capabilities with human intelligence and manipulation skills. Furthermore, those are technologies that have been thoroughly investigated for many years and find themselves in a rather mature developmental stage.

The issue of space debris demands a quick response to mitigate the increasing growth of debris population. Concerns are running high about the Low Earth Orbit environment, which could soon become unstable if nothing is actively done. Currently, there are different approaches under discussion to actively remove debris. Methods based on space robots, nets and harpoons are being analyzed. Space robots are arguably more complex and expensive but more flexible in terms of provided services.

On the other hand, it is expected robots will play a major role in future Mars and Moon exploration missions. Recent Mars and Moon exploration missions have already shown the potential of robotics in this field.

2 Force-feedback in Space

In 2005, ROKVISS (Robotic Component Verification on the ISS) was launched [8], [9]. The robot was a 2 degrees of freedom (d.o.f.) development with integrated torque sensors at each joint to allow compliant interaction with the environment. The robot was installed on the outer part of the Russian module of the ISS. A force feedback joystick along with the video streaming data was used to teleoperate the robot. A dedicated bidirectional point-to-point link - from the DLR to the ISS - was used which resulted in round trip delays of around 30 ms.

In 2008, the ARTEMIS telerobotics experiment was conducted [10]. In this experiment, the european geostationary satellite Artemis was used as space mirror to communicate a light-weight-robot (LWR), configured as a haptic device, and another LWR, used a teleoperator. Both systems were physically located in the DLR, separated by a distance of 5 meters. The communication link however traced a path of approximately 36,000 km: From the DLR, in Oberpfaffenhofen, to an ESA relay antenna in Redu, Belgium, through the GEO satellite Artemis in both directions, resulting in an average time delay of 620 ms.

In 2009, first experiments were conducted to investigate the effects of time delay in human performance when teleoperating such distant robots in space with force reflection. One of the results of this study revealed that a complex task whose mean execution time required 15 seconds in the absence of delay, demanded 115 seconds in the presence of 620 ms round trip delay. Clearly, time delay impairs human performance to very high levels. However, all the telemanipulation tasks were successfully fulfilled [10].

In 2011, KONTUR-1 mission was conducted. This mission was aimed at globally extending the communication link used in ROKVISS to virtually anywhere on Earth. The packages received from the ISS at the DLR-GSOC S-Band Antenna in Weilheim were rerouted to several locations in Germany and Russia through standard internet infrastructures (UDP), resulting in a hybrid link that was shaped by the delays, data losses and jitters of the space link and the internet communication.

It is well known in robotics, and in particular in the control field, that closed loops systems that include non-negligible time delays can produce negative effects on system stability. This issue is magnified in those closed loop systems that are characterized by tight couplings, that is, where high frequency control actions are required to capture a reasonable spectrum of the dynamics of the controlled system. For instance, in order to capture the interaction of a robot's end-effector while contacting a hard surface, a well established control-loop frequency is 1000Hz.

In general, these systems are governed by a bilateral controller because the control action takes place at both sides: At the master side, in order to control the haptic interface being manipulated by a human operator; and at the slave side, where the robot, or tele-operator, is located. The requirements for such a bilateral controller are remarkable as it needs to cope with a) large time delays, which furthermore are b) variable, producing therefore c) communication jitter and d) data losses. Further insight into the developed bilateral controller follows in the next sections.

In 2014 and 2015, an important milestone in on-orbit servicing has been achieved. The DLR's on-orbit servicing facility (OOS-SIM) was linked through the European communication satellite, ASTRA [11]. A haptic interface was used to control the robot manipulator mounted on the OOS-SIM's *servicer* satellite in order grasp, stabilize and dock the *target* satellite of the facility. The communication channel between haptic interface and servicer robot, shaped once again by space and internet links, resulted in an average round trip delay of 540 ms.

From August to December 2015, KONTUR-2 addressed scientific and technological questions for future planetary exploration. In this mission, ROKVISS' robot & haptic interface constellation was reversed, that is, a cosmonaut in the ISS controlled different robots located in the DLR through a force-feedback joystick. In

KONTUR-2, Earth and ISS have been used as a test-bed to evaluate and demonstrate a new technology for real-time telemanipulation from space [12].

3 Space Communication Infrastructures

Table 1 shows communication parameters registered during the main DLR telerobotics missions.

Experiment	**Type**	**RT-Delay**	**P.Loss**	**Bandwidth**
ROKVISS	ISS Link	20-30 ms	0.1%	256Kbps/4Mbps
ARTEMIS	GEO-Sat	620 ms	5.8%	4 Mbps
ASTRA	GEO-Sat	540 ms	2.6%	4 Mbps
KONTUR-2	ISS Link	20-30 ms	0.1%	256Kbps/4Mbps
K2 Training	Internet udp	65 ms	10%	10Mbps

Table 1
Main DLR space telerobotics missions communication parameters. P.Loss:Package Loss; RT:Round Trip

As it can be seen, time delay varies substantially depending on the particular communication infrastructure. Geostationary satellite communications (ASTRA, ARTEMIS) average higher than 0.5 seconds [13], [14]. The direct link used in ROKVISS on the other hand presents less delay.

In general, two communication approaches have been tested so far: n overflight point-to-point communication link and links based on geostationary satellite relays.

Table 2 compares the main features of both approaches.

Link type	**Window (s)**	**Avg. RTD (ms)**	**Tested in**
Direct link	8-10	20-30 ms	ROKVISS KONTUR-1/-2
Geo Relay	≥ 45	540 - 820 ms	ARTEMIS ASTRA, Haptics

Table 2
Direct link and geostationary relay based space links comparison

In KONTUR-2, two scenarios had to be considered in the design of the bilateral controller: ISS and training. The first is the nominal mission case, where the cosmonaut controls the robot from the ISS through a S-band link. The second, is a geographically distributed scenario for cosmonaut training purposes (see Fig. 1). Since the exact same system needs to operate in both, the requirements for the bilateral controller are clearly strengthened as both links are characterized by different communication parameters.

The cosmonaut training took place at the Gagarin Research and Test Cosmonaut Training Center (GCTC), located in Moscow. During the training, the cosmonaut practiced with a joystick qualification model (QM) with identical characteristics of the ISS flight model (FM), and controlled the robot located at the DLR, in Germany, through the internet.

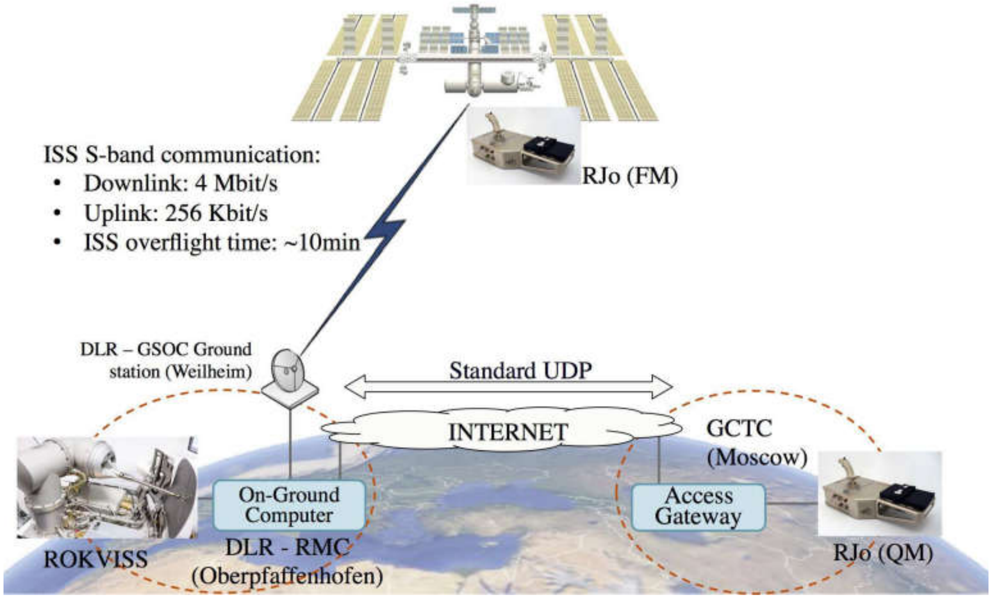


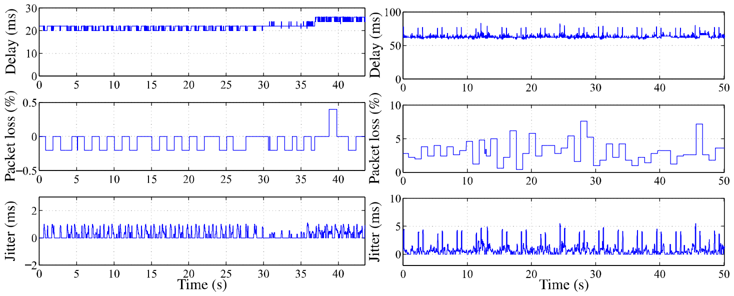
Figure 1
KONTUR-2 scenarios

Fig. 2(a) and Fig. 2(b) show the performance of ISS and internet UDP links. The nature of these two links is quite different in terms of time delay, data losses and jitter. The time delay for the ISS communication varied from 20 to 30 *ms* (corresponding to azimuth and horizon points) with mean negligible data losses. The internet training setup introduced a mean delay of 65 *ms* and highly oscillating package loss ratio, from 5% to 15% (due to the UDP protocol). Though more limited in bandwidth, the ISS link is higher in performance. However, shadowing can occur resulting in signal attenuation and in turn higher package loss ratios or even communication blackouts. On the other hand, the internet link measurements confirm a typical UDP behaviour.

On the other hand, the communication Ka-Band link used in the ASTRA experiment resulted in much larger time delays. Fig. 4 shows time delay, package loss ratio and jitter registered during one of the experiments in 2014 for a single trip. The round trip delay is therefore approximately twice as large.

4 Robotics and Space Debris

Spacecrafts are the only complex engineering systems without maintenance and repair infrastructure. Occasionally, there are have been space shuttle based servicing missions, starting with the Solar Maximum Repair Mission (SMRM) in 1984, but there are no routine procedures foreseen for individual spacecrafts. Most malfunc-



(a) Comm. Pars. ISS link

(b) Comm. Pars. GCTC internet link

Figure 2
Space and Internet links parameters registred in the KONTUR-2 mission. Very similar results were obtained in ROKVISS.

tioning spacecrafts require only a minor maintenance operation on orbit, a so-called On-Orbit Servicing (OOS) mission, to continue operational its work. Instead, they have to be replaced due to the lack of OOS opportunities. The accomplishment of OOS missions would, similar to terrestrial servicing procedures, be of great benefit for spacecraft operators, since a wide spectrum of use cases exists as, e.g. spacecraft assembly, orbit transfer, maintenance and repair, resupply, or even safe deorbiting.

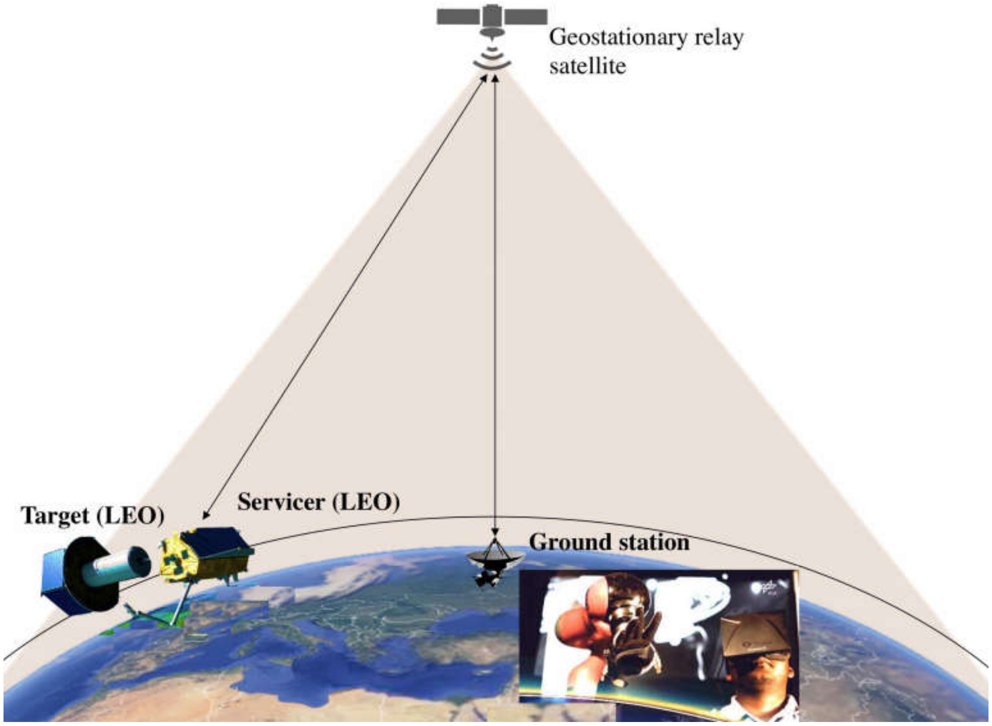


Figure 3
Targeted GEO relay based teleoperation system for on-orbit servicing

Roughly, a space robot consist of one or more manipulators mounted on a servicer spacecraft. The robot is capable of grasping a free-tumbling target and docking it onto the servicer, either to de-orbit it or for on-orbit servicing. Compared to classical robotics, the use of space robots for OOS presents some unique challenges that characterize its complexity and efficiency. Among the most remarkable are a) controlling the manipulator on a free-floating base, b) addressing impact dynamics c) reliability of visual sensors in space conditions and d) time delay between servicer and ground station.
In general, there are two strategies to control the space robot: semi-autonomy, in which the robot is controlled through visual servoing, and teleoperation, in which a human operator controls the robot from ground in real-time through a haptic device. Advantages and disadvantages of each approach are closely related to the mentioned challenges.

In general, the semi-autonomous system is higher in complexity and its effectiveness is highly dependent on the sensor capabilities to cope with extreme lighting conditions. On the other hand, teleoperation can be arguably more rudimentary but is less dependent on the reliability of the sensor and vision algorithms. In this paper we explore feasibility of the second strategy, also known as telepresence. One of the key elements in this approach is the combination of robotic feedback control capabilities with human manipulation skills. Generally speaking, the increased complexity of an autonomous system is well justified in applications characterized by systematic or repetitive tasks. OOS tasks are, however, rather unique and distinctive and might be better addressed by means of teleoperation.

In particular, On-Orbit Servicing (OOS) in LEO presents a special difficulty since direct contact between a ground station and the servicing spacecraft is only given in small time intervals, that is, when the spacecraft is flying over the terrestrial antenna(s). However, the feasibility of OOS operations is highly dependent on whether and how long a communication link between the controlling ground station and the servicer spacecraft can be established. A good example is given by the space shuttle based OOS missions of the Hubble Space Telescope (HST). Each task required several EVAs resulting in a total EVA time of more than 24 hours. An OOS mission, which is telepresently controlled from ground demands, therefore an equivalent amount of contact time. According to Table 2, using direct communication links in LEO would require several weeks or a complex ground station network of antennas globally distributed on Earth. Since the HST orbits the Earth at approximately 570 km, 4-8 orbit revolutions per day exist, in which a human operator could teleoperate a robotic servicer for maximum 10 minutes per orbit revolution.

Thus, the use of geostationary satellites a promising approach for space telerobotics as it can increase the mean acquisition time of the spacecraft in LEO up to more than 1 hour per orbit revolution. The two space missions mentioned above, ARTEMIS [10] and ASTRA [11] address these questions (see Fig. 3). It is clear that the use of geostationary data relay satellites drastically increases the round trip delay of the signal, that is, the time between operator action and spacecraft feedback. The main goal of both experiments was to prove that the utilization of geostationary (GEO) data relay satellites for OOS is reconcilable with a telepresent control of the servicer spacecraft, that is, with force-feedback teleoperation. The real-time link given by the geostationary ARTEMIS satellite resulted in a mean delay of 620 ms; similar results were obtained using ASTRA (see registred singe trip delay plots in Fig. 4).

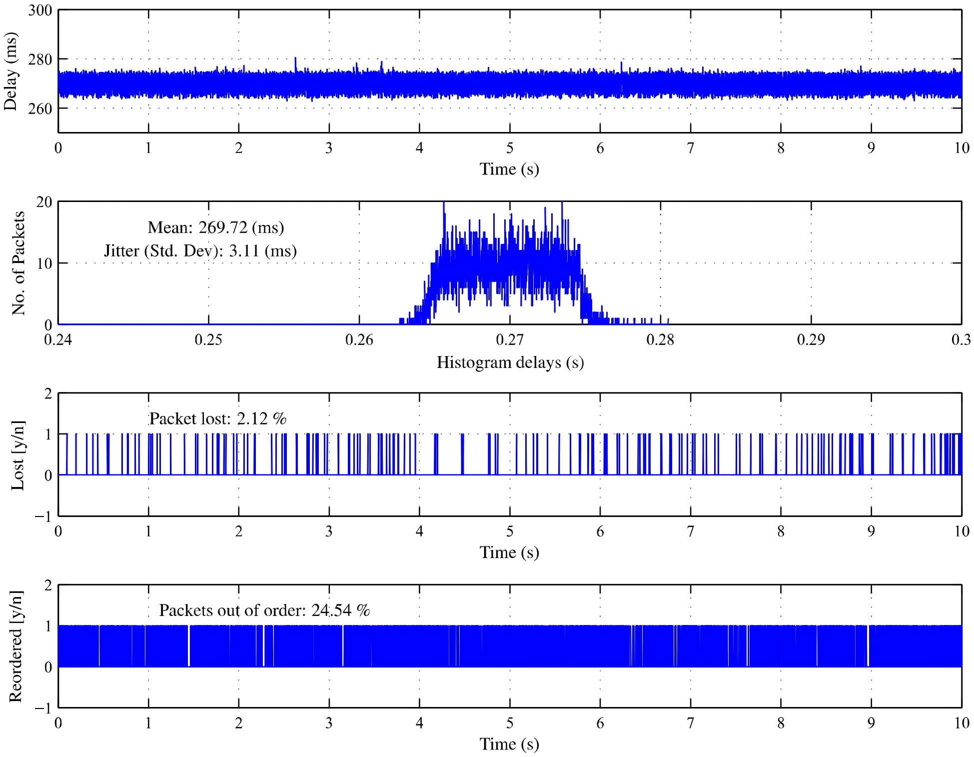


Figure 4
Communication link properties for a single channel (i.e. forward or feedback channel, see Fig. 5)

At the present time, it can be concluded that bilateral controller is an effective mechanism to deal with large and variable time delays, that is, the control structure between the space robot and the haptic interface on ground. In other words, stable and reliable force-feedback from the task space to the operator can be provided. This has been proved from a stability and control performance point of views. Efficiency in dealing with human factors was initially investigated during the ARTEMIS experiment. However, further studies are required to evaluate the efficiency of the approach for e.g. performing satellite grasping and docking maneuvers.

5 Controlling robots *in* and *from* Space: Bilateral Control

The bilateral controller enables a human operator to control the space robot using a haptic interface, through which he feels the interaction forces from the slave. In general, bilateral control is challenging as it establishes a very long closed control loop. For instance, the systems mentioned above with geostationary relays results in closed loops systems of length of approximately 36,000 Km. Furthermore, the controller needs to be robust against data losses and jitters, i.e. variations of time delay at each sampling step. Furthermore, a special feature of this loops is that they run at high sampling rates. This is required to achieve reliable force-feedback since the bandwidth of the human haptic spectra is characterized by very frequencies, i.e. greater than 1000 Hz. This can be well seen in hard contact situation in which the force transition happens in very short time intervals. In all of the previous experiments, the Time Domain Passivity Control approach (TDPA) with the Time Delay Power Network (TDPN) concept has been successfully applied. This control approach is based on monitoring the virtual energy that results from the delayed communications and applying a variable damper - called Passivity Controller.- which is a function of the observed energy (Passivity Observer). See [15], [16] and [17] for a review on the TDPA and TDPN concepts.

A final remark follows related to the two well established methods for controlling a robot manipulator: position and torque control. The first is widely used since a position interface is available in every robot. The second requires torque sensors inside the robot structure, something that is only available in a few comercial robot manipulators due to its high costs. Nevertheless, the trend in the last years is evolving towards torque controlled robots, specially in service robotics. The main reason to that is that a torque interface allows to implement impedance controllers. With impedance control, a desired compliant behaviour can be implemented at the robot end-effector. The robot can behave as soft and flexible manipulation tool or e.g. as a heavy and stiff tool. Position control achieves higher accuracy degrees but in general it does not allow to render compliant behaviors. Therefore, it is less tolerant to uncertainties in the task execution and modelling. This is specially true in space telerobotics missions as they are characterized by harshness environments. Extreme lightning conditions result in limited sensor capabilities; limited satellite geolocation capabilities result in limited positioning accuracy; and non-realtime / low-bandwidth communication infrastructures result in delayed tasks executions. Arguably, position control can achieve higher positioning accuracies in well-structured environments, enjoys higher technical readiness levels (TRL) and is less expensive. On the other hand, impedance control can naturally handle inaccurate physical interactions, can better cope with latencies and can adapt its impedance to each task (e.g. for matching impedance between the robot manipulator and a target spacecraft). For theses reasons, torque control (i.e. impedance control) in all of the above experiments.

6 Conclusion

After our long term investigations on up to which amount of roundtrip delay force reflection works at all, we may now state that up to around 650 ms delay, time domain passivity algorithms can compensate the delays, with a satisfactory performance. Larger roundtrip delays, approximating 900 ms, are still possible, but of course with a decaying efficiency. But, interestingly enough this is more or less the resulting delay to control a robot system in lower Earth orbits via a geostationary relay satellite (assuring communication coverage of typically around 45 minutes). As seen in the various experiments presented in this article, controlling a robot through a link based on a geostationary relay plus an internet connection leads to unavoidable delays of 540 to 620 ms. Today's fast internet infrastructures allow data streams between continents with roundtrips delays of less than 100 ms. Force-feedback and so telemanipulation can therefore not only be globally covered but also be used to in the earth's orbital space.

Our future work will seek to further establish force-feedback teleoperation as a technology for supporting astronautic tasks. To that end, the use of geostationary relay satellite is crucial to achieve intervention times close to one hour. It's worth mentioning that once it has been proved that internet allows real-time transmission of haptic streams (by using appropriate control methods), we expect that force-feedback teleopera-tion will be key technology for terrestrial applications too: From elderly care and tele-nursing to maintenance and repair of energy plants.

References

[1] G. Hirzinger, "Rotex the first space robot technology experiment," in *Experimental Robotics III*, ser. Lecture Notes in Control and Information Sciences, T. Yoshikawa and F. Miyazaki, Eds. Springer Berlin Heidelberg, 1994, vol. 200, pp. 579–598. [Online]. Available: http://dx.doi.org/10.1007/BFb0027622

[2] G. Hirzinger, K. Landzettel, and J. Heindl, "Rotex: space telerobotic flight experiment," in *Proceedings of SPIE International Symposium on Optical Tools for Manufacturing and Advanced Automation*, Boston, USA, 1993.

[3] T. B. Sheridan, "Space Teleoperation Through Time Delay: Review and Prognosis," *IEEE Transactions on Robotics and Automation*, vol. 9, no. 5, pp. 592–606, October 1993.

[4] A. Bejczy, "Towards advanced teleoperation in space," *Teleoperation and Robotics in Space, Prog. Astronaut, Aeronaut*, vol. 161, no. 5, pp. 494–501, 1994.

[5] A. Bejczy and W. S.Kim, "Predictive displays and shared compliance control for time-delayed telemanipulation," in *Intelligent Robots and Systems '90. 'Towards a New Frontier of Applications', Proceedings. IROS '90. IEEE International Workshop on*, Jul 1990, pp. 407–412 vol.1.

[6] W. Kim, B. Hannaford, and A. Bejczy, "Force-reflection and shared compliant control in operating telemanipulators with time delay," *Robotics and Automation, IEEE Transactions on*, vol. 8, no. 2, pp. 176–185, Apr 1992.

[7] J. William F. Ballhaus, *James Webb Space Telescope (JWST) Independent Comprehensive Review Panel (ICRP) Final Report*, ser. NASA contractor report. National Aeronautics and Space Administration, Scientific and Technical Information Branch, 2010, no. v. 3.

[8] G. Hirzinger, K. Landzettel, D. Reintsema, C. Preusche, A. Albu-Schäffer, B. Rebele, and M. Turk, "Rokviss-robotics component verification on iss," in *Proc. 8th Int. Symp. Artif. Intell. Robot. Autom. Space (iSAIRAS)(Munich 2005) p. Session2B*, 2005.

[9] A. Albu-Schäffer, W. Bertleff, D. Rebele, B. Schäfer, K. Landzettel, and G. Hirzinger, "Rokviss - robotics component verification on iss current experimental results on parameter identification," in *Robotics and Automation, 2006. ICRA 2006. Proceedings 2006 IEEE International Conference on*, May 2006, pp. 3879–3885.

[10] E. Stoll, U. Walter, J. Artigas, C. Preusche, P. Kremer, G. Hirzinger, J. Letschnik, and H. Pongrac, "Ground verification of the feasibility of telepresent on-orbit servicing," *Journal of Field Robotics*, vol. 26, no. 3, pp. 287–307, 2009.

[11] J. Artigas, Balachandran, M. De Stefano, M. Panzirsch, R. Lampariello, J. Letschnik, J. Harder, and A. Albu-Schaeffer, "Teleoperation for on-orbit servicing missions through the astra geostationary satellite," in *(to be pusblished) Aerospace Conference, 2016 IEEE.* IEEE, 2016, pp. 1–20.

[12] J. Artigas, R. Balachandran, M. Stelzer, B. Weber, J.-H. Ryu, C. Riecke, and A. Albu-Schaeffer, "KONTUR-2: Force-feedback Teleoperation from the International Space Station," in *To be published at IEEE ICRA 2016*.

[13] E. Stoll, U. Walter, J. Artigas, C. Preusche, P. Kremer, G. Hirzinger, J. Letschnik, and H. Pongrac, "Ground verification of the feasibility of telepresent on-orbit servicing," *J. Field Robot.*, vol. 26, no. 3, pp. 287–307, Mar. 2009. [Online]. Available: http://dx.doi.org/10.1002/rob.v26:3

[14] R. Lampariello, N. Oumer, J. Artigas, W. Rackl, G. Panin, R. Purschke, J. Harder, U. Walter, J. Frickel, I. Masic, K. Ravandoor, J. Scharnagl, K. Schilling, K. Landzettel, and G. Hirzinger, "Forrost: Advances in on-orbit robotic technologies," in *Aerospace Conference, 2015 IEEE*, March 2015, pp. 1–20.

[15] J. Artigas, J.-H. Ryu, C. Preusche, and G. Hirzinger, "Network representation and passivity of delayed teleoperation systems," in *Intelligent Robots and Systems (IROS), 2011 IEEE/RSJ International Conference on.* IEEE, 2011, pp. 177–183.

[16] J. Artigas, J.-H. Ryu, and C. Preusche, "Time domain passivity control for position-position teleoperation architectures," *Presence: Teleoperators and Virtual Environments*, vol. 19, no. 5, pp. 482–497, 2010.

[17] J.-H. Ryu, J. Artigas, and C. Preusche, "A passive bilateral control scheme for a teleoperator with time-varying communication delay," *Mechatronics*, vol. 20, no. 7, pp. 812–823, 2010.