Challenges and Solutions for Communication in Space Robotics

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Abstract

This paper provides an overview on the challenges in communications for space robotics. The emphasis is put on the individual communication requirements for different types of space robotics, where the aspects reliability, security, latency, jitter and bandwidth are taken into account.

The knowledge is taken from different projects and activities where SCISYS has drawn insights into the requirements for robotic communication systems.

As a result the existing and conceptual communication solutions for the different mission types are presented. In addition the needs in communication are described pointing out the need for tunable solutions using flexible protocols.

1 Introduction

For today's spaceflight missions automation and robotics are enabling technologies to support unmanned missions. Taking this into account, future space missions - also in the commercial sector - will increasingly make use of telerobotics. There is already a variety of missions utilizing telerobotics like exploration incl. landers, surface mobility and in-situ experiments and also new application areas like on-orbit servicing (OOS). The robotic nature of the spaceflight missions requires for different autonomy levels, requirements on operations, ground control and especially communication infrastructures.

Within the last years SCISYS contributed to a number of activities where autonomy and communication were the key enabling technologies for the robotics.

Within the study "Mission Control Concepts for Robotic Operations (MICCRO)" the communication requirements when using teleoperation or telepresence control for robotic manipulators in Earth orbit have been deeply analyzed. It has been demonstrated how different virtual communication channels can be handled by implementing an end-to-end demonstration prototype for On-Orbit Servicing (OOS) type missions [1], [2]. In project phase I the underlying operational and communication concepts have been developed, aiming to find a representative mission control concept for robotic space missions. Phase II was used to deploy a demonstration setup using the engineering robot model of the former mission ROKVISS simulating the manipulator arm in an OOS type mission at the German Aerospace Center (DLR) in Oberpfaffenhofen, Germany. The different types of data to be transferred are managed by a central component called Communication Gateway, where data is handled according to the following categories: cyclically distributed synchronous data, the acyclically or event-driven distributed asynchronous data, and data distributed on request only. For data transfer, several protocol proposals from different sources were available, e.g. CCSDS, ECSS and TCP/IP. As these standards are widely used, the communication design of MICCRO was following these standards.

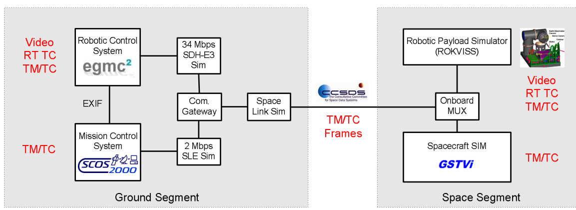

Figure 1: MICCRO Communication Setup [2]

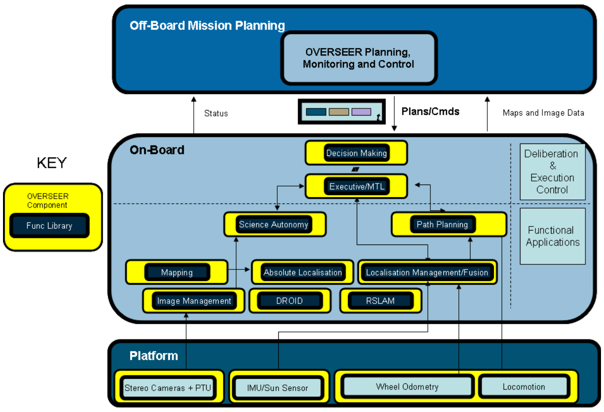

Figure 3: SEEKER Communication based on OVERSEER [3]

As part of the ESA StarTiger program SCISYS contributed to the study SEEKER, which demonstrated long-range fully autonomous navigation in the Atacama desert [3]. The figure below presents the high-level system concept implementation including the OVERSEER component orientated autonomy framework. Although the rover implemented a high level of autonomy, the communication to the offline functions are essential for resource management and mid-term and high level tactical decision making.

Based on the expertise gained during the study MICCRO, SCISYS contributes to the German on orbit servicing mission "Deutsche Orbitale Servicing Mission (DEOS)" [4], currently in phase B2. SCISYS is responsible for the design of the software within the robotic control system (RCS) also handling the data streams towards the robotic payload. Depending on the experiments performed the requirements on the communication link differ a lot. Especially for so called telepresence phases where an operator controls the robotic manipulator on board via a force feedback interface device from ground the requirements on link latency, bandwidth and jitter are demanding.

In addition to the involvement into the above studies and missions, SCISYS implemented the network simulator for the SpaceBot Cup 2013 hosted by the German Aerospace Centre (DLR) [5]. The tasks to be performed by the participating teams were based on a moon rover scenario including the challenging communication requirements. The teams had to cope with representative transmission delays,

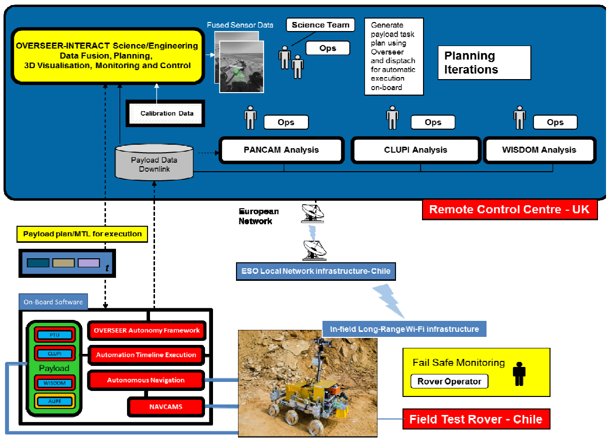

Figure 2: SAFER System including Operations in the UK and the Rover Software/Hardware subsystem in Chile [6]

loss of signals, etc. In order to support the teams the network simulators were provided during the preparation phases for test. The contest at the end once more revealed that handling the given communication conditions between a ground control system and the space segment are crucial for this type of contest and also missions.

Using the results of the SEEKER study and using ExoMars Rover (EMR) as a point of reference, the ESA SAFER project involving SCISYS sought to investigate the proposed operations philosophy and procedures by conducting mission simulations in a remote and highly representative environment. As part of this work the authors provided the core software and the sole autonomous elements of the mission. These comprised autonomous localization and navigation software for the Rover, the on-board software executive which automated plan execution and the Overseer Interact mission planning and data co-registration tool used for operations at the UK site and in Chile [6].

As for other rover missions the long range communication via the European satellite network has been integrated into the communication link between the UK operations site and the rover at the other remote end.

Another recently started study focusing on communication for space robotics is linked to the ESA "Multipurpose End-To-End Robotic Operations Network" (METERON) program [7] to test various scenarios by controlling robots on Earth from the interior of the International Space Station (ISS). Adopting this approach for a Mars exploration scenario, a time window of about twenty minutes would be available for real-time haptic teleoperation, also called telepresence. Due to the different size of the Earth and the flight altitude of the ISS, a comparable METERON test scenario would allow a much shorter time window of about eight minutes.

The study “Uninterrupted Hand-Over between Ground Stations during Immersive Telerobotics Real-Time Control Phases” (UINTGS) led by SCISYS in cooperation with the German Aerospace Center (DLR) and Makalumedia, aims to extend the time window for an uplink between Earth and the ISS up to twenty minutes, comparable to the situation on Mars. Divided into two phases the study will first focus on the detailed analysis of the haptic telerobotics communication requirements. A recommended solution will be defined for the implementation of an uninterrupted handover scenario within the existing network of ESA ground stations (ESTRACK). In phase two a deeper analysis of the recommended solution is addressed together with the detailed design for the implementation. Depending on the former results, a prototype implementation into the ESTRACK ground stations in Mas Palomas, Villafrance and Weilheim is planned for demonstration purposes.

Taking into account the experiences made the following section provides an overview on the challenges in communication for robotic missions.

2 Challenges in Communication for Robotic Missions

When analyzing the formerly mentioned selection of activities in the field of space robotics it becomes obvious that the challenges are strongly bound to the related mission type. A selection of mission types and their demands in terms of bandwidth as a counterpart to the other measures distortion, latency and jitter are shown in the following figure. As a rule of thumb space robotics that is operated in an Earth orbit will make use of a higher bandwidth than robots operated over a longer distance, which is driven by the physical limits of the available communication systems. Also depending on the communication distance the number of distortions, latency and jitter is likely to be increased. Common to all mission types is the demand for a reliable and secure data link.

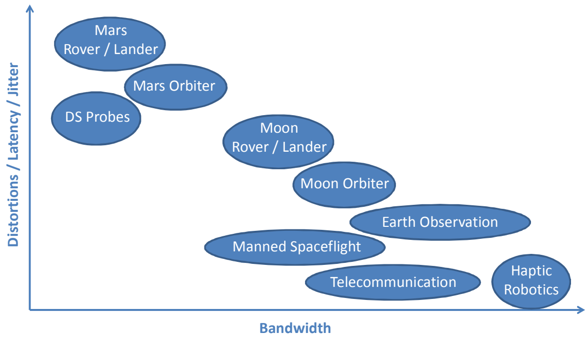

Figure 4: Communication for Different Types of Robotic Missions

During the SpaceBot Cup 2013 hosted by the German Space Agency (DLR) [5], ten teams were asked to solve a sample return task using robotic systems in a simulated Moon scenario. The link simulator provided by SCISYS induced a delay of 2 s and also simulated the loss of signal due to the Moon rotation. The analysis of the results revealed that for this type of contest the teams underestimated the influence of the delay on the transmission link. Most monitoring and control systems were not performing as specified. Especially, in case of unplanned events a remote operation turned out to be unusable. Although all teams were relying on sophisticated robotic systems and on board autonomy a direct communication between the control room and the simulated Moon environment was required.

Taking planned or already implemented robotic space missions with strong requirements on the communication system, on orbit servicing involving a haptic user interface for the operator is a good example. In order to support the force feedback control loop the data packets containing the control and monitoring information need to be exchanged at a high rate of appr. 1-5 ms. Taking the estimated packet size of 50-100 bytes into account the required usable bandwidth would be 80-800 kbit/s. The limit for telepresence is defined by the maximum round trip time of appr. 500 ms. By that the mission is limited to an operation of these robotic systems in LEO or GEO orbits. For LEO telepresence operation a continuous

Figure 6: Examples for Near Earth Robotic Operations (DEOS and Robonaut 2) [Airbus/ESA]

connectivity is required in order to execute longer tasks. This is currently not possible as the contact times are limited to a single ground station contact.

Apart from the above OOS scenario other robotic systems in space put similar demands on the communication infrastructure. The NASA Robonaut 2 project and the METERON program preparing manned mars exploration also require for near real time communication that can support haptic teleoperation or telepresence control of a remote robotic system.

At the other end planetary and deep space exploration mission need to cope with different challenges. Considering Moon, Mars or deep space missions, signal latencies are inevitably high. The less reliable communication links together with the high latencies on the space links are to be handled. Disruptions are caused by the loss of line of sight, which is required for the data transmissions and the available power at the remote side is limited. For Mars rover scenarios the data messages are not always sent directly to the deep space ground station network on Earth but uplink information can also be sent towards orbiting spacecraft. The orbiting spacecraft are acting as a relay for the data transmission to Earth and the rovers on the planetary surface, which requires for a store and forward architecture. Also the available bandwidth for the deep space communication is limited, depending on the available transmission power for transmissions towards earth.

In summary the requirements on the communication system for space robotics strongly depends on the specific mission characteristics and by that may vary a lot. For operations in

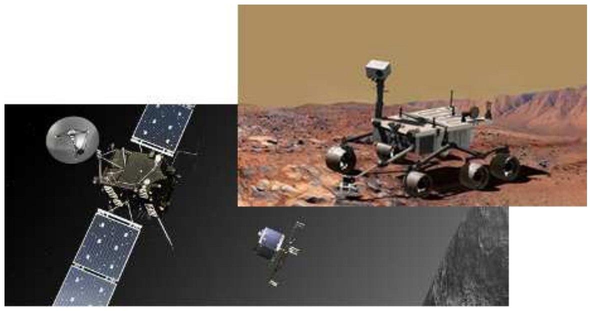

Figure 5: Examples for Planetary Exploration and Deep Space Robotic Operations (Rosetta and Mars Science Laboratory) [ESA]

Earth orbit the following needs are identified:

- High bandwidth
- Low latency
- Continuous communication link

For the operations of deep space and planetary exploration the focus in terms or communication requirements differs:

- Transmission safety
- Link robustness against distortions and interruptions
- Capability to cope with high latencies

The above mentioned requirements aim to point out the differences in the most crucial needs. In general all communication systems should allow a fast and fully reliable information transmission. Depending on the boundary conditions induced the communication system needs to be adjusted.

3 Communication Solutions for Space Robotics

For space communication and mission operations required infrastructures are implemented and commonly used. This section provides a short overview of available implementations. In addition also specific solutions are described that are not covered by the available standard systems.

The protocols for the communication on the space data links as well as the terrestrial links are standardized by a variety of standards provided by different organizations, e.g. CCSDS, ECSS, SCaN, AES, and others.

For the terrestrial links between the ground stations and the control centers the CCSDS SLE protocol layer based on the TCP/IP stack are used, ensuring the reliable transport for all packets including the required re-transmissions in case of packet losses or corruptions. For the specific application of telepresence control loops for OOS applications this implementation cannot be used. For these types of utilization the SLE service could use UDP for the transport layer in order to avoid packet jitter or latencies. This approach is currently discussed, but not yet available for operations. In a past experiment ROKVISS [8] implemented a specific solution that realized a “serial interface” for the terrestrial data transmission via a leased line to the ground station. In addition to channels having the nature of data streams, standard TM/TC is transferred in addition. The different data streams need to be multiplexed and de-multiplexed either in the ground station or within the control center. The synchronous nature of the data streams requires prioritized multiplexing functions to generate the TC packets for the uplink as shown in the figure below. A prototype implementation of this functionality the Communication Gateway has been implemented as part of the study MICCRO. Telecommands (TCs) as provided by the Mission Control System (MCS) as well as cyclic synchronous data in different formats to control the robotic system can be multiplexed and encoded into CCSDS compliant stream of CLTUs that can be forwarded to ground stations via the SLE network, which has not been considered within the study. Each input queue can be handled according to different rules and assigned to e.g. different APIDs or virtual channels (VCs). Handling the received telemetry the data can be separated checking the APIDs and VCs in order to separate the for e.g. the MCS and the robotic control system receiving the force feedback data stream or video streams.

These examples show that for non-standard TM/TC traffic induced by the MCS extensions to the current implementations are required in order to handle other channels for the uplink.

Considering the space data link the CCSDS standards defining the TM/TC packets and frames are clearly defining the protocols used for

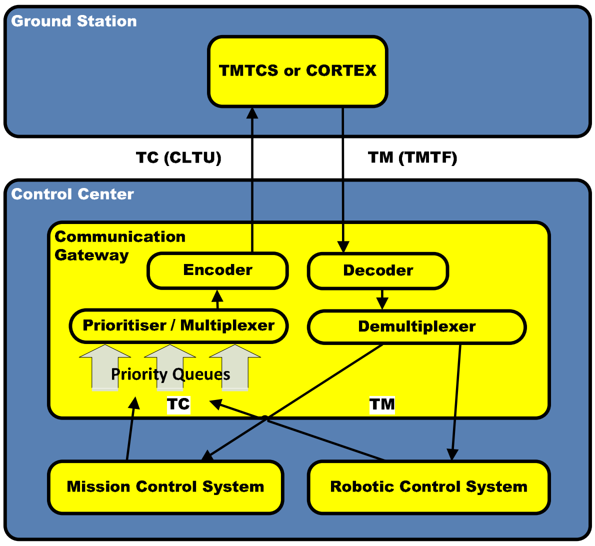

Figure 7: Multiplexing of Prioritized Virtual Channels

all space robotic applications. Almost all ground stations are equipped with harmonized TMTCS or CORTEX interfaces that serve these standards. Further activities to implement additional services on top of the data link as described by the exiting SCPS protocol descriptions or the Delay/Disruption Tolerant Network (DTN) activities are ongoing. Within the DTN it is the goal to enable an “interplanetary internet” including implementations of the required DTN hardware nodes. The different services foreseen include:

- Efficient reliability,
- Security,
- In-order delivery,
- Duplicate suppression,
- Class of service (prioritization),
- Remote management, and
- ‘DVR-like’ streaming service

including rate buffering, and data accounting, all over possibly asymmetric and time-disjoint paths.

The infrastructures implemented by many space agencies like the NASA DSN and ESA ESTRACK networks include all assets to enable the communication towards near Earth as well as deep space spacecraft. The bandwidth that can be realized for the space data link depends mainly on the capabilities of the spacecraft and the power available for the transmission. This together with the fact that Mars orbiters are providing longer visibility periods are the reasons why Mars orbiters acting as relays are the preferred communication path. Using the SLE network service the different ground stations can be accessed by the control centers according to the assignments as scheduled. The study UINTGS addresses the handover of uplinks between different ground stations to increase the visibility periods for spacecraft in LEO orbits. The current implementation will always cause interruptions in the uplink and solutions to overcome this problem for haptic teleoperation or telepresence operations are requested.

Especially for space robotics another aspect apart from the communication needs to be considered when analyzing the solutions implemented and planned, which is onboard autonomy. Onboard autonomy is used because of different reasons. One of those is a high timely reactiveness onboard, e.g. to implement FDIR mechanisms or to increase the efficiency for Mars missions avoiding the high signal latencies. The onboard autonomy is deployed to compensate the leak of fast and reliable communication to the robotic system in space.

4 Acknowledgments

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5 Conclusions

The communication infrastructures available for operating space systems are implemented based on proven standards and designed to fit to most space mission needs. When operating space robotics as part of a space mission special demands are raised that require modifications of the existing infrastructures.

The operation of the SLE service over UDP, multiplexing functionality to combine prioritized data for the uplink as well as de-multiplexing downlinked data and the implementation of mechanisms between ground stations to enable seamless uplink handovers are identified within this paper.

Mission specific adaptations should be avoided as far as possible and rather be integrated into the existing infrastructures to make them available also for future missions.

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