# END-TO-END CONCEPT DEMONSTRATION FOR ON-ORBIT SERVICING TYPE MISSIONS

11TH INTERNATIONAL SYMPOSIUM ON ARTIFICIAL INTELLIGENCE, ROBOTICS AND AUTOMATION IN SPACE (I-SAIRAS) 2012
TURIN, ITALY, 4-6 SEPTEMBER 2012

Dr. Markus Plura (1), Martin Stelzer (2), Andreas Ohndorf (3)

(1) SCISYS Deutschland GmbH, Borgmannstr. 2, 44894 Bochum, Germany, Email: markus.plura@scisys.de, Phone: +49 234 9258 244
(2) German Aerospace Center (DLR), Robotics and Mechatronics Center (RMC), Muenchner Strasse 20, 82230 Wessling, Germany, Email: martin.stelzer@dlr.de, Phone: +49 8153 28 2153
(3) German Aerospace Center (DLR), Space Operations and Astronaut Training, Muenchner Strasse 20, 82230 Wessling, Germany, Email: andreas.ohndorf@dlr.de, Phone: +49 8153 28 2772

## ABSTRACT

This paper presents the design, planned utilization and implementation of an end-to-end demonstration prototype for On-Orbit Servicing (OOS) type missions.
Within the study "Mission Control Concepts for Robotic Operations (MICCRO)" in the project phase I the underlying concepts have been developed, aiming to find a representative mission control concept for robotic space missions. After presenting these conceptual ideas, the demonstration setup using the example of an OOS type mission, developed in project phase II, is described as deployed at the German Aerospace Center (DLR) in Oberpfaffenhofen, Germany.
Using this facility, aspects like the handovers between mission phases and consequence on roles and responsibilities can be assessed. A particular emphasis is also put on new functional components like operator support functions on ground, communication gateways or an integrated Mission Control System (MCS) for the satellite platform and the robot in space.

## 1. INTRODUCTION

The achievements in telerobotics are the enabling technology for future exploration, on-orbit servicing (OOS) or space debris removal missions. In order to support these classes of missions, the development of a common concept for robotic mission operations is required. The currently ongoing study "Mission Control Concepts for Robotic Operations (MICCRO)" aims to find an abstract, representative mission control concept applicable to multiple future missions that involve robotic systems [3][4].
During the project, a prototype implementation is developed in order to verify the generic mission operations concept, which includes robotic as well as autonomous components. The project started at the end of 2010 and runs for 24 months. It is structured into two phases as shown in Figure 1.

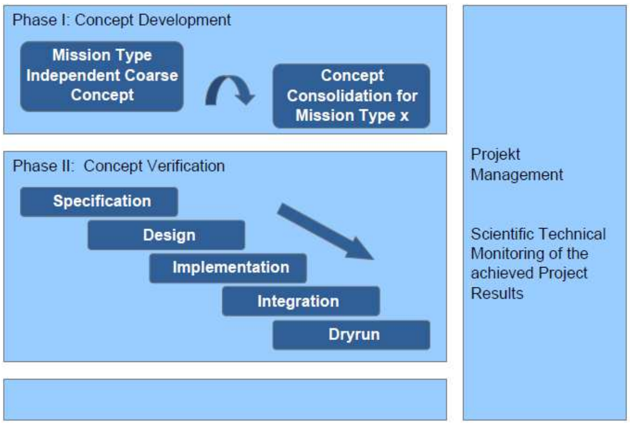

Figure 1. MICCRO Project Phases

Project phase I *Concept Development* comprised the conceptual work and focused on the review and analysis of past, current and future robotic space missions in order to identify the characteristic needs as well as the commonalities. A general approach described as *Mission Type Independent Coarse Concept* has been developed. This coarse concept was further refined in a *Concept Consolidation for Mission Type X* which was finally selected to be an OOS type scenario. The focus in this phase was on the operational organization, incl. the roles and responsibilities concept, the communication concept, incl. aspects for the robotic components, the autonomy and a user concept.
The concepts described and documented in phase I are verified in project phase II *Concept Verification*. For this purpose, an OOS demonstration prototype is realized on-ground in order to get the proof of concept.
Looking at future missions, one particular space robotic mission that will definitely rely on these technology areas is the German Orbital Servicing mission DEOS ("Deutsche Orbitale Servicing Mission") [1][2].
The objectives of the DEOS mission are to capture a tumbling, non-cooperative client in low earth orbit

(LEO) and finally to de-orbit the mated configuration of both satellites in a predefined orbit corridor. Other goals are the demonstration of several Rendezvous & Docking (R&D) maneuvers and maintenance activities. For more details regarding DEOS please refer to [1][2]. Details on the relevant experiences of all project partners can be found in [4].

## 2. CONCEPTUAL IDEAS FOR ROBOTIC MISSIONS

### **2.1.** Organizational Structures

The organizational structures and roles & responsibilities in the context of robotic missions have been analyzed during the first study phase for required changes with respect to other space missions.

An intuitive and proven method for the design and preparation of mission operations is to mirror the space segment's primary functionalities and interfaces. A robotic Mars exploration mission, for example, consisting of an orbiting spacecraft and a rover on the planet surface, has a well defined interface between the two space segment components. Hence, it is appropriate to cluster the ground segment infrastructure accordingly into two control centers and to operate the space segment components fairly independently.

OOS missions like DEOS have a strong coupling between the robotic component, e.g. a manipulator arm, and the satellite platform of the servicer because the manipulator's motion has a strong feedback to the servicer's attitude. This fact almost inevitably requires some kind of on-board interaction between the Robot Control System (RCS) and the Attitude and Orbit Control System (AOCS) of the host platform [10]. Furthermore, during the capture phase, collision avoidance must consider both robotic and platform operation, whereby decisions have to be taken on short notice. For this mission type, it is therefore essential to conduct platform and robotic operations concurrently from one control room staffed with an integrated Mission or Flight Operations Team (MOT, FOT).

An integrated FOT has key advantages because essential mission elements are in a good overview and short-notice decisions can be based on an integrated information base. Hence, a hierarchical command structure, as usually implemented in control centers, fits well to the general situation. Telepresence operations introduce however a new dimension into space operations, as robotic missions shorten the time scale to make a decision from hours or a couple of minutes down to seconds in worst case. Furthermore, the requirement for telepresence conditions limits the response time down to a few hundred milliseconds. Therefore, a direct control loop, parallel to the regular TM/TC communication loop, between the robotic system in space and the robotic payload operator is mandatory. This also affects the communication architecture for the robotic mission.

### **2.2.** Roles and Responsibilities

In order to assign the responsibilities between the Flight Director (FD) and the Robotic Operator in more detail, we analyzed general criteria for designing a concept for roles and responsibilities applicable to robotic missions.

With respect to the short timescales during telepresence operations, the standard way of commanding by voice loop from the Robotic Operator via the FD to the Command (CMD) operator has to be modified. Also for other mission subsystems like the AOCS the robotic payload operator needs to get the control authority for the time of the operation. Mission responsibility, nevertheless, should not change, i.e. the FD is always responsible for the complete system and the subsystem operator always responsible for his subsystem.

The roles and responsibilities between the FD and Robotic Operator are similar to those of a Space Shuttle commander and its pilot: While the robotic operator has the control authority for his subsystem, and thus also limited authority for the system during telepresence operations, the FD is always responsible for the entire mission and the general decisions on a time scale of seconds and minutes. These decisions can include also an abort of robotic or telepresence operation. The exact procedure for such an abort of robotic operations depends on the situation and phase. It should be predefined as much as possible and trained thoroughly with representative simulations during the mission preparation phase.

### **2.3.** Communication

Communication infrastructure is an essential key component of all space missions and a number of general constraints must be respected during its design.

Cost induces constraints for space missions and this holds especially true for the ground segment with its ground station network. Carrying out the routine operations phase of a space mission is therefore always a compromise between a higher degree of onboard autonomy or robustness and the number of (costly) ground station contacts required to control the spacecraft.

The required bandwidth, latency time and protocol must be analyzed and also the ground stations that are planned for supporting that mission if they are compliant to those requirements.

The space segment needs to satisfy a number of mission-specific communication requirements. These cannot always be described in advance as it strongly depends on the communication path and possible other spacecraft. An example for special constraints is that imposed by the requirement for telepresence, as described later.

The involvement of robotic components – especially when operated in telepresence mode – induces a new time scale in decision making. Teleoperation allows delayed access to an application in space. The commanding for each process step has to be identified in advance and all the steps are then assembled in a script-like procedure. Direct interaction, especially in emergency or contingency cases, is usually impossible.

Telepresence enables a direct feedback to an operator of the physical correlation between action and reaction. Such a telepresence communication link is characterized by bandwidth, jitter, latency, reliability of transmission, and contact duration and signal propagation time. Each of these characteristics has direct impact on the quality of service and control. If telepresence involves the feedback of onboard reactions caused by operator-initiated actions, the maximum operational distance reduces to Geostationary Orbit (GEO) height as the total roundtrip time is approx. 500 ms.

The ground contact time per orbit can be prolonged through usage of a GEO relay satellite system, e.g. the National Aeronautics and Space Administration's (NASA) Tracking and Data Relay Satellite System (TDRSS), or a network of ground stations with or without overlapping reception areas. Due to increased complexity and involved hardware, both options have implications on latency.

Common to all remote operations is the idea of transferring information via logical/vitual channels, which are de-serialized logical channels for transmission over the physical radio link by multiplexing. Available physical link bandwidth is thereby automatically and priority-based shared over all active channels. A flexible adaptation to changing requirements is important as effective available link bandwidth is inversely proportional to signal propagation distance.

The transmitted data can be categorized into three groups, the cyclically distributed synchronous data, the acyclically or event-driven distributed and synchronous data and asynchronous data, distributed on request.

For data transfer, several protocol proposals from different sources are available, e.g. CCSDS, ECSS and TCP/IP. As these standards are widely used, the communication design of MICCRO is also based on the standards.

## 2.4. Autonomy

Autonomy has many different aspects for robotic missions, which have been investigated in the MICCRO study.

Autonomous functions may be spread all over the application domains of a space mission, e.g. Guidance Navigation and Control (GNC); Failure Detection, Isolation and Recovery (FDIR); Managing and Intelligent Sensing and Data Handling, both in the space and the ground segment. A variety of technologies to achieve low level autonomy are already commonly in use.

Special requirements to space autonomy have been identified for the approach and docking phase of an OOS mission. Due to hardware performance limitations it may not be feasible to permanently update the complete dynamics model on board the servicer satellite but to transfer the computational load to the ground instead. This requires a closed loop between onboard sensors, actuators and ground equipment. It is important to note that with this approach the robotic control authority is implicitly moved to the ground – especially during telepresence activities – which in turn introduces a new potential failure scenario in case of a link loss to the space segment. A risk mitigating solution could be a collision avoidance maneuver (CAM) based on an up-to-date state of the system, which is regularly uploaded to the servicer and automatically activated in case of a major problem.

When considering an on-ground autonomy concept, it can be employed in two ways, either affecting operations directly, e.g. by a procedure execution (PEX) executing event-based tasks as an autonomous reaction, or the autonomy component may be intentionally decoupled from the real space system and instead provide its output to an operator as a suggested solution (assistance system).

The latter autonomy component is used within MICCRO as an assistance system while control authority is kept with human personnel.

## 2.5. User Interface

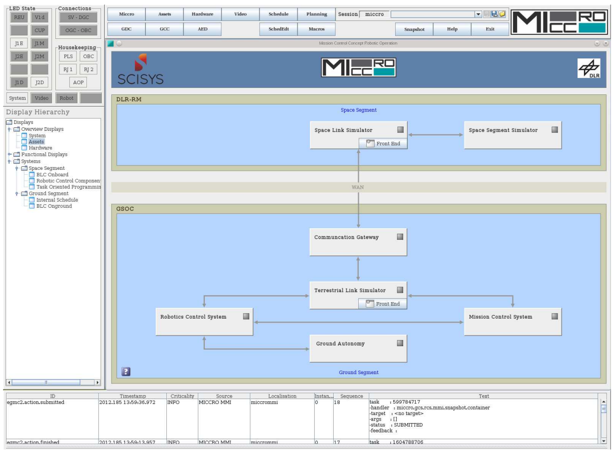

Figure 2. Overview HMI

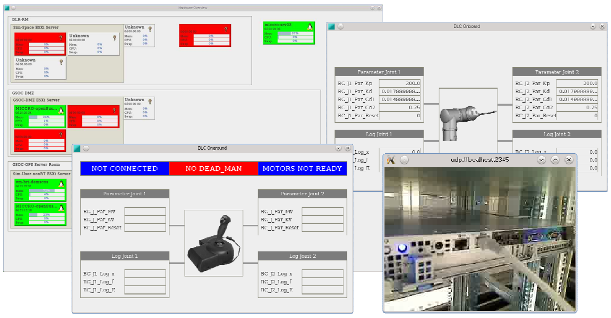

Figure 3. Specialized Subsystem HMIs

For a robotic satellite mission, the Monitoring & Control (M&C) software suite SCOS-2000 and the SCISYS egmc² framework provide well-proven HMIs that have been already used successfully to support other space missions. The new robotic mission element, however, demands additional specialized subsystem HMI component.

The displayed data can be grouped into three different categories. The satellite uplink/downlink data including conventional TM/TC data as well as data transmitted through real-time channels. Another data class is the data that is exchanged between operators and other on-ground applications such as ground data, ground autonomy, video processing and similar assistance applications. And finally the management and status data for all ground facilities including means to start, stop, reset and supervise these systems.

These data should be visualized through HMI components that plug into a standardized application framework. The composition of these components varies with respect to the responsibilities of the particular operator, whereas some components may be repeatedly used for several or all interfaces.

## 3. DEMONSTRATION PROTOTYPE

### 3.1. Design

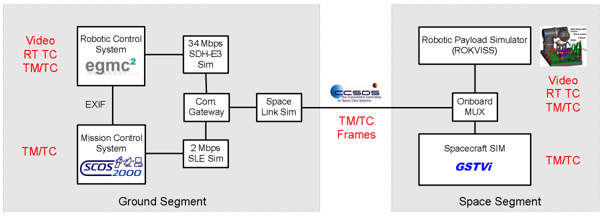

Figure 4. Demonstrator Design

For the verification of the concepts and components as developed within the MICCRO project, a system demonstrator for an OOS type mission has been implemented. For this system we use standard building blocks as already used in other mission setups wherever possible. This can not be done for all components as also a few new components have been implemented, e.g. in order to implement the required multiplexing and de-multiplexing functions for the virtual data channels (Figure 4 Communication Gateway & Onboard MUX).

The Robotics Control System (RCS) consists of many different subcomponents responsible for the monitoring and control of the robotic payload simulator. For the realtime telecommands (RT TC) a dedicated VxWorks based platform is coupled with the DLR Force Feedback Joystick [6]. In addition to the RT data handling, a further server platform handles all non-realtime (non-RT) data flows. The server is responsible for receiving all housekeeping data from the robotic system, configuring the parameters for the RT data transmission and also the non-RT commanding of the robotic components. These commands as well as the housekeeping data for the robot are transferred via standard spacecraft TM/TC and the interface towards the SCOS based on its External Interface (EXIF). The server itself is implemented on the proven egmc² framework developed by SCISYS and the interface to SCOS to send all non realtime data via the same data channel has been implemented for this purpose. This required changes in the control software of the Robotic Payload system (ROKVISS) in order to make it more compliant to existing standards. Furthermore, the RCS also hosts all HMI components that are specific to the robotic component and the on-board video data is received and visualized on the RCS workstation connected to the RCS server.

The RCS server also orchestrates a ground autonomy subcomponent. It is based on an adaptive short term planning system that is working on problems defined in the Problem Domain Definition Language (PDDL). The details are explained in Figure 5. A Long Term Plan (LTP) is generated in an offline task in the Mission Planning System (MPS) and the plan is then usually executed in the Mission Control System (MCS). For the demonstrator, the planning component has been integrated in the RCS as it is used here as an early warning system only. Life telemetry as received from the robotic or spacecraft simulator can be fed into the PDDL based problem description. By that, the planning system is capable to validate the Short Term Plan (STP) according to the current system status. Further it would also be possible to trigger the Procedure Execution (PEX) automatically using the Time Based Execution (TBEX) based on the schedule derived. However, for the demonstrator an assisting early warning system for the robotics operator is the considered focus. The telemetry within the RCS is held in a Space System Model (SSM) compliant format.

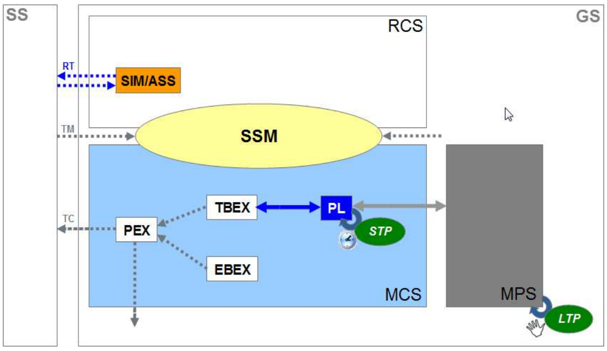

Figure 5. Ground Autonomy and Short Term Planning

The Mission Control System (MCS) is the software and hardware solution running in the Mission Control Center to monitor and control the space segment. It has to provide the functionality to connect to one or a network of ground stations. Therefore, it needs to receive telemetry transfer frames data based on data stream and virtual channel identifier (VCID), as defined in given standards, to deliver telecommand frames and also to receive administration messages of the executing NCTRS/NIS system. For the MICCRO demonstrator we use SCOS 2000 by ESA, as it is already used within the GSOC for other missions and it is considered as the de facto standard for European space missions. A specific mission information base (MIB) has been created for the project.

The Communication Gateway is a new component that was designed for supporting robotic missions within the ground segment. It is a central component to support the routing of different virtual channels as explained in the communication concept via the protocol standards usually used for the standard satellite TM/TC. The RT TC and Video data is received, converted and multiplexed into the standard satellite communication. For this the full protocol stack has been implemented and also sophisticated multiplexers are implemented. Towards the simulated space link, the frames are transmitted over a UDP link as no ground station and physical RX/TX equipment is used for the simulator. The Communication Gateway is the enabling component implemented in C++ to transfer the different virtual channels mutiplexed according to given priorities on the standard protocols.

For the different terrestrial and space link simulators based on the open source tool WANem are implemented to be able to simulate the effects of latency, jitter and packet losses. Two terrestrial links between the control center (SLE network for TM/TC and SDH-E3 link for Video and RT TC) are simulated. For the space link these characteristics can therefore be adjusted to allow investiations on the effects on robotic operations.

The Onboard MUX which is based on the same application code as the Communication Gateway acts as its counterpart to multiplex or de-multiplex the data send to the ground or received from ground. Usually the data as sent by the ground station would be de-multiplexed based on the virtual channel ID or the APID onboard the spacecraft. This is now done in the Onboard MUX and the data to the robotic component is separated from the TM/TC towards the satellite platform simulator.

The Robotic Payload Simulator is implemented using DLR’s HIROSCO Framework [5] (cp. Figure 6). The HIROSCO Supervisor performs monitoring and control of its attached components. Low-rate TM/TC such as housekeeping data or telecommands to configure the simulator is exchanged between the TM/TC Component and the Onboard MUX. The engineering model of the ROKVISS experiment is used as manipulator in this setup. It is connected to the Robot Control Component via Sercos II interface. This component implements an impedance controller and various interpolators so the operator can move the manipulator either in tele-operated mode using the Task Oriented Programming (TOP, [7]) Component or in telepresence mode using the Bilateral Control Component. The latter is transferring high-rate telepresence data to the onboard MUX. All components run on a workstation with VxWorks 6.9 operating system.

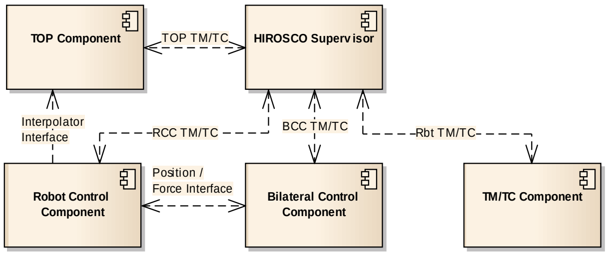

**Figure 6. Robotic Payload Simulator**

For the simulation of the satellite platform an addition simulation tool GSTVi by ESA is used to allow an interfacing to the data as send by SCOS. The powerful S/W suite is deployed in a minimal configuration to answer the commands send and to create a minimal set of telemetry. This telemetry is created by a satellite model simulating a spacecraft in LEO orbit as applicable for the envisaged OOS scenario. Platform and payload simulation are not connected to each other as a manipulator with a fixed base is assumed in this scenario.

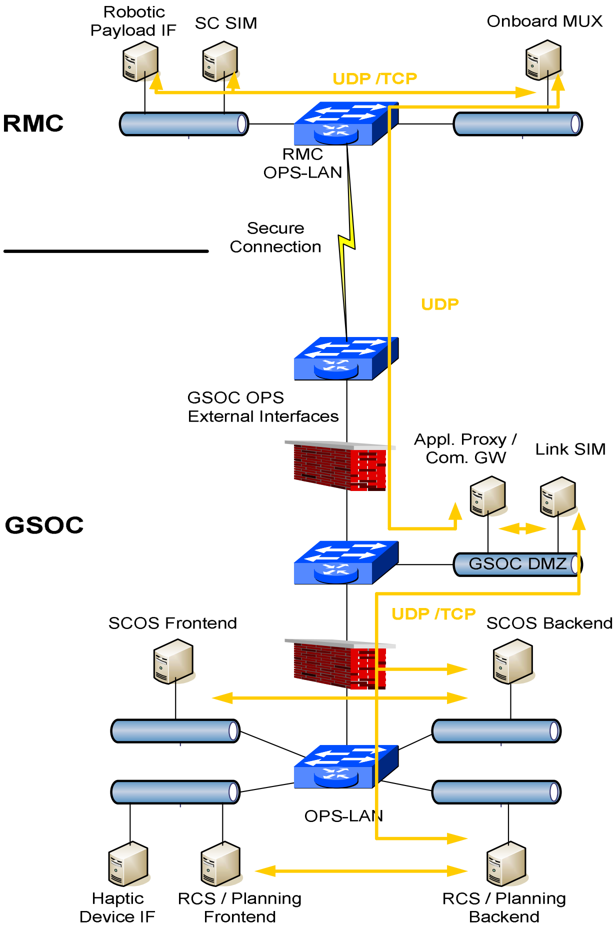

Figure 7. Network Topology

### **3.2.** Deployment

In order to achieve a smooth integration of the different system components, three different integration steps are performed until the final system setup is implemented. In order to simulate the separation between space and ground, all ground components will be located within the DLR-GSOC and the simulated space components will be installed within the DLR-RMC laboratory. The link between both sites will be based on the locally available LAN.

The integration has been performed using a three-stage approach. First, the system has been integrated at SCISYS premises. Simulators for all relevant interfaces are used, as the robotic component was not available. The environment remains at SCISYS and is used as development environment for the ongoing activities. As a second step, the on-site integration in a local deployment has been completed. The entire system is implemented within the laboratory of the DLR-RMC allowing a direct LAN based connection to all components, incl. the robotic component.

Recently, the site integration applying the distributed deployment, the third stage, has been realized in order to prepare the system demonstration. In this step, all ground components of the system have been moved into the DLR-GSOC infrastructure. By this the real separation and all networking and infrastructure issues have been are covered. All user interfaces are integrated within the control rooms.

The integration into the network topology of the GSOC, as well as the integration of the remote elements outside the GSOC, turned out to be challenging as also the realtime requirements need to be considered. Figure 7 provides an overview of the used network topology. The system entities are spread over three subnets and the data transferred needs to pass a high number of routers and three firewalls. Including all components a round trip time of approximately 10°ms has been achieved. This remarkable small latency was not expected due to the high number of routers, computer platforms and firewalls involved. This very good performance is a good starting point for systematic investigations on the influence of link delay and jitter using the link simulators with different communication characteristics settings.

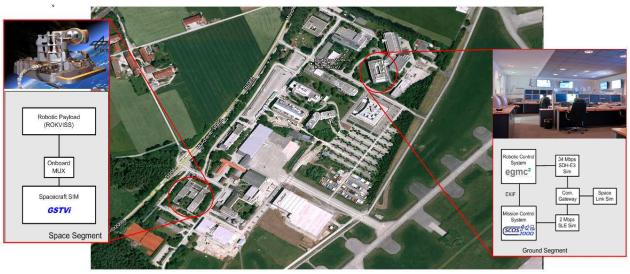

Figure 8. Demonstrator Deployment

In order to ease integration, all computer platforms with the exception of the workstation platforms used to host the HMIs and the realtime platforms controlling the haptic input device and the ROKVISS robot, have been virtualised. By that, the different server platforms can be easily transferred from on VMWare ESXi host platform to another or also into a different environment.

### **3.3.** Scenario based Verification

Organizational aspects are covered by running different scenarios in a GSOC control room, from where all functions of the simulated space segment are controlled. Handovers between mission phases and consequences on roles and responsibilities are assessed in the system demonstration. Assistance systems used for early warning or plan optimization are also integrated and their usability for robotic missions is tested.

In order to verify the concepts that were already detailed in section 2, six different scenarios were selected to proof the concept utilizing the MICCRO demonstrator. These scenarios are designed to cover the following control states which were identified for the servicer of an OOS mission (compare Figure 9). An orange background indicates that a connection to ground is required and for the sake of clarity not all possible state changes are depicted.

As long as the servicer has no contact to a ground station, it will by default perform autonomous operations. For example, it will recharge its batteries, maintain the correct temperature or perform an approach to a malfunctioned satellite. After the TM/TC link has been successfully established, the operator can choose to either supervise the autonomous operation or to tele-operate the satellite. Once the signal was lost (LOS), the servicer will switch back to its autonomous state. Usually, the first commands from ground after AOS are dedicated to the satellite platform, e.g. to alter the pose of the satellite for the upcoming robotic operations. After that, the control authority may be handed over to the robotics operator. He will operate the payload (e.g. the manipulator) to achieve the mission objectives, to prepare the payload for a subsequent telepresence phase or to wrap-up past operations. Of course, in any of these states failures can occur. A failure could be detected by monitoring activities on board or by an operator on ground. To respond to presumably less critical errors (e.g. temperature warning), commands issued by an operator will be sufficient. Critical errors such as an imminent collision must be handled by the on board autonomy which will try to solve the problem and subsequently put the servicer into safe mode.

The following scenarios map these general control states to the demonstrator setup. The first scenario represents the teleoperation of the servicer platform right after begin of ground station contact. Telecommands and telemetry will be send and received using monitoring and control system SCOS 2000. This scenario corresponds with many other satellite missions in Europe and, therefore, accustomed roles and responsibilities can be established. There will be two incremental steps for this scenario. The first step is to establish direct communication between SCOS and GSTVi. The second step also integrates Communication Gateway and Onboard MUX in order to test their non-real-time capabilities.

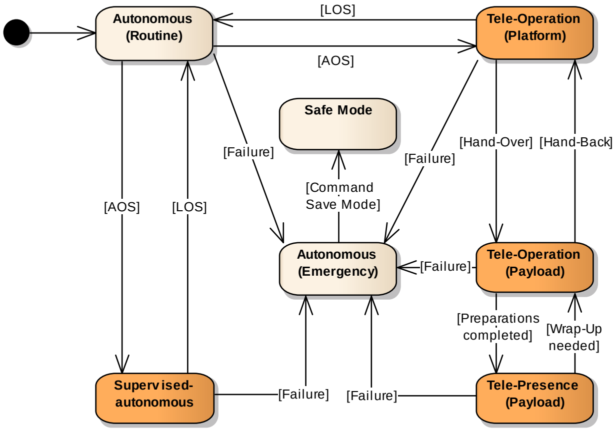

Figure 9. Control States During an OOS Mission

After that, the control authority will be handed over to the robotic operator in the context of the second scenario. For the demonstration, the control room will therefore be staffed with an integrated control team according to section 2.2.

Having the control authority, the robotic operator can prepare the teleoperation of the manipulator during scenario three. He will initialize and configure the required components and communication links. Once completed, the operator will execute exemplary robotic tasks. Additionally, a ground autonomy component will be used to create a resource-optimal schedule for a sequence of experiments and to supervise the execution of this schedule to determine whether there is enough time left to complete it or not.

Tele-presence experiments will be conducted in the fourth scenario. During these experiments, the Communication Gateway will be stressed most because real-time data together with video data must be transmitted between onboard and ground components in addition to standard TM/TC data.

The main focus of the supervised autonomy mode, which is enabled in scenario five, is to demonstrate the red button concept. An autonomous task performed by the manipulator will be interrupted by an operator pressing the red button. This will force the robotic components to shut down autonomously which brings our setup into a safe state.

Finally, during the last scenario, the robotic operator will end telepresence operations, move the manipulator back to its parking position and rehandover control authority to the FD who resumes mission operations.

## 4. CONCLUSION AND OUTLOOK

The end-to-end system demonstration prototype implemented within the project MICCRO will be used to verify and proof the concepts for robotic mission operations as described in section 2. The system demonstration is planned for the 20/09/2012 for a realistic scenario with components deployed within the DLR-GSOC and DLR-RMC in Oberpfaffenhofen, Germany. The selected mission type is agreed to be an on-orbit servicing mission incorporating robotic manipulators on board the spacecraft. The scenario has been selected as it induces a number of challenging requirements in all discussed areas and aspects of the common mission operations concept can be presented.

Future robotic missions will benefit from the gained results. The conceptual ideas and the prototype implementations are available to set up the ground segment in a harmonized way. With the perspective of the upcoming DEOS mission, the conceptual ideas for OOS type missions are prepared and ready to be use.

## 5. ACKNOWLEDGMENTS

The MICCRO project is funded by the Space Management of the German Aerospace Centre (DLR) with federal funds from the Federal Ministry of Economics and Technology in accordance with the parliamentary resolution of the German Parliament. (Grant no. 50 RA 1015 and 50 RA 1016).

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