MISSION CONTROL CONCEPTS FOR ROBOTIC OPERATIONS: EXISTING APPROACHES AND NEW SOLUTIONS

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ABSTRACT

This paper gives a preliminary overview on activities within the currently ongoing *Mission Control Concepts for Robotic Operations* (MICCRO) study.
The aim of the MICCRO study is to reveal commonalities in the operations of past, current and future robotic space missions in order to find an abstract, representative mission control concept applicable to multiple future missions with robotic systems involved. The existing operational concepts, responsibilities and information flows during the different mission phases are taken into account.
A particular emphasis is put on the possible interaction between different autonomous components (on-board and on-ground), their synchronisation and the possible shift of autonomy borders during different mission phases.

Key words: MICCRO; Mission Operations; Robotics; Ground Autonomy; SSM.

1. INTRODUCTION

For the development of a common concept for mission operations of robotic systems experience in different fields needs to be brought together. Within the project team consisting of the *VCS AG*, *DLR Institute of Robotics and Mechatronics* and the *German Space Operations Center (GSOC)* expertise in robotics, in spacecraft operations and ground mounitoring and control (M&C) as well as data distribution systems are combined.
Especially for robotic missions, the autonomy aspects need to be analysed. For most space missions the spacecraft is designed to operate autonomously for a limited time of appr. 48 hours on a provided schedule. Depending on the nature of the robotic mission the underlying common mission operations concept needs to cope with different needs. When running in a *teleoperation* mode, the robotic operations requires control within seconds, or in the special case of *telepresence* within a few milliseconds. On the other hand a rover scenario can introduce requirements for autonmous planning systems e.g. for path finding, etc.
Robotic subsystems have been demonstrated in different use cases. During the *ROTEX* experiment [8] as part of the D-2 mission in 1993 a small 6-axis robot equipped with a 6 degrees of freedom (DOF) wrist-mounted force torque sensor (FTS), laser range finder and video cameras performed about 10 sets of experiments in LEO within 10 days. A number of prototype tasks in different operational modes within the pressurized SpaceLab module were demonstrated. These included direct teleoperation by astronauts on-board with 6 DOF I/O devices, teleoperation on-board by locally executed sequences of predefined commands in automatic mode refined by local sensor data and teleoperation on-board by operator on-ground with time delays in the order of several seconds and autonomous catching of free-flying objects having the ground in the loop.
In 1999 DLR's *German Technology Experiment* (GETEX) [13] operated a 6 DOF robot arm equipped with wrist-mounted FTS and various stereo cameras in LEO on the outside of the Japanese ETS-VII satellite in free space for 15 experiments within a week. The tasks during this mission had been performed using VR methods and the *vision&force* control scheme, by closing sensor control loops directly on-board (using measured forces) and via the ground track (using vision), thus, proving DLR's sensor-based autonomy features, verify a 6 DOF dynamic model for the interaction between the robot and its free-flying carrier satellite in free motion mode without AOCS intervention.
For the *ROKVISS* experiment [9] a small 2 DOF manipulator equipped with torque sensors, joint-position sensors and stereo cameras was mounted outside the Russian Service Module (Zvezda) on ISS in LEO to demonstrate the fitness of DLR's light weight robotics technology for space between 2005 and 2010. Aims of ROKVISS had been in-flight long term verification of highly integrated modular robot joints developed by DLR, evaluation and monitoring of evolution of dynamical parameters (especially friction, motor constant and stiffness) over the course of the mission in order to validate the long term stability of the system and performance of high-quality telepresence operation including haptic feedback.

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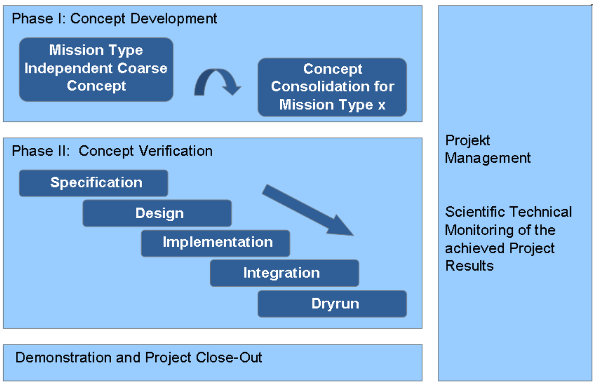

Figure 1. Project Structure

Common to the above mentioned experiments is an integration of the different robotic components into an existing mission concept and by that also existing system infrastructures, incl. the spacecraft. The robotic component was integrated and handled as a payload system. For future systems where the robotic component has a very close coupling and interaction with the spacecraft itself, the integration as a payload leads to a number of problems as the satellite platform itself is influenced during the robotic operations phase. A new mission operations concept is required as an enabler for the implementation of robotic missions.
The operational experience from running more than 50 space missions in the GSOC [16] over the last 40 years amended by the special conclusions drawn from already implemented missions involving a high degree of autonomy are used within this project.
Finally this knowledge is brought together with the VCS experience in implementing M&C solutions in the ColCC at the GSOC and also in the Galileo ground segment implementing the GACF, CMCF and GNMF elements [17]. By that, a deep insight into the control centres and also the operational concepts was gained. Interviews with VCS operators working at the European Space Operations Centre (ESOC) allows to compare the concepts as run in different control centres.
The combination of the project team partners allows to create an open minded review of the known mission operation concepts and to synthesise a common mission concept covering future robotic missions or also missions involving autonomous components.

2. PROJECT OBJECTIVES

The project objective is to develop and verify the above mentioned generic mission operation concept that can be utilised when implementing space missions including also robotic or autonomous components. The project started end of 2010 running for 24 month and structures into two phases as shown in Figure 1.

In phase I *Concept Development*, the conceptual work focusses on the review and analysis of past, current and future robotic space missions in order to reveal the individual needs as well as the commonalities. A general approach is identified as *Mission Type Independent Coarse Concept*. The coarse concept is later on refined in a *Concept Consolidation for Mission Type x*. Here a specific mission scenario is selected for the refinement.
In phase I the focus of the analysis is put on the:

- Autonomy Concept: Describes different implementations of autonomy and provides guidelines which aspects shall be considered. Services required for the missions and possible implementations are discussed.
- Operational Organization, Roles and Responsibilities Concept: Analyses the integration of the robotic component into the mission infrastructures as well as the organisational structures and hierarchies.
- Communication Concept: General as well as specific constraints that are introduced by the robotic components are analysed.
- User Concept: Description of the required human machine interfaces (HMIs) to operate the robotic mission as a bundle of standardised and also mission or problem specific interfaces.

The concepts developed and documented in phase I are verified in phase II *Concept Verification* of the project. For this purpose a prototype representing the mission type that was used for the concept consolidation is used to achieve the proof of concept.

3. AUTONOMY CONCEPT

Multiple definitions and classifications for autonomy have been proposed by different academic disciplines and for space applications in particular. While some of them focus on dedicated use cases or foster a close relation between planning and autonomy we want to stick to a rather comprehensive description where the degree of autonomy is determined by the interplay of *cerebral and spinal functions* in order to achieve a certain task (see Figure 2).

Spinal vs. Cerebral A spinal function is a highly reactive, reflex like action, e.g. in case of an unexpected situation or failure. Spinal functions usually save a system from bigger damage. Thus FDIR mechanisms often fall into the category of spinal functions. In contrast to this we define cerebral functions which represent long term strategies. These operate on a larger time scale and are usually not adequate to solve realtime problems. Talking about architectures spinal and cerebral functions correspond to the concept of reactive and deliberative layers. Both, spinal and cerebral functions are categorized by two aspects. The application domain is determined by space specific operations functions like Managing, GNC, FDIR, Intelligent Sensing, Data Handling and M&C (compare to CCSDS 520.0-G-3). Second we distinguish different technologies used to implement autonomous behaviour. These technologies reach from simple time and/or event based automated execution over classical control engineering and machine learning techniques to highlevel planning and scheduling approaches.

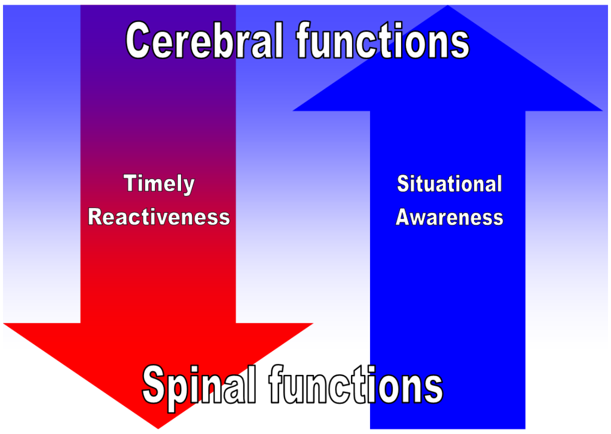

Figure 2. Autonomy as an Interplay of Cerebral and Spinal Functions

According to this categorisation even simple procedure execution systems (PEX) like surveyed in [18] establish autonomous functions. It is important to note that spinal functions may have significant influence on the system state which in turn may require a reaction of the cerebral functions. If spinal functions are too powerful they may even lead to autonomous but destructive behaviour. A well balanced interplay between spinal and cerebral functions is what makes a reasonable autonomous system and poses the main challenge for any autonomy concept [11] [19] [15]. On the other hand sometimes a simple concert of spinal functions alone can create rudimentary autonomy [3]. The increase and combination of cerebral functions usually composes a higher situational awareness (SA). SA means that a system has a domain spanning perception of its current state and is capable of projecting it into the near future which in turn allows it to deduce sensible behaviour. Cerebral functions shall be activated when a cool head is needed. Spinal functions instead are optimized for dedicated tasks and work in niches. They do not have an overview of the complete system within its environment. However, spinal functions because of their capabilities to react very timely are an essential component especially of embodied systems.

Shifting Autonomy Spinal and cerebral functions are spread across the system of a space mission. They may generally be located in the space segment as well as on ground. But due to their reactive character spinal functions are usually tightly coupled to their host, like e.g. on-board FDIR routines or star trackers providing autonomous lost in space acquisition and delivering quaternion attitude determination. It is noted, though, that there are also ground-based spinal functions like automatic failover scenarios. The decision where to implement a cerebral function is likewise primarily driven by locality and connectivity aspects, but performance limitations of on-board systems often enforce trade-offs and outsourcing of functions to the ground. A possible way to increase efficiency here can be the distribution of autonomy [2] or the dynamic shift of dedicated cerebral functions between agents, e.g. between space and ground segment or between a planetary rover and an orbiter. The ”execution of time tagged or event-based commands” and ”goal-oriented mission re-planning” designate spinal and cerebral functions of the four levels of nominal mission execution autonomy as defined by ESA’s standard for space segment operability (ECSS-E-ST-70-11C). The standard focuses on on-board capabilities but the same technologies can in principle also be applied to the ground segment and, thus, be shifted and/or shared between ground assets and on-board components. This is especially true for cerebral functions like re-planning where already as of today optimisation tasks are accomplished offline by ground assets and final schedules are uploaded to an on-board execution engine. For most spinal functions - especially FDIR routines - such an approach is not feasible. However, if a permanent connection to the space segment is available, scenarios for robotic missions like on-orbit servicing can be identified where spinal functions with the ground in the loop are possible. An example could be the complex, resource consuming simulation of a physical model during a telepresence operation [16] as an assistance system.

Advanced FDIR The FDIR autonomy level F1 as per ECSS-E-ST-70-11C requires to ”establish a safe space segment configuration following an onboard failure”. In the above on-orbit servicing example any movement of an externally attached manipulator has direct influence on the satellite bus’ attitude. This can lead to failure scenarios where a coordinated interaction of manipulator and AOCS is required which in turn implies the calculation of complex physical models on-board. The spinal function must be implemented on-board and sufficient hardware performance must be foreseen. This touches the research area of advanced FDIR mechanisms [10] [7] [12].

Ground Autonomy This study focuses on ground autonomy concepts, i.e. the implementation and interplay of spinal and cerebral functions located in the ground segment. Generally ground autonomy - other than on-board autonomy - can be employed in two ways: The respective function affects the operations directly. This is e.g. true for a PEX executing event-based tasks. We denote this flavour as *direct autonomy*. On the other hand a ground asset capable of producing autonomous output may be intentionally decoupled from the real space system and instead provide its output to an operator as a suggested solution. In this case the autonomy component is used as an assistance system and control authority is kept with human personnel. We denote this as *indirect autonomy*. Arguably current offline mission planning systems (MPS) like [1] [4] belong to the latter category but the employed technologies obviously form the basis for future direct autonomy assets [6]. As a first outcome of the analysis we propose a generic ground autonomy concept for robotic missions (see Figure 3). A spinal direct autonomy function is provided via event-based procedure execution (EBEX) in order to support ground segment FDIR routines. Time-based procedure execution (TBEX) is accomplished following a dedicated short term plan (STP)

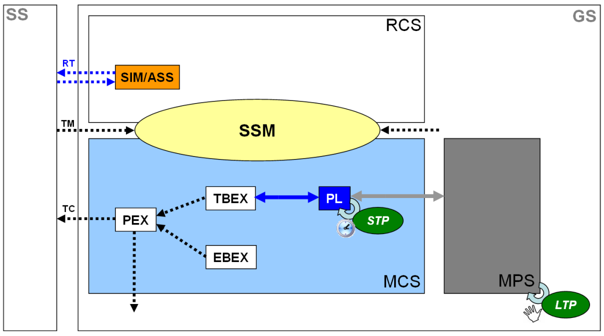

Figure 3. Ground Autonomy Architecture

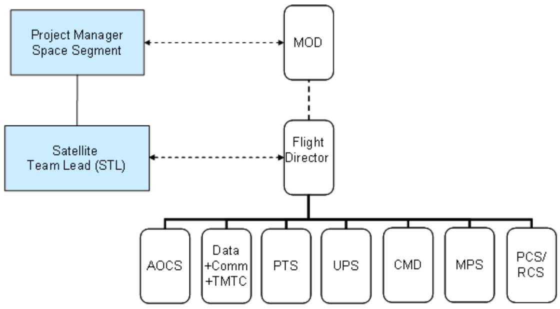

Figure 4. Example for an integrated mission operations team

which is regularly validated by an internal planner (PL, e.g. using PDDL [14]) and ideally - as a cerebral direct autonomy function - repaired in case of a detected problem. The STP is initially ingested to the Mission Control System (MCS) by the Mission Planning System (MPS) where it is derived from a long term plan (LTP) potentially using offline planning tools. It is important to note that the integrated planner in contrast to these offline tools and similar to [5] is regarded to implement what we defined as *direct autonomy*. Both, TBEX and EBEX make use of a common procedure execution engine (PEX, e.g. following the PLUTO standard as per ECSS-E-70-32C) which forwards tele commands (TC) to the space segment (SS) or triggers actions within the ground segment (GS) itself. The calculation of complex physical simulation models (SIM) as mentioned in the on-orbit servicing example is part of the Robotic Control System (RCS). Control authority can be given directly to such a component or it can be used as an assistance system (ASS) for the operator. Usually such components need a real-time (RT) closed loop to the space segment being set up. A core component in this architecture is the so called Space System Model (SSM, ECSS-E-ST-70-31C) representing the overall configuration of the mission as well as the current state as perceived by incoming telemetry (TM) and other monitoring data. Any of the above components can access the current state of the mission via the SSM.

4. OPERATIONAL ORGANIZATION, ROLES AND RESPONSIBILITIES

Roles & Responsibilities for standard satellite missions An example for the roles within a standard mission operations team is shown in Figure 4. The positions and the command structure are comparable to the situation on a marine vessel: the only position which is allowed and able to send commands to the spacecraft is the command operator (CMD) comparable to the helmsman. The decision to send a specific sequence of commands is taken by the Flight Director which can be compared to the captain of the vessel. The other positions are so called subsystem engineers which match to the position of seamen. Each subsystem engineer is responsible for a specific component of the space segment. The subsystems which are shown in Figure 4 represent following positions:

- AOCS: Attitude and Orbit Control
- Data + Comm. + TMTC: Data System, Communication System and Telemetry & Telecommand
- PTS: Power & Thermal System
- UPS: Unified Propulsion System
- MPS: Mission Planning System
- PCS / RCS: Payload Control System / Robotics Control System

It should be mentioned that this is just an exemplary list. The number and kind of subsystems may vary from mission to mission. Additional positions are Mission Operations Director (MOD) who has the over all responsibility for the ground segment of the mission. MOD and Flight Director correspond to the Project Manager of the Space Segment and the Satellite Team Lead (STL). In general the communication between the operators and the Flight Director is via voice loop which is recorded (*the spoken word is law*). Typically, the Flight Director is informed by the Subsystem Engineers in order to be able to take well informed decisions. The CMD operator will execute the decisions by sending a stack of commands.

Roles & Responsibilities for Robotic Missions In the following we investigate the question whether there should be a modified concept for roles and responsibilities in the context of robotic missions, especially the share of responsibilities between the Flight Director and the Robotic Operator. A concept for roles & responsibilities has to regard following questions:

- How much time do you have to make decisions?
- How much information is needed to make these decisions?
- Does the robotic operation include a real time reaction via telepresence?
- What is the optimal way to cluster or fragment certain areas of responsibilities?
- Does this imply an integrated mission operations team in a single control room or a distributed team at spread locations?

The first question we should answer is how the ground segment infrastructure of a robotic mission should be designed. A logical method to design a ground segment infrastructure is to mirror the space segment structure regarding functionalities and interfaces. The ground segment infrastructure should minimize the complexity of interfaces between distributed components. Usually it is a good idea to operate the robotic payload and the space vessel it is mounted on within an integrated operations team since the robotic system heavily interacts with the spacecraft. Examples are the operation of a rover or an On-Orbit Servicing mission like *DEOS*. An exception is the operation of the robotic experiment *ROKVISS* on the ISS where the interaction between the robotic manipulator of *ROKVISS* and the ISS is negligible. Whenever the robotic system and the spacecraft platform are operated by an integrated operations team the robotic control system RCS should be integrated like an extended payload control system (see Figure 4). However, when telepresence and real time operations are required a new dimension is introduced into space operations. For non-robotic missions the time scale for decision taking is usually hours or minutes. On the other hand the requirement for telepresence conditions is to limit the response time to a few hundred milliseconds. Therefore, the standard way of commanding by voice loop from the Robotic Operator to the Flight Director to the CMD operator has to be modified. A direct control loop between the robotic system in space and the robotic payload operator has to be introduced. During a robotic phase the communication link is shifted from the standard link to a telepresence link. At the same time the control authority is be shifted from the command operator to the robotic operator (CMD and RCS positions within Figure 4).

Control vs. Responsibilities Contrary to the control authority responsibilities should be never shifted: The Flight Director will always be responsible for the complete system; a subsystem operator will always have the responsibility for his subsystem. In certain phases this even implies that e.g. the AOCS subsystem engineer is responsible to keep the AOCS deactivated. The share of responsibilities between Flight Director and Robotic Operator are similar to the roles of a Shuttle commander and pilot: The robotic operator has the control authority on time scales of milliseconds whereas the Flight Director is responsible for the overview and general decisions on a time scale of seconds and minutes which includes a possible decision to abort a robotic operation. The procedure how to abort robotic operations depends on the situation and phase. It should be predefined and trained as much as possible.

5. COMMUNICATION CONCEPT

For space missions the communication infrastructure is a key component. Therefore, the communication concept for robotic missions describes the general contraints influencing the concept and introduces and details the specific demands induced by the robotic components.

General Constraints Cost induces *financial constraints* for space missions and this holds especially true for the ground segment with its ground station network. Carrying out the routine phase of a space mission is always a compromise between a higher degree of on-board autonomy or robustness and the number of (costly) ground station contacts to control the spacecraft. For almost all national security-related missions, the ground segment with its control center and ground stations is restricted to be located within the country of the owner of the satellite (*political constraint*). Different criteria inducing *connectivity constraints*, the bandwidth, latency time and a third one, which is protocol need to be deeply analysed. Effective scheduling of the customers requests for satellite contacts is the key to running a ground station economically successfull. To reduce schedule problems and also to use support equipment and facilities that are needed to operate an antenna more efficiently, ground station support providers often build more than one antenna per ground station. The antenna *availability constraints* depending on the ground station schedule priorisation needs to be considered. The involved ground station and the control centre must support the encryption standard required by the mission (*security constraints*). If special hardware must be used or modifications to the ground station equipment must be carried out, the number of potentially usable ground stations is limited to special ground stations run by national services, e.g. armed forces or intelligence services. The space segment needs to satisfy a number of mission specific communication related requirements, which induces *space segment constraints*. These can not be described in advance as it strongly depends on the communication path and possible other spacecrafts.

Robotic Constraints Future activities in space will be more and more complemented by robotic support. Remote control concepts which rely on system access via *teleoperation* have already been used in the past [8] [13]. This operation mode allows just a delayed access to an application in space. The commanding for each process step has to be identified in advance in order to assemble a script-like *to-do list*. A typical but normally not time-critical mission control service in that context is the management of uplinking those *robotic scripts* to and downlinking stored results from the spacecraft. Direct interaction especially in case of any contingency is impossible. On the one hand such a static operation concept is without any alternative in case of having strict temporary requirements or bridging great distances (e.g. deep space missions or planetary exploration). On the other hand its static nature shortens the flexibility required for direct servicing (e.g. in earth orbit). A concept to overcome that lethargical behaviour is *telepresence*, where the physical correlation between *actio and reactio* is directly fed back to the operator. This allows for a highly flexible handling of the current situation (especially useful for servicing and repairing). From its basic nature *telepresence* is a distributed control loop imposing harder constraints on the communication link compared to *teleoperation*.
From a robotic point of view a *communication link* is characterised by bandwidth, jitter, latency, reliability of transmission, duration of radio contact and signal propagation time. Each of them has direct impact on the quality

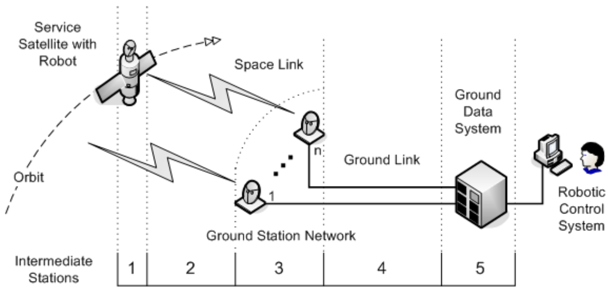

Figure 5. Communication Concept for Robotic Missions (Intermediate Stations)

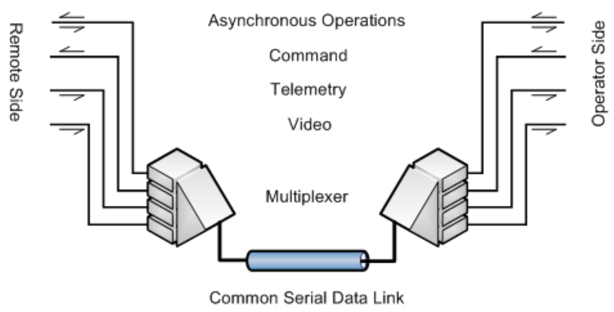

Figure 6. Configuration of Communication Link

of service and control. For example *telepresence* works nonsatisfying as soon as the data latency exceeds about 500 msec what corresponds to a theoretical maximum operational radius of about 72000 km around the operator. Any additional artificial source of latency should be minimized. Typical sources are extensive buffering, coding, decoding and preprocessing of data at each intermediate station on the way from ground to space and vice versa. As a matter of fact standard communication infrastructure on-ground (Figure 5) is currently not designed for minimal latency. It turns out that their artificial latency may dominate the overall signal propagation delay especially in case of LEO applications. But even for LEO the effective signal propagation time may be magnified significantly by methods in order to extend the duration of radio contact. The visibility of a satellite orbiting earth can be extended by using data relays. For an increased coverage a network of communication satellites in space and/or ground stations on earth can be hooked-up, but such a scenario increases the effective distance, requires from time to time a signal rerouting and adds both more hardware components and consequently more latency. As a matter of fact, each method for extending the visibility of a remote system in space results inevitably in degradation of its corresponding link characteristics.
Common to all remote operations is the idea of transferring information in dedicated *logical channels*. These logical channels are de-/serialized for transmission over the physical radio link by multiplexing (Figure **??**). In general the available physical link bandwidth is shared priority based amongst all active channels automatically. A flexible adaptation to changing requirements is very

Internal Cycle Time	1.0-5.0ms	
Cycle Jitter	0.5*Internal Cycle Time	
Uplink Rate	256.0-512kBit/s	*telepresence* mode with 7 axes robot (50 byte).
Downlink Rate	4.0-12MBit/s	*telepresence* mode with 7 axes robot and live-video (e.g. 20Hz, 256x256 stereo, lossless 50% compression rate, bw and 15% add-on for telemetry and asynchronous data).
Artificial Signal Propagation Delay	less than 10.0 ms	Not included is here the wave propagation time which depends on the spatial distance.
Wave Propagation Time	less than 600.0 ms	Specific constraint for *telepresence* mode.

Table 1. Range of Communication Parameter for Future Robotic Missions.

important because the effective available link bandwidth is inverse proportional to the signal propagation distance. Apart from the physical transfer capacity transmitted data can be categorised into three qualities:

1. Synchronous data cyclically distributed,
2. Synchronous data acyclically or event-driven distributed and
3. Asynchronous data distributed as requested.

A typical representative is online telemetry for category 1, single-shot commands for category 2 and isolated data requests (e.g. house-keeping data, file-transfer) for category 3. For data transfer several protocol proposals from different source are available (e.g. CCSDS, ECSS, TCP/IP). From a robotic point of view the common drawback of all these definitions is their focus on realizing a perfect lossless transfer of all data which is not necessary for all kind of robotic data (e.g. cyclic TM/TC). Making the usage of a save protocol standard practice will add so much computational protocol overhead that a deterministic transfer-rate cannot be guaranteed all the time. In that case it is more acceptable to lose some data using an unsafe protocol alternatively. Just the usage of bit correction codes (like Reed-Solomon) and an automatic re-establishment of the connection seem to be acceptable in order to minimize the effect of data losses or a physical *Loss of Signal*.
Table 1 outlines the range of communication parameters as proposed for future robotic *telepresence* missions. Those requirements also cover the more unpretentious *teleoperation* mode. They are based on practical experiences gained during past missions mentioned in section 1. The most critical aspect is the high downlink rate mainly used for online video streaming. At this point a mission specific trade-off between resolution, rate and compression has to be identified taking limited on-board resources into account. However an extraordinary effort seems to be acceptable in order to support both smooth

stereoscopic real-time visualisation and high-resolution image processing on-ground.

6. USER CONCEPT

The user concept is driven by two main aspects which are the operational organzisation, roles and responsibilities, which have been discussed before and the HMI concept. The latter one will be discussed in this section.
SCOS-2000 and the VCS egmc^2 framework provide well-proven HMIs that have been used successfully to support spacecraft missions. If robotic components are involved in a mission, these interfaces can still serve their purpose and, thus, may be used as a starting point from which robotic features can be integrated once they are demanded.
Missions characterized by long transmission time delays or high autonomy levels on-board will generally rise less demands on robotics and MCS integration. Coupling of the MCS and the robotics control may then be realized loosely allowing every party to perform their duties more or less independent from each other. However, new challenges arise when it comes to direct operation of satellite based robots from ground (close coupling). Efficient flight operations structures and highly intuitive interfaces must enable quick and correct decision making then. Therefore, robotics needs to be tightly and seamlessly integrated into the MCS. Thus, we choose to integrate the robotic operations analogous to operations for other satellite subsystems into the same control room using similar control structures and user interfaces.
Generally, there are three categories of data which need to be presented to human operators through their HMI:

- Satellite uplink/downlink data including conventional command and telemetry data as well as data transmitted through realtime channels
- Data exchanged between operators and other on-ground applications such as ground data, ground autonomy, video processing and similar assistance applications
- 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 which plug into a standardized application framework (Figure 7). 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.
From experiences gathered during past missions the following requirements from the robotics viewpoint have been compiled:

- The user interfaces for the robot operators should comply with high level software ergonomics standards. This respects the task complexity and heavy responsibility of the operator actually guiding the robot.
- For the same sake the robotics operator should be provided an augmented virtual reality display of the situation on-board the spacecraft. Such an interface comprises a 3D graphics visualization augmented with key values and hints such as force measurements and planned access pathways (see Figure 8).
- HMI components common to all robotics team members should comprise a state summary of the overall systems on-ground, on-board and a more detailed summary of the robotics subsystem.
- A mission timeline should depict planned and actual procedures and events.
- A video display should alleviate imagination of the situation on-board for all robotics team members.
- High-end haptic input devices should enable the robotics operator to actually feel what is going on on-board during telepresent manipulation.

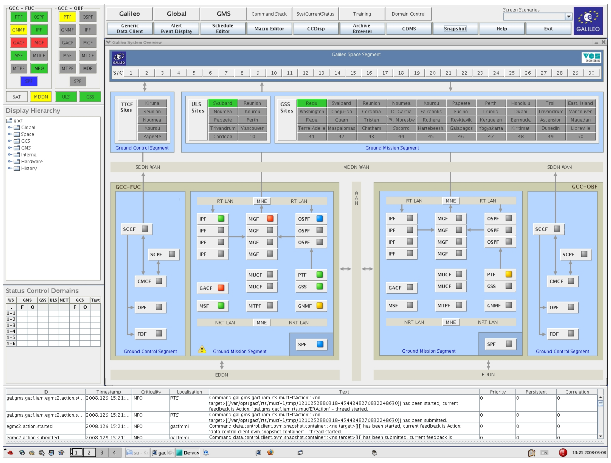

Figure 7. Example: egmc^2 User Interface Framework

Figure 8. Augmented Reality Interface

7. CONCEPT VERIFICATION

The concept that is developed and refined for a selected mission type during the first 12 month is afterwards verified in a prototype implementation. The selected mission type is agreed to be an on-orbit servicing mission incorporating robotic manipulators on-board the spacecraft. This special scenario has been selected as it induces a number of challenging requirements in all areas discussed in this paper and by that allows to demonstrate most aspects of the common mission operations concept. The prototype will allow to demonstrate all main concepts and innovations identified.

8. CONCLUSION AND OUTLOOK

Future missions involving robotic components as key elements require to develop new common mission control concepts. This is in particular driven by the close coupling and interaction of the robot with the satellite bus itself, which induced new challenges. Apart from the technical aspects like communication, user interfaces and autonomy also the more organisational aspects focussing on e.g. roles and responsibilities need to be changed, when having in mind operational concepts as used for standard spacecraft missions.
The study provides a common guideline for the implementation of future robotic mission concepts. Using this common concept can save costs as main concepts or components can be reused across different missions.

ACKNOWLEDGMENTS

The *MICCRO* project is funded by the Space Agency 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 ID 50 RA 1015 and Grant ID 50 RA 1016).

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