# INTRODUCING CCSDS MISSION OPERATIONS SERVICES TO THE METERON OPERATIONS ENVIRONMENT

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**ABSTRACT**

The METERON Robotic Services were invented to support human-robotic exploration experiments by providing a generic interface that eases the integration of new robotic systems into the METERON Operations Environment. The services were prototyped as a set of web services but have recently been evolved to achieve full compliance with the CCSDS Mission Operations (MO) Services concept. ESA's reference implementations were reused for functionalities common to the domains of spacecraft and robotic operations whereas dedicated robotic services were newly defined in alignment with the existing standards. A poof-of-concept experiment was conducted in collaboration between ESOC and ESTEC to demonstrate the successful migration and the applicability of the MO Services in the field of robotics.

## 1. INTRODUCTION

The objective of the ESA METERON project (Multi-purpose End-To-End Robotic Operations Network) is to evaluate and demonstrate concepts and technologies that are being considered for use in future human-robotic exploration missions in the areas of communications, operations and robotics. METERON is an international collaboration lead by ESA and involves partners in NASA, DLR and industry [1].

METERON aims to demonstrate the feasibility of controlling advanced robots on Earth in representative scenarios, providing essential experience for operations concepts and preparing real human exploration missions. In this context METERON can be seen as a test-bed for future missions to the Moon, Mars and other celestial bodies.
The activities in the scope of this project are organised in dedicated experiments, supported by a generic, system level infrastructure, which includes the "plug & play" METERON Operations Environment (MOE) system.

In order to facilitate the plug and play of different rovers and rover control systems, to reduce time to retrain operations engineers and to stimulate standardisation and interoperability, the so called METERON Robotic Services (MRS) were invented to abstract from proprietary software interfaces of specific systems and to present a high-level interface to the user. These services were initially designed in the scope of the METERON experiments as a set of web services and were reliably supporting the monitoring and control of the distributed systems in MOE throughout several experiments.

As a member agency of the Consultative Committee for Space Data Systems (CCSDS), ESA has an interest to foster standardisation concepts in different areas and to actively contribute to their definition. As a result, a migration activity has been performed to replace the web services of the MRS with an implementation fully compliant with the current standards of the CCSDS Mission Operations (MO) Services. The activity serves as input for the definition of a standard for Telerobotic Operations and evaluates the applicability and reusability of parts the MO Services which were primarily designed for spacecraft operations.

## 2. THE METERON OPERATIONS ENVIRONMENT

MOE is the Mission Control System (MCS) used by the ground operators in various METERON experiments conducted since 2012. An impression of the user interface is given in Fig. 1.

Using a system of systems architecture, the MOE provides the operators with an overview of the entire experiment, including the monitoring of the telemetry produced by the robotic assets, the health and status information of the hardware used during the experiments, as well as the status of all the systems and the delay tolerant network (DTN). All the information monitored via the MOE are distributed among all operators, also connected from different geographical locations, allowing in fact a high level of collaboration and sharing of the experiment data.

The MOE supports the ground operators also during the preparatory and closure phases of an experiment, allowing commanding of the robotic assets to execute initial status checks, the positioning of the assets prior the actual driving performed by the commanding crew, as well as the final parking after the completion of all the activities.

The implementation of the MOE was heavily based on the reuse of the existing ESA Ground Segment Test and Validation Infrastructure (GSTVi) and selected elements of the ESA EGOS infrastructure. As the MOE provides generic Monitoring and Control capabilities, it was tailored for the various robotic systems to support the different experiments conducted [2].

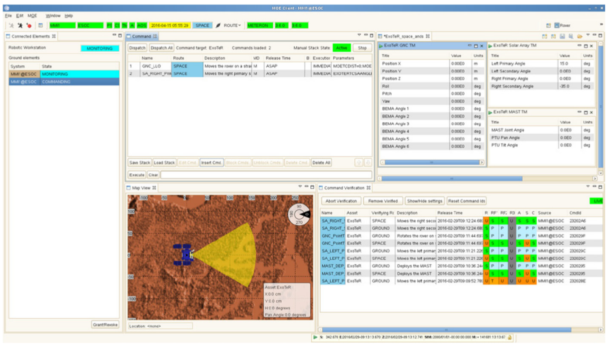

Figure 1. The MOE Mission Control System

## 3. THE METERON ROBOTIC SERVICES

Following the approach of a service oriented architecture the MOE uses the MRS to interface with the systems used in the experiments performed with different parties. In detail, the MRS have the objective to provide generic capabilities to control the motion of a rover, its camera and manipulators, to execute plans, to set configurations and to deliver telemetry and activity tracking notifications to clients. By developing these high-level functionalities and by analysing the requirements of the robotic systems in different experiments, the MRS is intended to give valuable input for the conceptualisation of a standard for telerobotic operations.

The MRS expose their abstracting interface via a simple API (available in Java and C++, see Fig. 2) which allows to spend a reasonable small effort on the development of an adaptation layer that leads to the integration of proprietary rovers and rover control systems into the METERON infrastructure.

The development of the first version of the MRS started in 2012. The services were in general designed to follow the concepts of the Message Abstraction Layer (MAL) and Common Object Model (COM) specifications of the CCSDS (cf. section 4) but are not using the Java APIs of ESA's reference implementations. Instead the MRS have been designed as a set of Web Services as underlying implementation technology. The use of the Java framework JAX-WS enabled the rapid development of the first prototype and does not require the use of third party libraries [3]. As a result the message format, the interaction patterns and the data types were depicted in the WSDL files and SOAP messages.

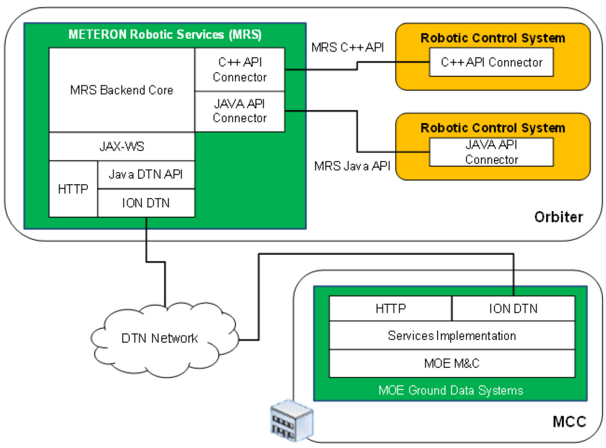


Figure 2. The METERON Robotic Services architecture

Even though the MRS are designed to control robotic systems it is important to notice that numerous aspects of robotic operations are not necessarily bound to the domain of Telerobotics. The retrieval and distribution of telemetry, commanding capabilities and the status tracking of issued commands are features which are well known from the field of spacecraft operations. As a consequence, it is assumed that ESA's reference implementation of the CCSDS Mission Operation Services can be reused to develop the MRS into a set of services fully compliant with the existing standards.

## 4. THE CCSDS MISSION OPERATIONS SERVICES

The CCSDS Mission Operations (MO) Services were devised by the Spacecraft Monitoring & Control working group of the CCSDS with the objective to establish a standardised and interoperable communication framework for mission operations. The design is based on a service-oriented architecture composed of different layers which allow to specify the services independently of the implementation or the underlying communication protocol. [4]

Fig. 3 shows the individual layers and the role of the services within the MO Framework. Applications are sitting on top of the service implementations and utilise their functionality to provide or consume services to and from other applications on the network. As the services are defined in terms of the underlying Message Abstraction Layer (MAL) which provides a generic messaging infrastructure, the interoperability between services implemented by different entities can be assured [5]. Furthermore, the MAL separates the services from the applied encoding and communication protocol by exposing a generic API that is implemented by the various existing transport bindings.

The MO Services Layer itself consists of a common set of services also called Common Object Model (COM) Services and a functional set of services. As stated in [6], the COM Services are supportive services which are deemed useful or even necessary for an efficient implementation of the functional services. They contain the following three services:

- **Archive Service**: The Archive services offers an interface to store and retrieve objects to and from an archive.
- **Event Service**: The Event Service provides the functionality to distribute events that occurred in the system and defines the archive interactions for events.
- **Activity Tracking Service**: The Activity Tracking Service make use of the Event Service to define a pattern of events that allows to track an activity, such as a telecommand, from its initial request up to its execution

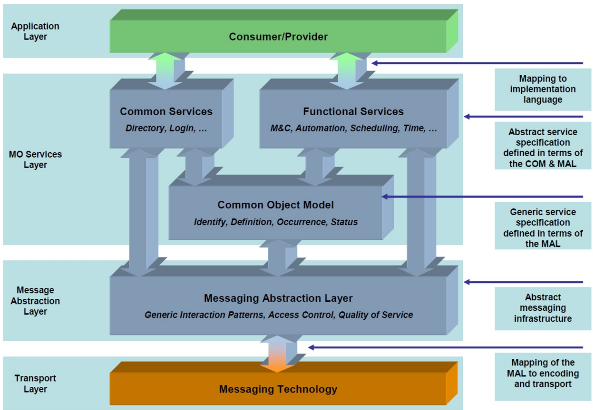


Figure 3. The CCSDS MO Framework [5]

The most important functional services in the scope of the MRS migration are the Monitoring & Control (M&C) Services. They were designed to perform basic monitoring and control tasks of a local or remote system. The full set of the services can be found in [7], while the ones relevant for the present topic are the following:

- **Action Service**: The Action Service provides the ability to control a remote system by issuing directives from a client to the service provider. It is also taking care of reporting execution verifications to the client via the Activity Tracking Service.
- **Parameter Service**: The Parameter Service allows the monitoring of system parameters by providing status updates periodically or change-based to subscribed consumers. The service does not limit applications to a defined set of parameters but specifies the structure of a parameter which allows applications to define the parameters via configuration or even to create new ones dynamically at runtime.
- **Aggregation Service**: The Aggregation Service is an extension to the Parameter Service providing the capability to group parameters into an aggregation and inform subscribed consumers about the current values in a single message rather than sending one message per parameter.

## 5. MIGRATION OF THE MRS

After using the MRS with their initial architecture in different METERON experiments, their applicability for human robotic exploration scenarios is proven. An evolution of the services from the prototyped web-service implementation to an implementation based on the CCSDS MO Framework appears to be the logical next step. Also the fact that the MAL and COM implementations reached a stable level and that the M&C Services are approaching the release of the blue book, constitutes a favourable point to perform a migration. As a result, this activity was initialised and conducted in the beginning of 2016.

Even though the MO Services have been primarily designed with the focus on spacecraft operations, many aspects are assumed to be applicable to the area of telerobotic operations as well. As a result, the reuse of the COM and M&C Services is one requirement that has been identified for the migration. Furthermore, the migration to the new service infrastructure should happen as transparent as possible to the users of the MRS as possible; meaning the exposed MRS API has to remain unchanged to keep already integrated robotic systems compatible.

### 5.1. Integration of the CCSDS MO Framework

To integrate the MO Services and the underlying layers, the existing MRS source code was investigated to identify the communication logic and the application logic of the MRS. The communication logic dealing with the creation of SOAP messages and the processing of web service requests was fully removed from the code and substituted with the functionality of the MO Framework. The high-level application logic of the MRS was kept but the entire integration with the former web services needed to be rewritten to access the interfaces of the COM and M&C Services.

As already indicated in section 4, the services which the MRS makes use of are the Archive Service, Activity Tracking Service, Action Service, Parameter Service and Aggregation Service. The latter has been integrated at a later stage of the project because it provides only an extension to the Parameter Service but no substantial functionality that would be otherwise missing for a proof of concept.

Whereas three out of the other four services have direct equivalents in the original MRS, the Archive Service offers new capabilities that have not been present before. The MOE MCS holds an internal archive used to populate the parameter history of the user interface but a centralised archive holding information about actions, parameters and activities accessible for any connected consumer did not exist as such.

### 5.2. Development of the Robotic Services

The Action Service provides only a very generic interface to control any remote system but no dedicated capabilities to execute operations of typical robotic systems. Hence, a set of Robotic Services has been specified in terms of the COM and MAL similar to the services present in the MRS.

The design of the Robotic Services was done with the help of the CCSDS MO Graphical Editor [8]. The graphical editor depicted in Fig. 4 is an Eclipse plugin which allows to define the structure and the functions of a service as well as the data types to be used. The output of this design step is an XML service specification which is needed to automatically generate the stubs and skeletons for the binding of the new services to the MAL.

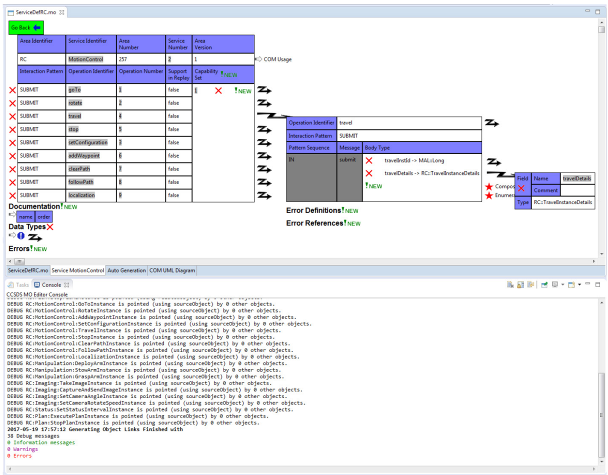

Figure 4. The CCSDS MO Graphical Editor

The Green Book of the CCSDS on Telerobotic Operations [9] gives a broad range of information on the concept of Telerobotic Services and is meant to help form a future standard. However, it does not hold any specifications yet on how such services might look like. As a result, the robotic services were specified with the MO Graphical Editor in a way that their functionality resembles the capabilities of the original MRS whereas their structure is aligned with the design of the M&C Action Service. For this purpose the WSDL files of the MRS have been examined to identify the interactions of each service and the information which are exchanged. The gathered information were then transformed into an XML service specification taking the according file for the M&C Services as a reference. By doing so, it is intended to provide a helpful starting point for the concrete definition of the CCSDS Telerobotic Services.

The implementation of the services itself on top of the generated stubs and skeletons is also following the same way the M&C Action Service has been implemented. The simple reason for this is that the robotic services provide an interface to control a specific capability of a robotic system whereas the Action Service provides a generic way of controlling any available capability. The robotic services currently implemented are:

- **Motion Control Service**: The Motion Control service provides the capability to navigate a rover across a surface to a desired position or to change its orientation.
- **Manipulation Service**: The Manipulation Service was designed to allow the controlling of the motion of robotic arms.
- **Imaging Service**: The Imaging Service provides the functionality to capture images with cameras mounted on the robotic system.
- **Plan Service**: The Plan Service allows to control the execution of plans that were loaded onto the robotic system as a file containing a defined stack of commands.
- **Status Service**: The Status Service provides an interface which allows to control the sending of status information.

### 5.3. Challenges

Some challenges appeared during the migration of the MRS which were mainly caused by the restrictions introduced by the standards of the COM and M&C Services. The MRS were initially designed following the MAL specifications in terms of the interaction patterns and the message structure. However, they are not adhering to the message contents as prescribed by the COM and M&C standards due to their non-existence back then.

In detail, the situation described above caused two main challenges. When more than one robotic system is controlled via the MRS the destination of the commands was previously encapsulated within the message body. The service definitions set by the CCSDS do not support such a parameter but create rather a one to one mapping between a service instance identified by its URI and the remote system to be controlled. This is not a problem by itself but causes many implications in the software design during the migration.

The second challenge is related to the restrictive design of the message body in the Activity Tracking Service compared to the previous implementation in the MRS. The initial action as source of the activity is only referenced by an ID within the message so that additional interactions with the archive are necessary to retrieve information about the action itself. Furthermore, time had to be invested to find the best way to identify the progress stage an activity refers to. A stage field is not included in the message body and the MRS is the central node for reporting several progress stages to the service consumer so that an identification based on the URI was not possible. The current solution derives the stage from the next destination parameter present in the message body.

### 5.4. Envisaged Service Implementations

In addition to the services mentioned in the previous sections the implementation of further services in compliance with the MAL and COM specifications is planned:

- **Transfer of Control Service**: This service is meant to act as a mediator to handle operation requests from different operators and to transfer the control following a defined policy.
- **Video Service**: The Video Service provides the capability of controlling a video source and to stream a video to the operator.
- **File Management Service**: The File Management Service enables an operator to perform file transmissions between filestores and to manipulate files on them remotely.

The Transfer of Control Service as well as the Video Service are services foreseen by the Telerobotic Operations Green Book so that a first implementation as part of the MRS can provide useful input for their standardisation by the CCSDS. The File Management Service should use the CCSDS File Delivery Protocol (CFDP) and follow the recommendations made in the according Blue Book [10].

The functionality of all three services is already partially available as part of the MOE. The planned services are supposed to standardise the implementations and to turn them into mature and harmonised components of the infrastructure.

### 5.5. Additional Software Components

Apart from the migration of the MRS itself, holding the core functionality, some peripheral software components were developed as well. They were not used for the simple proof of concept experiment presented in section 6 but will allow a full integration of the new services into an operational environment as present during typical METERON experiments.

The preferred networking technology for the communication between the MOE MCS and remote systems connected via a space-ground link is the delay tolerant networking infrastructure ION (Interplanetary Overlay Network). A draft of an ION transport binding was developed to be able to keep communicating via ION with the new services using the MAL. The already existing TCP/IP transport binding was taken as a reference to implement this missing adapter between the MAL and the library already used by the web services to access ION's interface.

Another important application in the MOE infrastructure is the broker application which is taking care of distributing published data to subscribed clients. The built-in broker functionality of the MO Services was extracted and extended into a stand-alone application to recreate the functionality present before the migration. A deployment of the broker application can be peered to other deployments to avoid a duplication of traffic on a space-ground link when messages are being distributed to several subscribers.

## 6. PROOF OF CONCEPT EXPERIMENT

It was decided to conduct a small telerobotic experiment as part of the migration activity in collaboration with the Automation & Robotics Section (TEC-MMA) from ESTEC. This experiment was designed as a proof of concept to show the applicability of MO Services in the field of Telerobotics and to validate the successful migration of the services. For this purpose basic monitoring and control tasks from distributed systems were performed with the Planetary Robotics Lab's ExoMars Test Rover (ExoTeR) shown in Fig. 5. The remote commanding of the rover was demonstrated with MOE as well as the remote observing of local command activities executed from the Local Control Computer (LCC), the ExoTeR control system used at ESTEC.

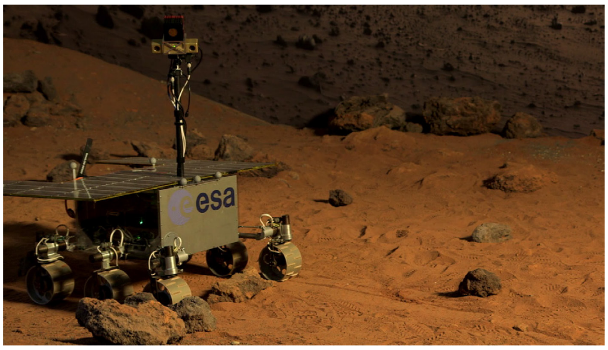


Figure 5. The ExoTeR rover at ESTEC

### 6.1. Configuration and Deployment

The systems involved in the experiment had to be prepared and configured to be able to perform the previously described tasks. As usual for a new robotic asset, a database was created in MOE with the telemetry expected from the rover and a list of commands that could be sent. Apart from this only the newly developed library with the consumer-side of the MRS had to be deployed and the remote endpoints to be set.

The provider-side of the new MRS was deployed at ESTEC where the LCC had to be interfaced with the provided MRS API as described in section 6.2. This integration allows MOE to issue commands via the MRS to LCC which will then relay the command to ExoTeR over the lab's local communication link which can stay completely transparent to MOE and the MRS. Moreover, MOE will receive telemetry and activity tracking updates being relayed by LCC via the MRS API.

In the experiment only an initial subset of the services was used. The COM and M&C Services listed in section 4 were fully implemented but from the Robotic Services only the Imaging Service had been prototyped as a first service to evaluate the chosen design approach. As a consequence, other robotic commands such as motion control directives were transmitted by using the generic Action Service. The MAL was set up to communicate via an already existing TCP/IP transport binding which was deemed most reliable and suitable for a direct connection between ESOC and ESTEC.

### 6.2. Integration of the MRS into the ExoTeR Local Control Computer

There were two possible approaches for the integration of the CCSDS Services in ExoTeR. The first one would have been to implement the MRS API interface within the rover on-board control software. The second, and the one that was chosen finally, was to include the MRS in the LCC application and establish the connection with MOE between these two control stations. This way the rover developments and the integration could be parallelised, as no modifications were needed at the on-board control software with regards to the MRS integration. Also the fact that the LCC had been coded in Java eased the MRS integration into it because of the available Java API. Finally, this also allowed that both MOE and LCC were capable of operating the rover and all telecommands and telemetry data were relayed through the broker and monitored by MOE and LCC.

In terms of effort invested, once the elements of the architecture that need to be integrated with the MRS were identified and studied the development time can be deemed reasonable and simple. The MRS API is easy to understand and integrated as it provides quite a high-level interface.

## 7. EXPERIMENT RESULTS AND OBSERVATIONS

The conducted experiment proofs that the COM and M&C Services, primarily designed for spacecraft, can also be applied to the domain of telerobotics. The ExoTeR rover could be monitored and controlled remotely from ESOC and also local command activities were tracked successfully.

The objective of leaving the MRS API untouched could be fulfilled so that a change from the old library to the library with the new service implementations can happen completely transparent to the user. Nevertheless, a new set of configuration files needs to be put in place to support the altered software architecture.

Even though performance improvements were no intended goal of the migration, it could be observed that the message sizes can be remarkably reduced with the MAL in contrast to the SOAP messages with their costly XML format. Sending a telemetry parameter as a MAL message with applied binary encoding adds up to roughly 350 bytes whereas the same SOAP message with applied gzip compression had a size of 1kB. A similar advantage can be noticed for a commanding message from the Action Service. Generally speaking, the message sizes could be reduced to one third of the original size. It was also observed that the archive interactions required to gather additional information upon the reception of an activity tracking event as stated in section 5.3, are significantly counteracting the benefit of the reduced message sizes. However, the current implementation still leaves room for optimisations to reduce those archive interactions to a minimum.

Independently of the proof of concept experiment it should be noted that the defined robotic services and the MRS API respectively are not entirely aligned with the recommendations made in the Telerobotic Operations Green Book due to the requirement of keeping the API in its current shape. For instance, the Imaging Service is currently designed to control the orientation of the camera while the Green Book proposes to use the Manipulation Service to control not only robotic arms but any kind of manipulators including movable cameras. Taking into account the age of the MRS API, it should be considered to modify the current design in order to integrate recommendations of the CCSDS and to change or extend functionalities with identified shortcomings.

## 8. CONCLUSION

The MRS demonstrated their usability throughout several METERON experiments by providing the needed functionality to support the distributed monitoring and control of different robotic systems in the MOE. With the objective of fostering the standardisation of mission operations as pursued by the CCSDS, the MRS were successfully migrated to a set of services compliant to the CCSDS MO Services specifications. It was possible to reuse the COM and M&C Services for common functionalities which are not specific to the domain of Telerobotics such as telemetry retrieval and distribution, command issuing and activity tracking. The services dedicated to robotics have been successfully recreated with the MO Graphical Editor to interface seamlessly with the MAL and COM implementations.

The control experiment performed with the ExoTeR rover proofed that the use of the COM and M&C Services in the domain of Telerobotics is a valid approach. The successful conclusion of the experiment using the newly implemented robotics services also demonstrates that it is worth the effort to further pursue the definition of a CCSDS standard for Telerobotic operations. Hence, the MRS API should be reviewed and reworked to allow closing the gaps between the current implementation of the robotic services and the recommendations made in the Telerobotic Operations Green Book.

By finalising remaining tasks on other infrastructural components of the MOE such as the broker application it is ensured that the redesigned services are fully embedded into the architecture and can support the more complex demands of upcoming METERON experiment.

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