A Space Data System Standard for Telerobotic Operations

David S. Mittman[1]
California Institute of Technology / Jet Propulsion Laboratory, Pasadena, California, 91109-8099

and

Lindolfo Martinez[2]
National Aeronautics and Space Administration / Johnson Space Center, Houston, Texas, 77058

The Telerobotics Working Group of the Mission Operations and Information Management Services Area of the Consultative Committee for Space Data Systems is drafting a document that will help bound the scope of an eventual international standard for telerobotic operations services. This paper will present the work in progress and provide background for how the international community is beginning to define standards in telerobotic operations that will help ensure the success of complex missions to explore beyond Earth orbit.

I. Introduction

Extending human presence and capability into space will require collaboration between mixed teams of human and robotic assets. Current space telerobotic operations concepts do not scale well beyond the "one operations team, one robot" approach, resulting in an inability to efficiently scale operations to multi-robot teams. By including humans in mixed human-robot teams, we add the additional complexity of human safety concerns, which generally further complicate telerobotic operations by imposing constraints on the robotic elements, such as keep-out zones, and movement, speed and force limitations. The most significant barrier to international cooperation in space telerobotics is the basic inability to intercommunicate; there is no common language by which a diverse set of human and robotic collaborators can share information for the purpose of achieving a common goal.

II. CCSDS and the Telerobotics Working Group

The Consultative Committee for Space Data Systems (CCSDS) was formed in 1982 by the major space agencies of the world to provide a forum for discussion of common problems in the development and operation of space data systems. It is currently composed of eleven member agencies, twenty-eight observer agencies, and over 140 industrial associate organizations. Through its association with the International Organization for Standardization — in which it also functions as the Space Data and Information Transfer Systems (ISO TC 20 / SC 13) Committee — CCSDS reaches agencies in over 17 spacefaring nations.

Since its establishment, CCSDS has been actively developing recommendations for data- and information-systems standards to promote interoperability and cross-support among cooperating space agencies, to enable multi-agency spaceflight collaboration (both planned and contingency) and new capabilities for future missions. Additionally, CCSDS standardization reduces the cost burden of spaceflight missions by allowing cost sharing between agencies and cost-effective commercialization.[1]

Since CCSDS started developing at the lower layers of the ISO protocol stack, their scope has grown to cover standards throughout the ISO communications stack, as well as other data systems areas, such as architecture, archive, security, and XML exchange formats.

The CCSDS Management Council (CMC) has patterned the CCSDS organization to adopt what is perceived to be the best common structural features of the World Wide Web Consortium (W3C) and the Internet Engineering Task Force (IETF) organizations, i.e., highly focused product-oriented "Working Groups" collected into functional "Areas."

[1] Deputy Manager, Planning and Execution Systems Section, 4800 Oak Grove Dr, MS 301-250D, AIAA Member.
[2] System Engineer, Mission Operations Directorate, 2101 NASA Parkway, JSC-DD23.

CCSDS currently has Working Groups in the following areas (Fig 1):

- Systems Engineering, providing overall architecture for space mission communications, operations, and cross-support,
- Mission Operations and Information Management Services (MOIMS), addressing all the flight execution phase applications that are required to operate the spacecraft and its ground system in response to mission objectives,
- Space Internetworking Services (SIS), providing services and protocols to address networked interactions of many forms,
- Cross Support Services (CSS), addressing how space network resources are made available by one organization to another,
- Space Link Services (SLS), developing efficient space link communications systems common to all participating agencies, and
- Spacecraft Onboard Interface Services (SOIS), defining generic services that will simplify the way flight software interacts with flight hardware.

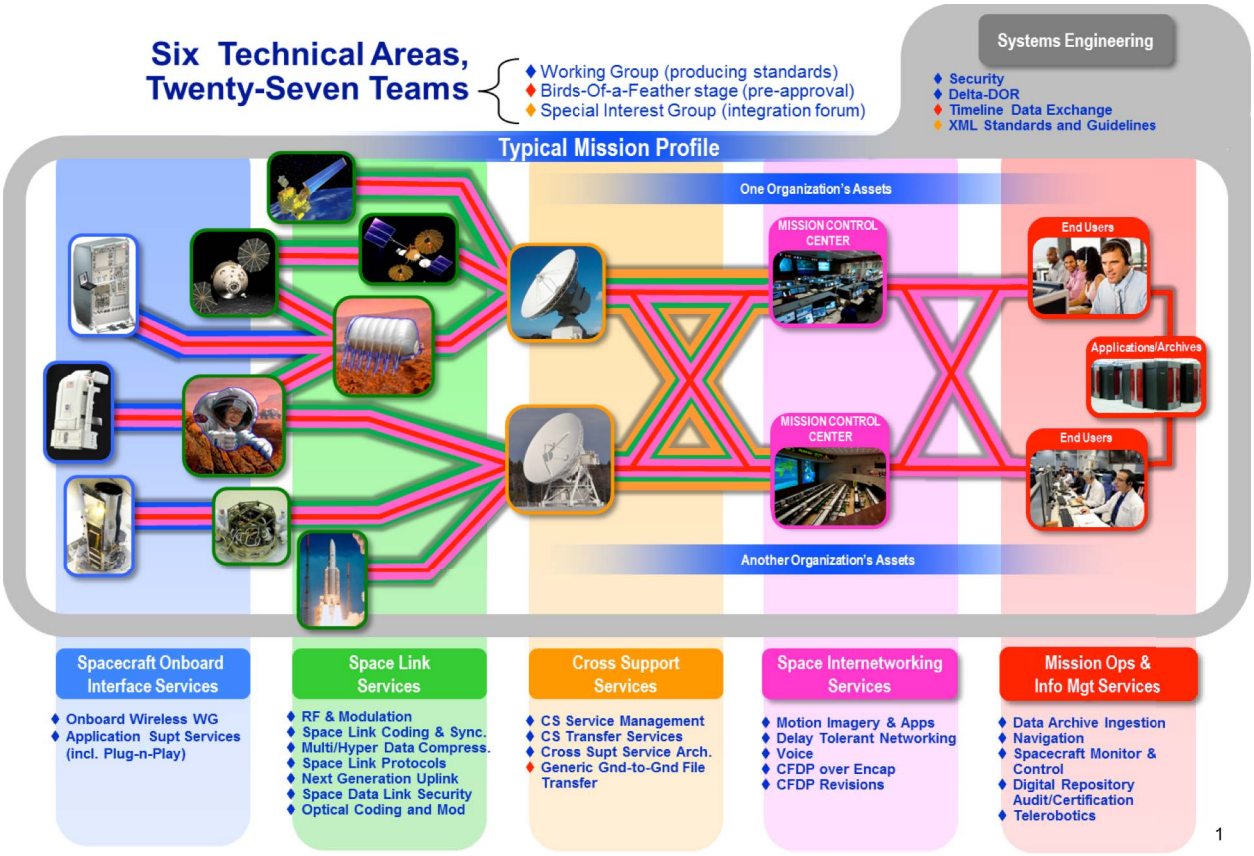

Figure 1. Current CCSDS working groups, birds-of-a-feather, and special interest groups.

In May 2013, the CMC voted to approve the formation of the Telerobotics Working Group (MOIMS-TEL) with the authors serving as co-Chairs. To date, MOIMS-TEL has held three meetings of the working group, attracting 63 members and 16 contributing authors to our current draft informational report on telerobotic operations. Introductory material on the purpose and scope of MOIMS-TEL can be found in the material developed during the working group's formative months, including the Telerobotics Concept Paper[2] and the Telerobotics Working Group Charter.[3]

The telerobotic operations specification is intended to be a common framework that will allow for diverse robotic assets to collaborate on mission goals and realize cost-savings from the cross-support provided by the participating Agencies. The MOIMS-TEL working group supports the goal of CCSDS to develop standards for space data systems that enhance interoperability and cross-support, while also reducing risk, development time and project costs, for government, industry, agencies, vendors and programs.

III. Approach to Standards Development

CCSDS has a well-documented approach to standards development and to the principles and details governing the organization and addressing the objectives, organization, participation, operations, and management of CCSDS activities.[4] The Telerobotics Working Group has fully subscribed to CCSDS's mantra of "adopt, adapt, develop" as its approach to developing interoperability standards for Telerobotics. We are — where appropriate — adopting the best of the existing telerobotics standards, adapting them for use in space, and developing new standards where needed to meet space exploration requirements. We are developing new standards in the areas of safe telerobotic and human-robot operations in the presence of disruption-prone and time-delayed communications links, as well as standards that facilitate the integration and operation of multi-sourced robotic exploration systems. Where appropriate, we will build the new standards upon the base of existing applicable CCSDS standards and we will also engage the standards community in extending existing standards in areas where current capability is not sufficient to support the needs of robust telerobotic collaboration.

There exist a number of potential technical solutions that are candidates for consideration and inclusion in this new telerobotic standard:

- CCSDS Asynchronous Message Service (AMS), which defines a set of standard protocols that enable communication over a "message bus".
- CCSDS Application Support Services (APP), which defines standard services that are provided to onboard software applications.
- Common Object Request Broker Architecture (CORBA), which is a standard developed by the Object Management Group (OMG) to provide interoperability among distributed software objects.
- Data-Distribution Service for Real-Time Systems (DDS), the first open international middleware standard directly addressing publish-subscribe communications for real-time and embedded systems.
- Delay-Tolerant Networking (DTN) technology, which provides interoperable communications with and among extreme and performance-challenged environments where continuous end-to-end connectivity cannot be assumed.
- Joint Architecture for Unmanned Systems (JAUS), an SAE International standard for communication, command and control of unmanned systems.
- Robot Application Programming Interface Delegate (RAPID), a software reference implementation for remote operations that promotes interoperability between robot software modules.
- CCSDS Mission Operations (MO), a framework for defining services in an abstract manner produced by the CCSDS Spacecraft Monitor and Control (SM&C) Working Group.

We believe that the standard being developed by the Telerobotics Working Group is best expressed through the initial development of an informational report, known as a Green Book in the CCSDS community. The Telerobotic Operations roadmap Green Book, currently in draft form, describes the Working Group goals, the products to be developed, and a strategic plan for the development of a complete set of services for supervisory telerobotics operations. Initial elements of the Green Book include a path towards the development of the recommended Telerobotic Operations standard, or Blue Book, that will include a description of the Message Exchange formats, interaction patterns and APIs required to interoperate in the telerobotics arena, along with any Working Group-identified prerequisites for Blue Book development. The initial goal of the Telerobotics Working Group is to develop the Telerobotic Operations roadmap Green Book; then after community agreement on the roadmap, we will then develop the Telerobotic Operations standard Blue Book.

IV. Structuring the Technical Standard

Telerobotic Operations utilizes a Service Oriented Architecture defined by the CCSDS Mission Operations Spacecraft Monitor and Control Working Group. Telerobotic Operations will act as a services layer just below the Device specific displays and machine/device layer at either end of the telerobotic operations as shown in Fig 2. The CCSDS MO layer will provide end to end communication and Monitoring and Control services to specific Telerobotic services such as Discovery, Robot Command, Robot Telemetry etc.

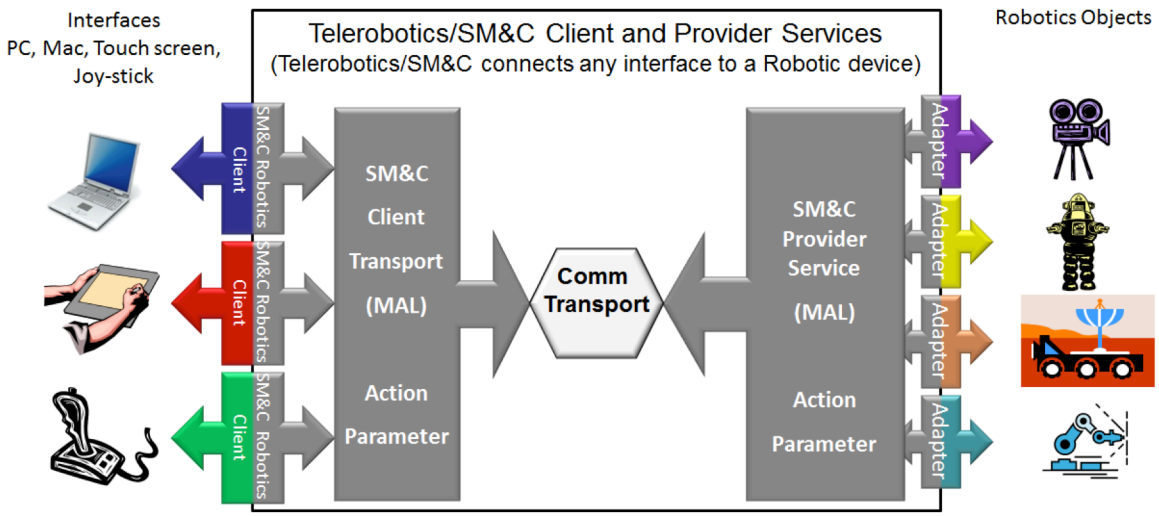

Figure 2. Telerobotic end-to-end model.

Each Telerobotic Operations service provides a set of well defined capabilities through a standardized, service contract (the interface, specified in the corresponding Blue Book). The Telerobotic Operations service contracts, shall be specified in an implementation and communication technology agnostic manner. For example, a Motion Control service would provide the capability to *Move* a robotic asset to a particular position (absolute or relative), without making any assumption about what programming language is used on the service provider or consumer side nor making any assumptions about what communication technology would be adopted in a particular deployment scenario to establish the link between the service consumer and service provider.

Each capability is specified in form of an abstract operation, which itself is defined by a set of exchanged messages between the service consumer and service provider, following a prescribed interaction pattern. The messages exchanged between the service consumer and the service provider, would contain both data (message body) and meta-data (message header). The data part of all messages exchanged between the service consumer and provider for all capabilities of a service, compose together the data or information model of a service.

The meta-data part of the messages (the header) captures usually the non-functional aspects of interactions between the service consumer and the service provider, such as the aspects related to:

- Addressing (how to reach the service consumer/provider)
- Service Taxonomy (the domain and the name and version of the service)
- Transaction management (how to correlate messages in asynchronous interaction patterns)
- Security
- Quality of Service (Service Level Agreements),
- etc.

In a concrete deployment scenario, the service consumer and service provider must implement the abstract (i.e. technology independent) service contract, in a concrete technology (e.g. a programming language such as Java or C, ADA, C++ or .NET). In the selected programming language the abstract service contract is typically realized through a language-specific API (interface definitions in form of operations/methods and data types).

V. The Telerobotic Operations Services

Telerobotic Operations defines common capabilities that greatly increase the ability of Agents to collaborate on common telerobotic tasks. Figure 3 depicts protocols for which well-established standards exist, coloring them in blue. Protocols that are being standardized within CCSDS are shown in grey. Protocols shown in white are where there still appear to be gaps in telerobotics standardization; these are the technical areas on which the CCSDS Telerobotics Working Group will focus.

We can think of the Telerobotic Operations standard in terms of a service catalog. The following services are currently being defined as part of that catalog:

- Manipulation Service: The Manipulation Service controls the motion of manipulators such as robot arms, booms, sample acquisition devices and cameras.

- Sequencer Service: The Sequencer Service enables time-delayed teleoperation of robotic agents through a synchronous command queue.
- Frame Store Service: The Frame Store Service provides location awareness between robots.
- Asynchronous File Transfer Service: The Asynchronous File Transfer Service provides a robust file delivery mechanism between Agents.
- Access Control Service: The Access Control Service authenticates Agents, authorizes their participation in the Agent network, and ensures the security and reliability of data in transit.

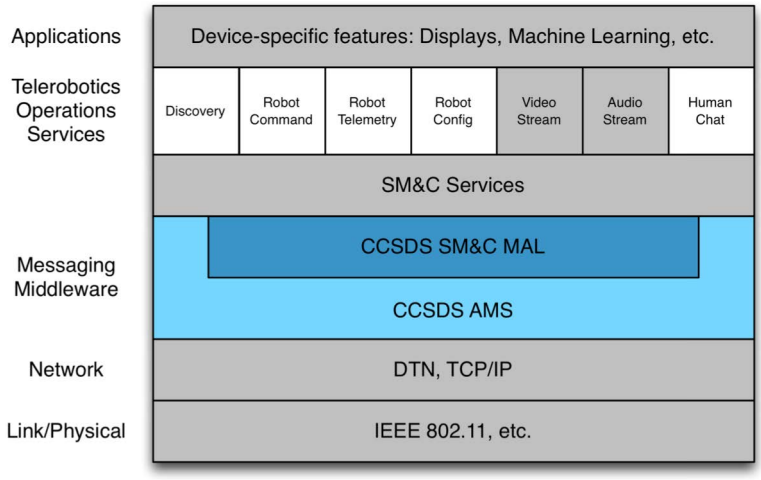

Figure 3. A strawman gap analysis.

- Transfer of Control Service: The Transfer of Control Service mediates requests by Operators to control Agents by ensuring that requests to transfer control between Agents are handled according to an established policy.
- Interaction Service: The Interaction Service provides a link between cause and effect and aids in understanding the relationship between action and reaction in a time-delayed a disruption-prone environment.
- Imaging Service: The Imaging service provides capabilities for messages in the Imaging area are used to capturing images from Agent-mounted cameras.
- Video Service: The Video Service provides moving images to the Operator as a natural way of representing the dynamic state of the environment in which the Agent is operating.
- Special Command Service: The Special Command Service provides access to Agent-specific commands not covered by other Services.
- Data Product Service: The Data Product Service provides type-specific access to operationally-relevant data collected by Agents.
- Discovery Service: The Discovery Service provides a method by which to find Agents and their capabilities as they join and leave the network.
- Administrative Service: The Administrative Service provides system-level managerial and organizational functions for test and control. The Administrative Service is likely going to be deleted and its functions transferred elsewhere. For now, consider the Administrative Service to be a "catch-all" service for items with no clear home in one of the other Telerobotic Operations services.
- Location Service: The Location Service establishes the relative or absolute position and velocity of of Agents during surface or free-flight operations.
- Mobility Service: The Mobility Service controls the motion of navigable rovers over a surface.
- Configuration Service: The Configuration Service provides information for describing the existence and state of various components that affect Agent operations.
- Command Service: The Command Service provides a signal that, when sent to an Agent, causes the Agent to perform one of its basic functions.

VI. Conclusion

The Telerobotics Working Group continues to refine the Draft Informational Report "Green Book" on Space Data System Standards for Telerobotic Operations with a scheduled initial issue date of November 2014 after the CCSDS Fall 2014 Technical Meetings in London, England. Individuals interested in contributing to the standards definition process are encouraged to review the CCSDS guidelines for participation[5] or contact the authors.

While we are working to better define the semantics of Telerobotic Operations within Mission Operations framework, we are also encouraging the increasing involvement of the robotics practitioner community in the

standards definition process. We want to ensure that the standard remains relevant to the terrestrial robotics community, and allows the space robotics community to take advantage of commercial developments while encouraging opportunities for infusion of new technology into the space operations domain.

We will shortly begin concentrating on tracing telerobotic operations use cases and scenarios back to the standard's services to ensure that we are supporting the broadest reasonable set of mission exploration scenarios. We are interested in hearing from the community about their use cases and exploration scenarios, whether aligned with the Global Exploration Roadmap[6] or not.

Acknowledgments

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