Space Project Mission Operations Control Architecture (SuperMOCA)

SuperMOCA SYSTEM CONCEPT

Volume 2

Architecture

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ORIENTATION

The goal of the **S**pace **Pr**oject **M**ission **O**perations **C**ontrol **A**rchitecture ("SuperMOCA") is to create a set of implementation-independent open specifications for the standardized monitor and control of space mission systems. Monitoring is the observation of the performance of the activities of these systems. Controlling is the direction of the activities performed by these systems. Overall, monitor and control is the function that orchestrates the activities of the components of each of the systems so as to make the mission work. Space mission systems include:

spacecraft and launch vehicles that are in flight, and;
their supporting ground infrastructure, including launch pad facilities and ground terminals used for tracking and data acquisition.

The SuperMOCA system concept documents consist of the following:

SuperMOCA System Concept, Volume 1: Rationale and Overview
SuperMOCA System Concept, Volume 2: Architecture
SuperMOCA System Concept, Volume 3: Operations Concepts
SuperMOCA System Concept, Annex 1: Control Interface Specification
SuperMOCA System Concept, Annex 2: Space Messaging Service (SMS) Service Specification
SuperMOCA System Concept, Annex 3: Communications Architecture
SuperMOCA System Concept, Ancillary Document 1: Ground Terminal Reference Model
SuperMOCA System Concept, Ancillary Document 2: Operations Center to Ground Terminal Scenarios
SuperMOCA System Concept, Ancillary Document 3: Operations Center to Ground Terminal – Comparison of Open Protocols

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1. Introduction

The Space Project Mission Operations Control Architecture (SuperMOCA) task is developing open standard specifications for the activities associated with the monitor and control of space vehicles and supporting ground systems. The SuperMOCA addresses the mechanisms required for a monitor and control dialogue between a user and remote, distributed space mission systems. The drivers for the concepts described in this document are discussed in SuperMOCA System Concept, Volume 1: Rationale and Overview.

1.1 SuperMOCA Purpose and Scope

Cost saving features of missions designed consistent with the SuperMOCA will include:

- a consistent and uniform means of executing monitor and control processes throughout the project life cycle.

- layering of functions and implementation components based on standard interfaces that allows levels of abstraction which enable monitor and control without user knowledge of low-level design details of system components, and which eases the introduction of new technology and the change out of one product for another of similar functionality.

- operator monitor and control functions that can be more easily transitioned to automated and autonomous implementation. Such implementations can also be more easily transported between ground and flight computing environments.

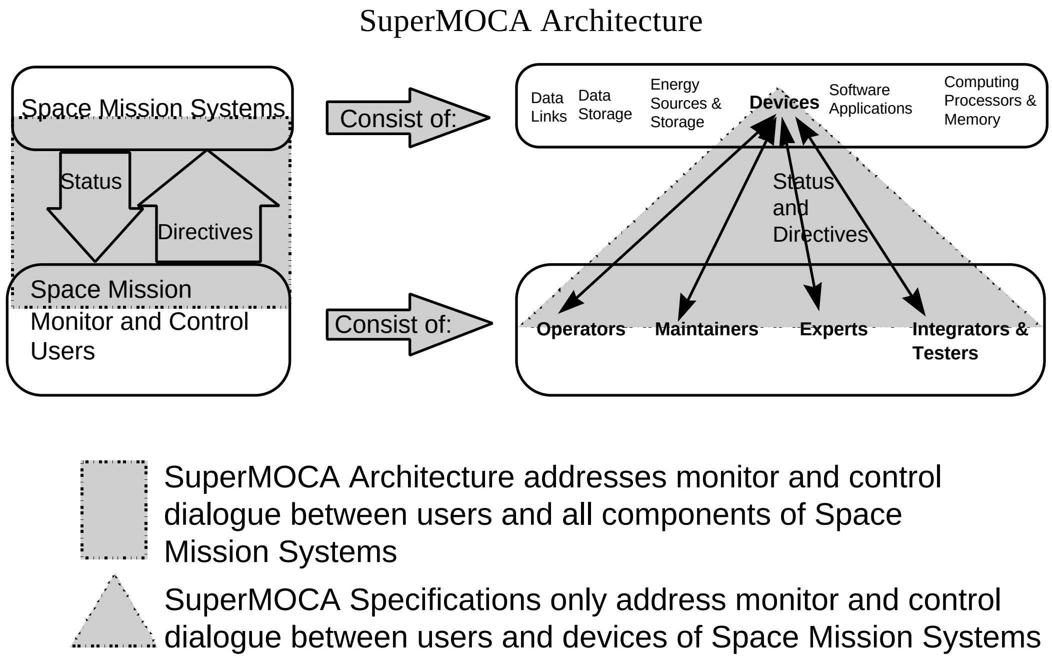

Figure 1-1 - SuperMOCA Scope

As shown on the left side of Figure 1-1, the monitor and control of space mission systems involves an exchange of status and directive information between those systems and users. The SuperMOCA architecture addresses this monitor and control dialogue. This document describes the architecture in two sections. Section 2 defines categories of users and mission systems that need to conduct monitor and control dialogues in order to implement and fly a space mission. Section 3 describes the SuperMOCA architectural views of the mission operations environment. These views form the basis for the SuperMOCA open standard specifications for monitor and control. As shown on the right side of Figure 1-1, these specifications address the monitor and control of devices in space mission systems. Section 4 of this document discusses the technologies and the associated open specifications that are key to SuperMOCA. This section shows how the open specifications fit into the architecture discussed in Sections 2 and 3.

1.2 Acknowledgment

Many of the concepts discussed in sections 2 and 3 of this document are based on work done by the Goddard Space Flight Center (GSFC) Mission Operations Control Architecture (MOCA) task. More information about GSFC's MOCA work can be found on the Internet at URL http://buster.gsfc.nasa.gov/Moca/Moca.html. We thank the folks who work on MOCA for their efforts and cooperation.

2. Space Mission Systems and Users

In order to achieve the objectives of a space project the activities carried out through the mission systems must be monitored and controlled. The types of mission systems and users monitoring and controlling them are discussed in this section.

2.1 Mission Systems

Even though there may be different types of systems (e.g., spacecraft, launch vehicle, ground terminals, launch pad facility) employed in a space project, the techniques for monitor and control of those systems have much in common. The SuperMOCA architecture addresses the monitor and control of these mission systems. The reasons for the commonality of monitor and control techniques can be explored by considering that these systems each consist of subsystems that, in turn, each consist of components. The left side of Figure 2-1 lists examples of the subsystems for each of the mission systems. Note that there are similarities between the systems at the subsystem level. For instance, all systems need power and communications. However, some subsystems are not common, such as the propulsion needed by systems in flight, but not required by ground terminals or launch pad facilities. The types of components needed to build the subsystems are listed in the right side of Figure 2-1. Not all component types are needed for all subsystems, but components from each of the types listed are needed for any of the systems.

Example Subsystems of Mission Systems

- Spacecraft and Launch Vehicles
  - Propulsion
  - Power
  - Thermal Control
  - Avionics
  - Attitude Control
  - Space Communications
- Ground Terminals
  - Antenna Pointing
  - Space and Ground Communications
  - Power
  - Data Processing
- Launch Pad Facilities
  - Ground Communications
  - Power
  - Positioning

Components of Mission Systems

- Structural items
- Energy sources
- Devices
  - e.g., effectors, actuators, sensors, computers, data storage
- Computing applications
  - e.g., real-time control, data analysis, data management planning
- Transport links
  - data, power, heat

Figure 2-1 - Mission Systems Components and Example Subsystems

Monitor and control in space missions can be performed at the system, subsystem, or component level and is frequently performed at all levels simultaneously. To the extent that monitor and control is done at the component level the attributes of the components that can be monitored and controlled are similar for similar component types even though they are part of different systems. Different component types may have differing attributes that can be monitored and controlled. As the level of monitor and control moves up to the subsystem and system level, the monitor and control attributes are less tied to the type of components. Monitor and control can be dealt with in terms of higher-level abstractions (such as “system functions” or object characteristics and behaviors). Such abstractions may be absolutely necessary if the typical users monitoring and controlling subsystems or systems are not intimately familiar with the components that make up those subsystems or systems.

2.2 Users

In the past, most of the users monitoring and controlling mission systems have been people. Increasingly in the future, these users will be automated “agents” operating both locally to and remotely from the systems they are monitoring and controlling. There are many different users monitoring and controlling mission systems for a space project. These users can be categorized by the roles they play in the project, by the mission elements they monitor and control, and by the level of abstraction (see previous paragraph) at which they monitor & control. The following types of users are addressed by the SuperMOCA architecture.

Integrators and Testers - These users put together subsystems and systems and test them to create delivered mission systems to support the achievement of mission objectives. The delivered mission systems can be built for a specific mission (such as a spacecraft or expendable launch vehicle) or can be built to support multiple missions (such as a ground terminal, launch pad facility, or reusable launch vehicle). Typically these users are mainly involved with mission systems early in their life cycle. However, integration and testing of new capabilities can continue during the operational phase of a project, particularly for systems designed to support multiple missions. These users usually perform their functions from a test and operations facility. For self-testing subsystems and systems, the user may be an automated agent operating within the subsystem or system.

Operators - These users operate the mission systems in order to achieve the mission objectives. These users typically monitor and control activities abstracted to the subsystem and system levels. These users usually perform their function from a mission operations center, but may perform work “on site” for manned spacecraft. Automated agents may work within subsystems and systems designed for autonomous operations.

Maintainers - These users maintain any mission components, subsystems, or systems that need “care and feeding” in order to continue performing to specified requirements. These users usually perform their function from a mission operations center, but may also perform work “on site” for ground terminals, launch pad facilities, or manned spacecraft. Automated agents may work within subsystems and systems designed for autonomous maintenance.

Experts - These users supply expertise on the characteristics and behavior of missions at the component, subsystem, or system level. Typically they design the mission systems and assist in their integration and test. They may have need to monitor and control mission systems during operations in order to respond to anomalies. These users may act from a mission operations center or from a remote site via a link to a mission operations center.

3. SuperMOCA Architectural Views

This section discusses several architectural views of space mission operations in order to explain in detail the context in which space mission systems are monitored and controlled. Each view discussed emphasizes one of the following features of SuperMOCA:

- layering of functions and implementation
- common functions and functional allocations
- performance needs and underlying resource limitations

The architectural views discussed in this section are closely related to the operations concepts documented in SuperMOCA System Concept, Volume 3: Operations Concepts. That document gives a more complete explanation of how SuperMOCA fits in mission operations for specific project phases and mission types.

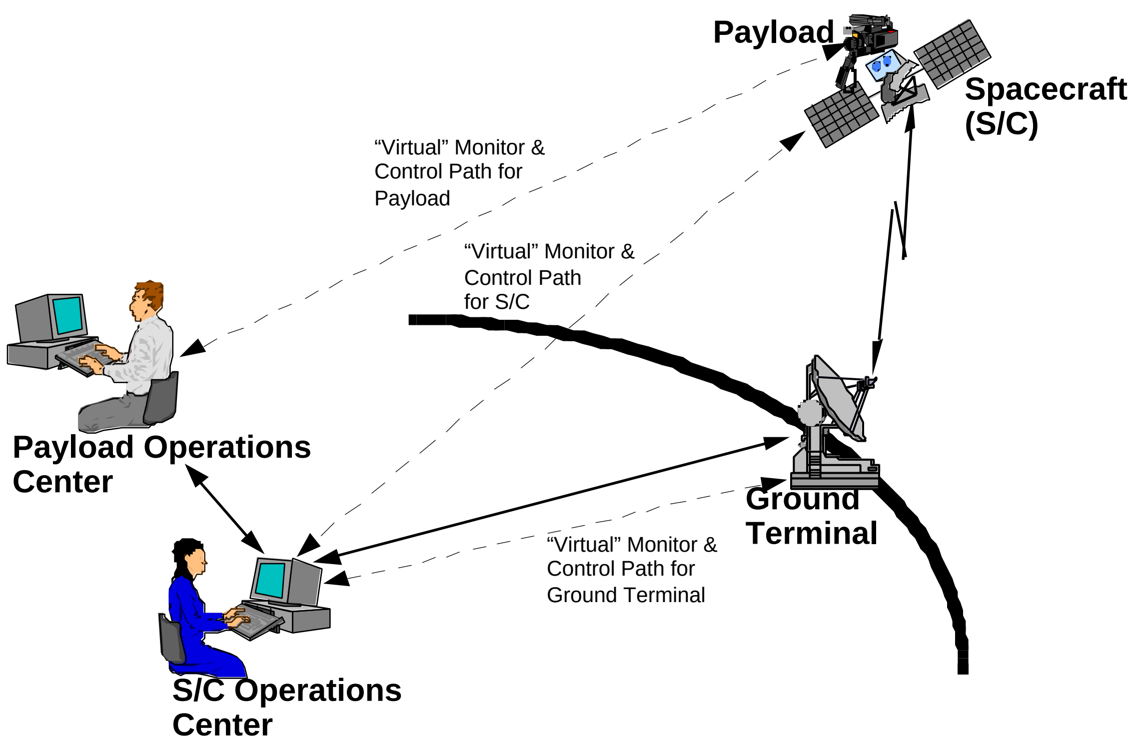

Figure 3-1 - Space Mission Monitor and Control

Figure 3-1 shows a simple schematic of the major flight and ground systems of an unmanned space mission operation. [To keep this schematic simple, only two operations centers (one for the spacecraft and one for the science payload carried by the spacecraft), one ground terminal, and one spacecraft/payload are shown. However a given space mission may be supported by a network of multiple operations centers, ground terminals, spacecraft and payloads. Also launch vehicles and launch pad facilities are not shown. The Operations Concept document referred to earlier in this section includes launch systems and other systems used in project phases other than mission operations.] In this simple model, some of the monitor and control of the ground terminal, spacecraft, and payload are carried out over "virtual paths" from the payload and S/C operations centers. The communications links to support these virtual paths are between the operations centers and the ground terminal, between the ground terminal and the spacecraft, and between the spacecraft and the payload. Some level of autonomy resides in the ground terminal, the spacecraft and the payload, allowing local monitor and control even though the ground terminal, the spacecraft, and the payload are unmanned.

3.1 Layered Views

Several views of SuperMOCA discussed in this document divide the system into layers. Layering allows increased visibility of commonality among the mission systems and enables the use of standards based on common interfaces between the layers. One key feature of a layered view of a system is that each layer provides services to the layers immediately above and below it. Each layer provides a higher level of services than the layer below resulting in the level of abstraction increasing in each higher layer.

3.1.1 Layered Monitor and Control in Distributed Operations

The first layered view is of monitor and control dialogues between users and systems in a "distributed operations" environment. Distributed operations for this document means that those users monitoring and controlling the payload operate from a geographically remote site from those users monitoring and controlling the spacecraft carrying the payload. This arrangement is increasingly in use, at least in the U.S. civilian

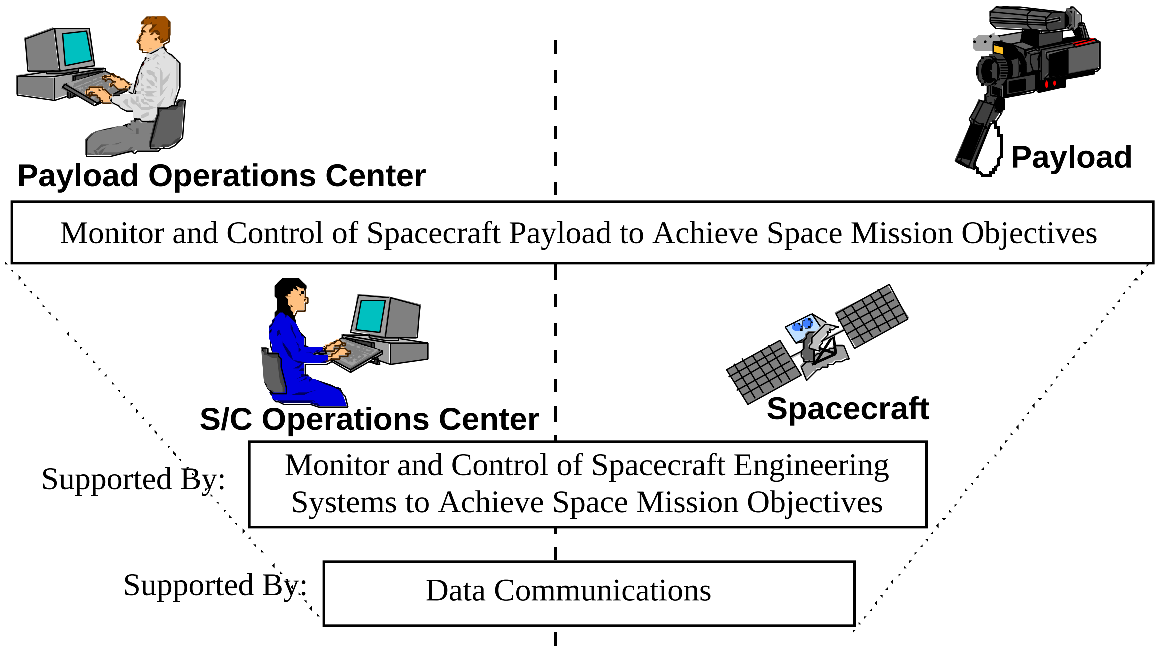

Figure 3-2 - Layered Monitor and Control in Space Mission Operations

space mission sector. The simple model depicted earlier in Figure 3-1 shows a distributed operations arrangement where the payload is operated from a site remote from the spacecraft operations. For distributed operations, both classes of users (payload and spacecraft) interact with the mission systems, but for very distinct and different reasons. A view that shows the layered dependencies of the monitor and control dialogues of these classes of users in shown in Figure 3-2. The top layer of this view includes only the direct monitor and control of the payload activities to achieve the payload mission objective. The middle layer of this view includes only the monitor and control of the spacecraft's activities that support the payload activities. The bottom layer is the underlying data communications capabilities that move data from point to point to support all the monitor and control dialogues in the higher layers.

For this type of layering to be most cost effective the spacecraft monitor and control must establish an envelope of resources (e.g., power, thermal control, pointing; see later discussion in this section) provided to the payload and the payload must operate within those resources. Spacecraft operational constraints that cause changes to the envelope of resources provided to the payload or payload demands for resource envelope changes must be minimized in order to minimize the interactions between the payload monitor and control activities and the spacecraft monitor and control activities.

3.1.2 Layered Monitor and Control Functions and Protocols

SuperMOCA monitor and control function and protocol layering is illustrated in Figure 3-3. The top layer is the user and the systems that are conducting a monitor and control dialogue and their interfaces to the supporting functions and protocols. For the user, this layer includes the interface that translates between the user's monitor and

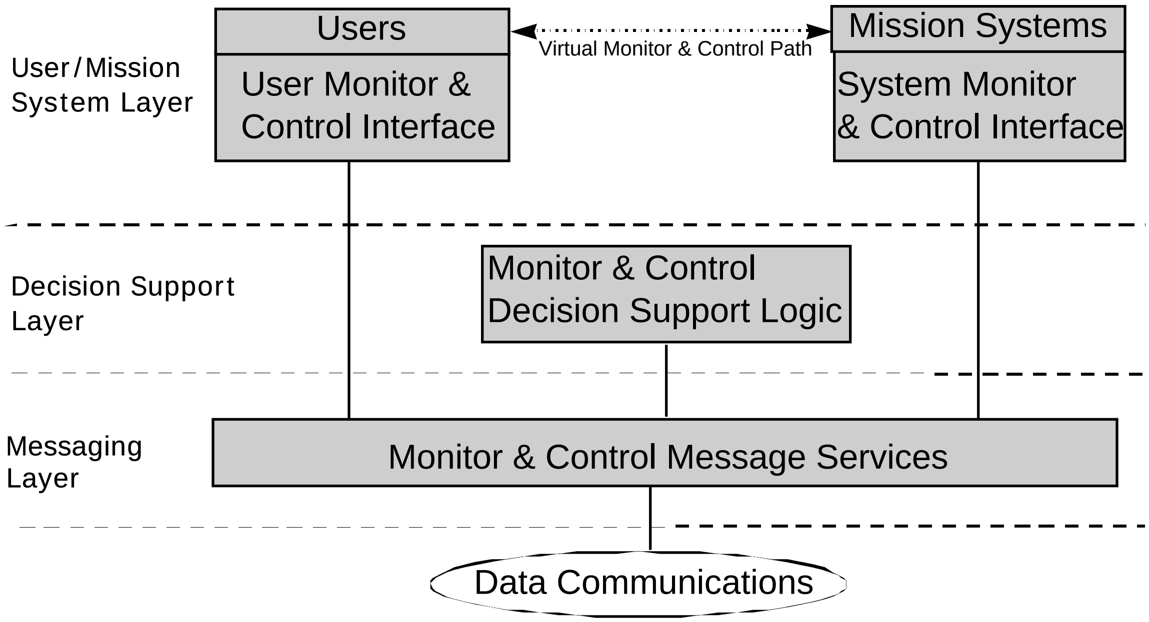

Figure 3-3 - Layered Monitor and Control Functions and Protocols

control language and the standard directive and status messages exchanged through the message services. The user's monitor and control language specified by SuperMOCA is described in Section 4.3. At the mission system, this layer includes a system monitor and control interface that translates between the standard directive and status messages exchanged through the message services and system-specific format and syntax. The interface specified by SuperMOCA is currently limited to devices in mission systems. This interface is described in Section 4.4 and 4.5.

The middle layer is the decision support layer. This layer contains the applications that provide decision support logic to assist the user in the monitor and control process. These applications determine whether directives are safe and effective and prevent the execution of any that are not safe and effective. This is further described in Section 4.3.

SuperMOCA monitor and control functionality is built upon the messaging services in the lowest layer, the messaging layer. These messaging services are the mechanisms that provide a consistent and universal way to communicate monitor and control information within SuperMOCA. Monitor and control information is placed in and extracted from messages at both the user and mission systems conducting the monitor and control dialogue. The messaging system specified by SuperMOCA is currently limited to devices in mission systems. This specification is described in Section 4.4. The

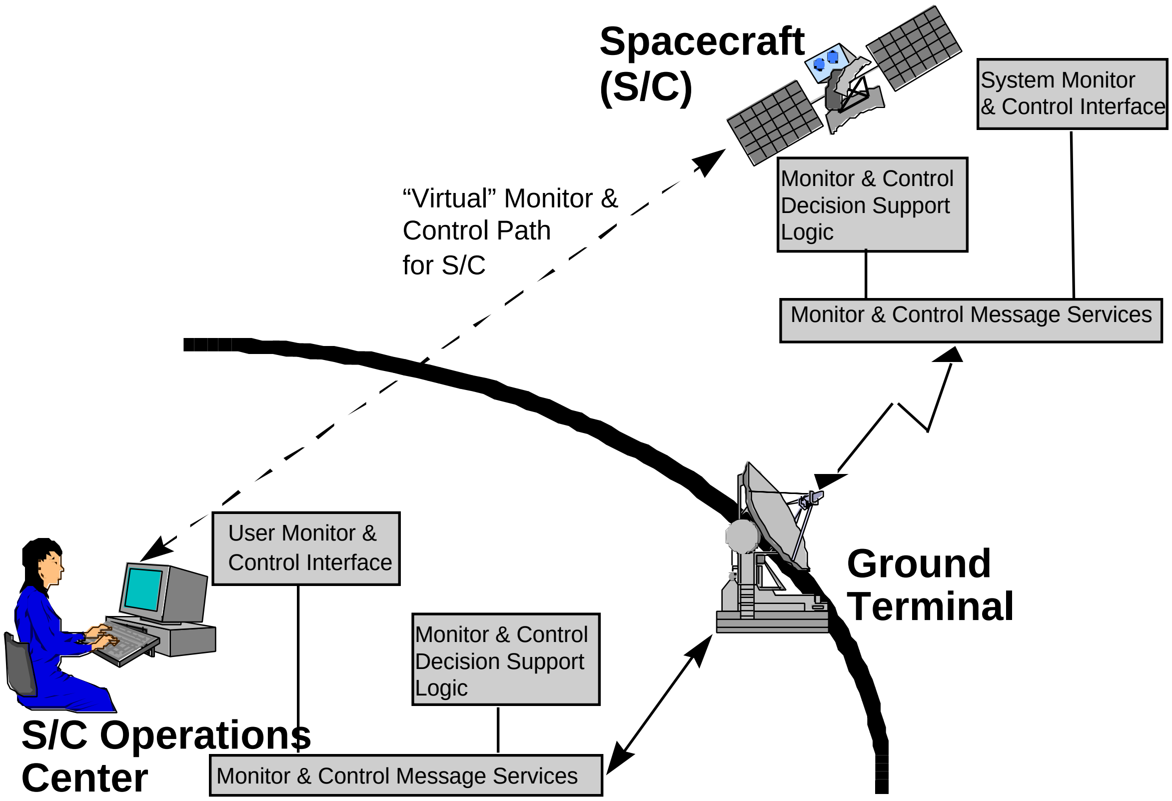

Figure 3-4 - Layered Monitor and Control in Spacecraft Operations

role of the layered spacecraft monitor and control functions and protocols in the simple model of spacecraft operations is shown in Figure 3-4.

3.1.3 Layered Implementation

SuperMOCA includes a layered system implementation approach as shown in Figure 3-5. This approach emphasizes that each mission system is a collection of software and hardware "applications" and supporting computing and communications resources that must be monitored and controlled to achieve mission objectives. The bottom layer includes basic computing and communications resources needed to communicate in the physical domain and to provide the hosting environment for software. The middle layer includes communications service software coupled with the computer's operating system or instruction set. In this layer are telecommunication and network interfaces, standardized operating system calls and returns, and distributed processing features. The top layer includes monitor and control applications and hardware and software components that are being monitored and controlled.

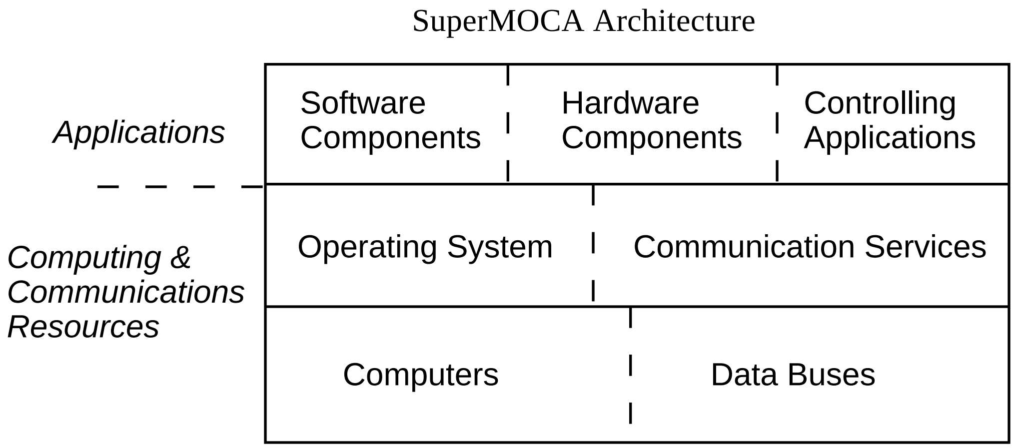

Figure 3-5 - Layered Implementation

3.2 Common Functional Views

This section discusses the SuperMOCA from the viewpoint of spacecraft operations. These views describe features of the SuperMOCA architecture that are common to all spacecraft mission operations. These views define the common space mission operational environment in which the monitor and control functions must be carried out.

3.2.1 End-to-End Engineering Operations Functions

Spacecraft engineering operations can be categorized into a few functions that are common to all space missions. These functions are "end-to-end"; that is, they are performed by coordinated activities at both the operations center and the spacecraft. For any given mission the allocation of activities between the operations center and spacecraft may differ, however these end-to-end engineering operations functions are done for all space missions supporting a payload. These functions all occur in the middle layer of the layered view of distributed operations described in Section 3.1.1. They are listed below and illustrated in Figure 3-6.

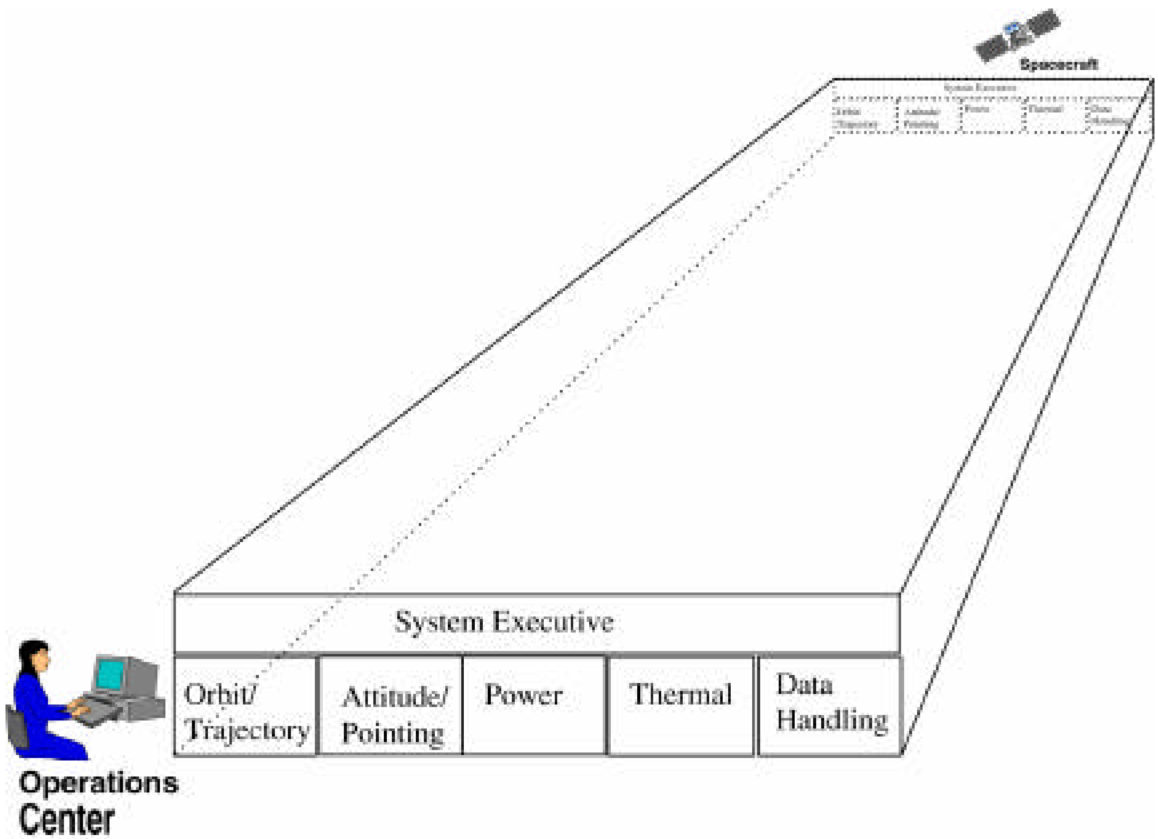

Figure 3-6 - End-to-End Engineering Operations Functions

- Orbit/Trajectory which includes those functions necessary to place the payload in the proper position/velocity in space

- Attitude/Pointing which includes those functions necessary place the payload in the proper orientation

- Power which includes those functions necessary to supply the payload with sufficient power,

- Thermal which includes those functions necessary to maintain the payload within allowable temperature range,

- Data Handling which includes those functions necessary to exchange data between payload elements, transform payload data, associate payload and spacecraft data, or preserve payload data, and

- System Executive which coordinates the functional areas listed above to the extent necessary to achieve space mission objectives.

3.2.2 Plan, Maintain, and Use Modes

The SuperMOCA architecture is based on the operational modes of Plan, Maintain, and Use. The Use Mode refers to the use of mission systems to achieve mission activities within any operational constraints imposed by those systems. As shown in Part A. of Figure 3-7, Use is the only mode needed for the operation of a very simple, robust mission system by one user.

The Maintain Mode refers to the safe and effective maintenance of mission systems and the maintenance of the knowledge of mission system constraints and system states and performance trends. As shown in Part B. of Figure 3-7, the Maintain mode becomes necessary, in addition to the Use Mode, when mission systems become more complex and/or less robust.

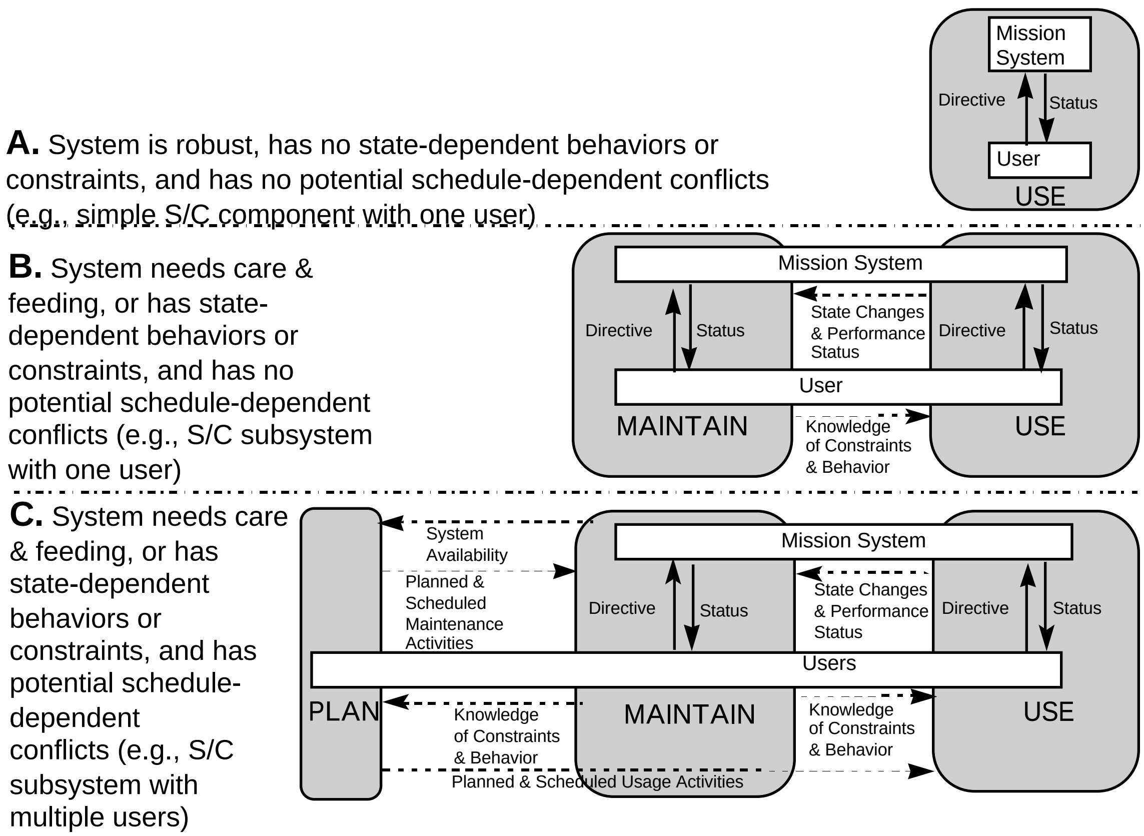

Figure 3-7 - Plan, Maintain, and Use Modes

The Plan Mode refers to the planning and scheduling of the mission system activities necessary to achieve mission objectives. As shown in Part C. of Figure 3-7, the Plan Mode becomes necessary, in addition to the Use and Maintain Modes, when a more complex, less robust system has more than one potential user. Almost all space missions fall into this category. These missions will operate in all three modes. The role of the user and the Decision Support Logic that is "in force" in the system is dependent on the operational mode. The operational mode also affects how much status data is made "visible" to various users and Decision Support Logic functions and where monitor and control loops are closed. See Section 3.3.1 for a further discussion of monitor and control loops.

Whether in a SuperMOCA end-to-end function, or within a specific ground terminal, spacecraft, or operations center, the Plan, Maintain, and Use Modes can be applied to SuperMOCA elements making up the total architecture.

3.3 Performance Views

Although the SuperMOCA end-to-end functions and the plan, maintain, and use concepts are common to the spacecraft operational environment for monitor and control, there are significant differences from mission to mission in requirements on monitor and control loop performance and constraints placed on monitor and control loop implementation by processing power and communication bandwidths available from the mission systems. These differences are discussed in this section.

3.3.1 Monitor and Control Loops

The monitor and control dialogue between the user and the mission system can be described as a monitor and control loop as shown in Figure 3-8. The loop consists of a directive (e.g. command) sent from the user to the mission system, the execution of the instruction by the system and an optional response (e.g., monitor information) from the mission system to the user indicating the results of the executed instruction. If the mission system is required to respond this is a "closed loop", if not it is an "open loop".

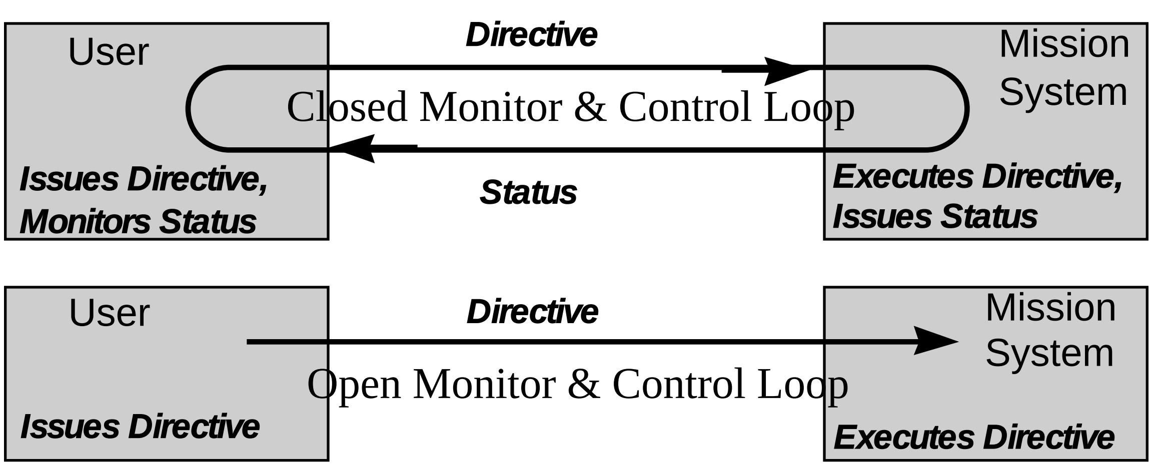

Figure 3-8 - Monitor and Control Loops

In a closed loop, the mission system response may give rise to another directive when the user monitors it and the cycle around the loop repeats itself. The total monitor and control dialogue for any given mission is made of many of these loops and repeated cycles around the closed loops. The requirements on timeliness of exchanges of information in these loops are driven by the mission objectives. Tightly coupled closed loops are necessary to execute some types of dynamic controls or to protect mission systems in case of anomalies. Other loops may be loosely coupled closed loops or open loops. Tightly coupled closed loops are characterized by short turnaround times and/or intensive exchange of monitor and control information. Loosely coupled closed loops are characterized by long turnaround times and/or sparse exchange of information.

The SuperMOCA architecture allows for these variations in monitor and control loop requirements by allowing for distribution and portability of monitor and control applications across the set of mission systems. Note that space missions that have (1) little space/ground communications bandwidth available to support the monitor and control dialogue, (2) long periods when space/ground communications links are not available, or (3) long two-way communication light times are, in general, forced to close the more critical monitor and control loops on board the spacecraft. This will be discussed more in the next section.

3.3.2 Spaceborne Processing and Bandwidth Considerations

In general, for ground applications of SuperMOCA monitor and control (such as control of a ground terminal), cost does not force consideration of processing power or communication bandwidth limitations. Both these technologies are continuing to advance rapidly for ground-based systems and costs are decreasing. However, for spaceborne systems, limitations (sometimes severe) are placed on computer, memory, and communications resources due to available mass and power and the radiation environment of space. Monitor and control applications are only one set of on-board functions vying for these resources. Yet, as mentioned in the last section, the natures of some space missions require that the processing and bandwidth be available to close the monitor and control loops on-board the spacecraft.

Simple missions (type A in Figure 3-9) may have relatively few monitor and control loops and need to only close a few of them on-board the spacecraft. These missions can be accomplished even though there is not much processing power and not much on-board or space/ground communications bandwidth available to support monitor and control applications.

As missions become more complex with relatively many monitor and control loops, various distributions of monitor and control capabilities in mission systems are needed to satisfy mission objectives. Mission type B shown in Figure 3-9 is an example of one design solution that has been used frequently in the past. The additional monitor and control loops are closed at the operations center, again except for those few that must be closed on the spacecraft. However, this has become quite labor intensive at the operations center and has tended to force almost continuous space/ground communications. These features drive up mission operations costs and are unacceptable solutions for most missions being designed to hold down life cycle costs. However, automated applications at the operations center acting as monitor and control agents for humans can reduce life cycle costs even for these types of missions.

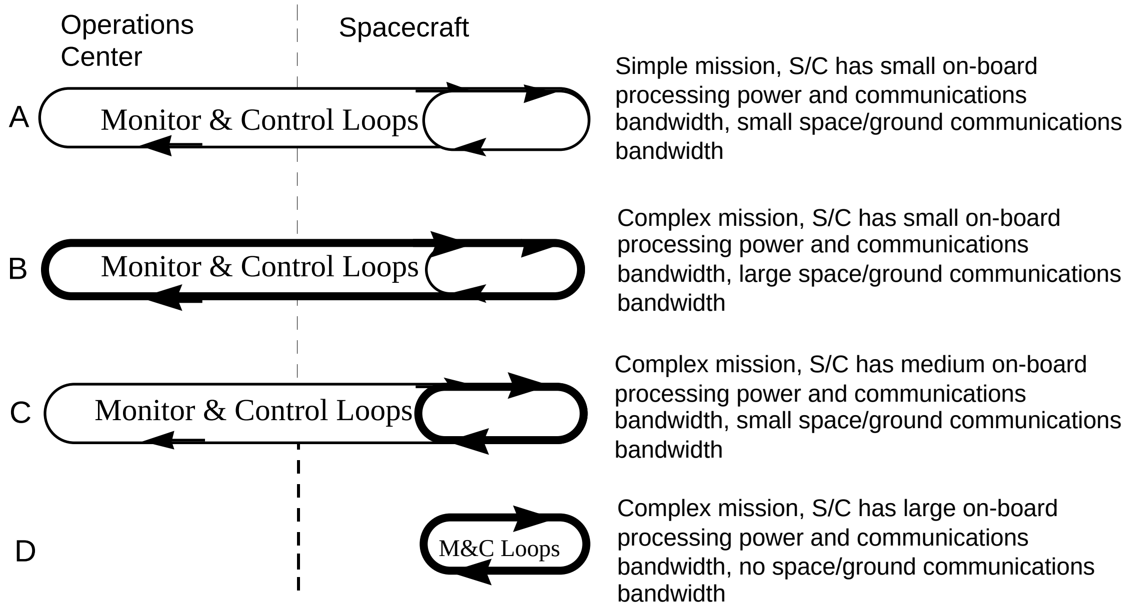

Figure 3-9 - Monitor and Control Loops in Space Mission Operations

Mission type C in Figure 3-9 is an example of building more "autonomy" into spacecraft monitor and control. There are still many monitor and control loops, but most of them are closed on-board the spacecraft. A minority of them are still closed at the operations center. This reduces labor at the operations center and allows less frequent space/ground communications, but at the cost of increased processing and communications bandwidth on the spacecraft. These types of missions are now being designed and built.

Mission type D in Figure 3-9 is the "launch it and wait for it to tell you the answer" space project design. The spacecraft is completely autonomous. All monitor and control loops are closed on board and therefore no space/ground bandwidth is used for monitor and control. Of course, for a complex mission this will require a large amount of processing capability and on-board communications bandwidth. These types of missions are the subject of current research and development.

4. SuperMOCA Technologies and Specifications

The SuperMOCA technologies, their relationships to one another, and to the set of SuperMOCA specifications is illustrated in Figure 4-1. The figure identifies the interfaces (indicated by capital letters in circles) to which the specifications apply. Each of the technology areas, with their associated SuperMOCA specifications, are described

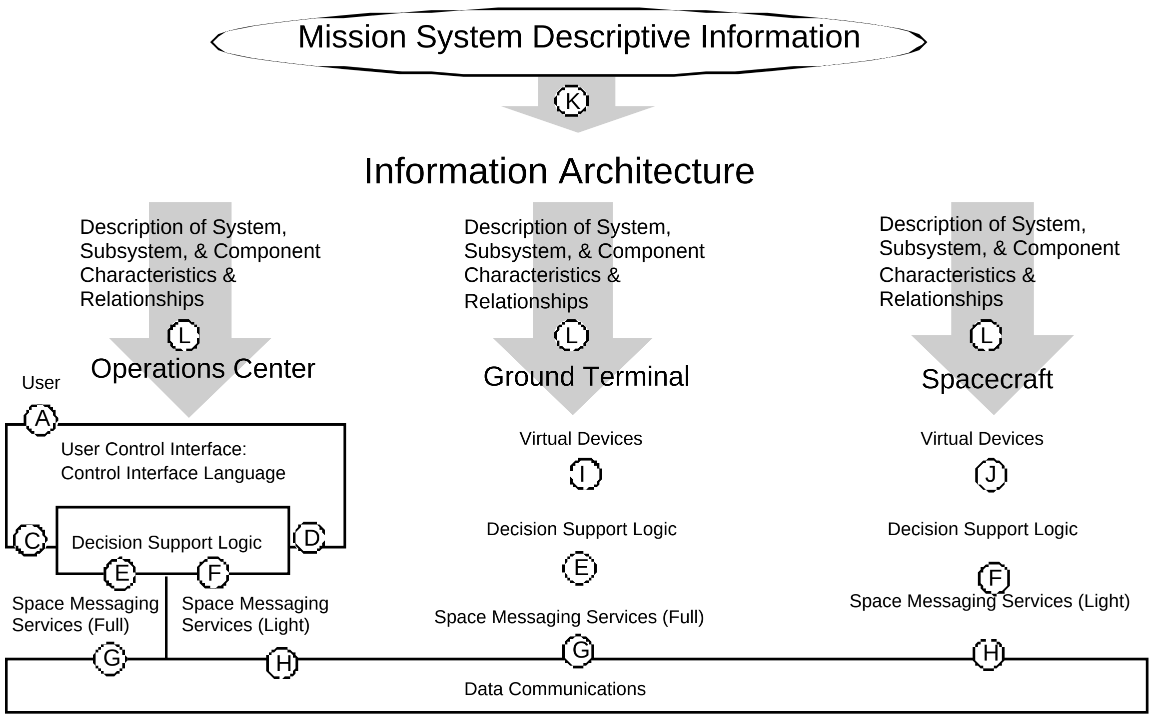

Figure 4-1 - Relationships Among SuperMOCA Technologies

briefly below.

4.1 Information Architecture

The Information Architecture is the standardized structure into which the monitorable and controllable characteristics of mission systems can be captured and described. These descriptions are gathered during the project design phase, thus supporting the progressive and seamless capture, refinement, extension and translation of information describing the monitorable and controllable characteristics of the mission systems. These data are the system descriptions that are used to configure the user interface, the messaging service, and the decision support logic. Thus, the Information Architecture technology does not correspond to a layer in the monitor and control function and protocol view described in Section 3.1.2, but is a basis for the implementation of all the layered functions in that view.

SuperMOCA specifications on the Information Architecture are contained in the SuperMOCA Draft Specification: Exchange of Descriptive Information (XDI). The XDI Specification describes a method for identifying and defining system descriptive information and exchanging such information between monitor and control applications in the system. The specified XDI method: (1) identifies each component of the system, (2) identifies each item of descriptive information used to describe the component and its relationships to other components of the system, (3) defines the semantics for each item of descriptive information, and (4) defines the conversions between the allowed syntactic and format representations of each of the items of descriptive information. Items # 1, 2, and 3 specify the interface labeled "K" in Figure 4-1. Item # 4 specifies the interfaces labeled "L" in Figure 4-1.

4.2 User Control Interface

This technology is included in the User/Mission System Layer of the monitor and control function and protocol view described in Section 3.1.2. The Control Interface Language (CIL) is a text-based, mission operator-oriented language allowing the mission operator to monitor and control activities of remote space mission systems. The SuperMOCA specifications on this language are contained in the draft SuperMOCA Control Interface Language Specification Document. This document specifies the interfaces labeled "A" in Figure 4-1.

4.3 Decision Support Logic

This technology is included in the Decision Support Layer of the monitor and control function and protocol view described in Section 3.1.2. The Decision Support Logic is the set of capabilities that preserve mission system health by preventing any directives from being executed that would damage the system. These capabilities check directives against current state of mission system and mission system environment, block any directives that would damage the mission system, and notify the issuer of the directive that the directive will not be forwarded for execution. If appropriate, upon blocking certain directives, decision support logic initiates the execution of a predefined alternative directive. A SuperMOCA specification in this area has not yet been drafted.

4.4 Space Messaging Service

This technology is included in the Messaging Layer of the monitor and control function and protocol view described in Section 3.1.2. The Space Messaging Service (SMS) provides messaging services that are the mechanisms used to communicate monitor and control information between a user or a decision support logic application and a virtual device. (See next section for a discussion of virtual devices.) The specification includes the messaging services, the protocols used to implement the services, the internal message data structures, and the message type identifiers that indicate which services and data structures are associated with a given message. The specified protocols define the roles of the monitor and control applications and the virtual devices in the execution of the services.

The “full” version of SMS applies to support of monitor and control dialogues among ground-based systems. This full version of SMS specifies the interfaces labeled “C”, “E”, “G”, and “I” in Figure 4-1. The “light” version of SMS applies to the support of monitor and control dialogues among spaceborne systems and between ground-based and spaceborne systems. This light version of SMS specifies the interfaces labeled “D”, “F”, “H”, and “J” in Figure 4-1. This version is designed to be compatible with the processing and communications bandwidth constraints of spaceborne systems discussed in section 3.3.2. The SMS Specifications are contained in the draft SuperMOCA Space Message Service Specification Document.

4.5 Virtual Devices

A virtual device is a collection of one or more software modules with a given device that allows any user of decision support logic application that is external to that device to monitor and control one or more aspects of the device’s functionality. Specifically for a device attached to a network, as shown in Figure 4-2, a virtual device is the network-visible representation of the attributes of the device.

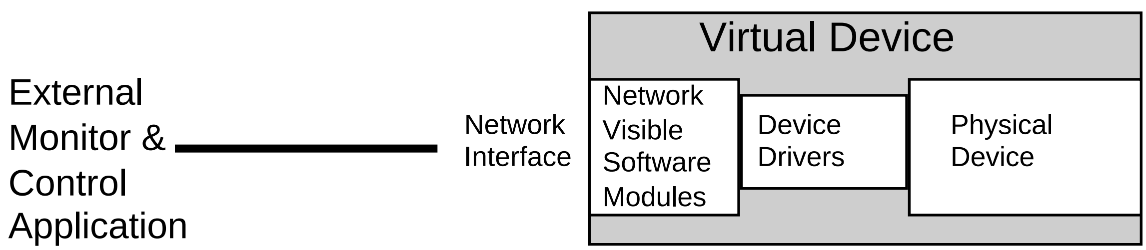

Figure 4-2 - Virtual Device on a Network

More generally, as shown in Figure 4-3, a virtual device is a representation of the externally visible attributes of a given device that can be monitored or controlled. Externally visible attributes are described by XDI (as described in Section 4.1) and are supplied via XDI to al users and decision support logic applications in the mission. Messaging services (as described in Section 4.4) are defined so as to facilitate the monitor, control, configuration, and trouble-shooting of these virtual devices.

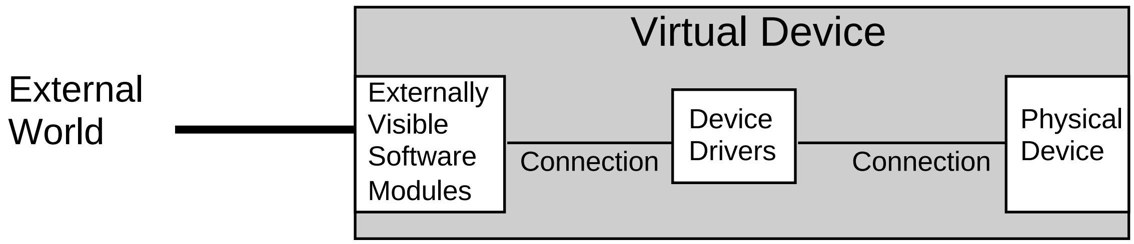

Figure 4-3 - Generalized Virtual Device Concept