Grand Challenge Problems in Real-time Mission Control Systems for NASA's 21st Century Missions

Barbara B. Pfarr, John T. Donohue, Peter M. Hughes
NASA Goddard Space Flight Center, Greenbelt, Maryland 20771
barbara.pfarr@gsfc.nasa.gov, john.dohonue@gsfc.nasa.gov, peter.hughes@gsfc.nasa.gov

Abstract

Space missions of the 21st Century will be characterized by constellations of distributed spacecraft, miniaturized sensors and satellites, increased levels of automation, intelligent onboard processing, and mission autonomy. Programmatically, these missions will be noted for dramatically decreased budgets and mission development lifecycles. Current progress towards flexible, scaleable, low-cost, reusable mission control systems must accelerate given the current mission deployment schedule, and new technology will need to be infused to achieve desired levels of autonomy and processing capability. This paper will discuss current and future missions being managed at NASA's Goddard Space Flight Center in Greenbelt, MD. It will describe the current state of mission control systems and the problems they need to overcome to support the missions of the 21st Century.

1. Introduction

NASA's Goddard Space Flight Center supports both NASA's Earth Science and Space Science Enterprises, managing numerous near-earth orbit and robotic spacecraft in varying orbits. The time from conception to operation for a spacecraft has been reduced from a decade to a few years, and the budget for each mission has been reduced even more severely. The real-time mission control systems that receive engineering telemetry data from satellites and transmit commands to them for routine operations and in the event of an anomaly have also evolved. Once custom built for each satellite and operated on expensive mainframe computers, today's systems are easily configured for any mission, are being built by companies and universities, and run on less expensive and readily available Unix computer systems.

NASA is entering a bold new frontier in science exploration and technology research and development. NASA is planning revolutionary new missions often comprised of constellations of spacecraft to explore our planet, the earth-sun interaction, and our universe. These missions are characterized by constellations of miniaturized spacecraft, advanced sensors, innovative communication schemes, increased levels of automation, onboard processing, and mission autonomy. Programmatically, these missions will be noted for dramatically decreased budgets and mission development lifecycles. Current progress towards flexible, low-cost, reusable mission control systems must accelerate to meet mission requirements. Furthermore, it must include provisions and strategies to accommodate rapidly emerging and developing commercial technologies for infusion into mission control systems.

To address the future mission needs, the Information Systems Center at the Goddard Space Flight Center formulated and began the implementation of a Strategic Technology Plan. The three mission information system technology thrust areas that comprise our Strategic Technology Plan are: Rapid Mission Formulation, Design and Execution; End-to-end System Autonomy; and Advanced Scientific Analysis Tools and Systems. Collectively these groupings of critical mission information system technologies are laying the foundation to enable innovative and less costly mission support for the 21st Century.

2. Supporting Goddard's Missions in the 1990's

NASA's Goddard Space Flight Center is the NASA Center of Excellence for Earth Science. The objectives of this program are to provide long term observations of climate and terrestrial and marine ecosystems and the supporting information system necessary to develop a comprehensive understanding of how the Earth functions as a unified system. Earth Science missions currently in orbit include the Upper Atmosphere Research Satellite (UARS), the Landsat series of Earth Imaging satellites, and the Total Ozone Mapper (TOMS). Soon to launch are the first four satellites of the Earth Observing System (EOS), a coordinated series of polar-orbiting and low inclination satellites for long-term global observations of the land surface, biosphere, solid Earth, atmosphere, and oceans.

Goddard supports NASA's Space Science Enterprise, managing key on-orbit satellites including the Hubble Space Telescope, the Compton Gamma Ray Observatory, the Solar and Heliospheric Observatory (SOHO), as well as several Small Explorer satellites, highly focused and relatively inexpensive space science missions.

There are many existing systems for control of spacecraft and spacecraft components during development, test, and on-orbit operations. The best systems are very similar in functionality and architecture. They perform six basic functions: telemetry ingest, command processing, a control system for highly automated processing under specified conditions, a spacecraft telemetry and command specification database processor, an events handler, which logs and displays messages generated by the spacecraft and the ground system, and a customizable user interface. Customization from mission to mission involves only a new database and changes to a small set of configuration files. Most systems run on Unix workstations although efforts are being made to convert to the Linux operating system to enable use on lower cost PCs

The real-time heart of the system is the command processing system. Commands are sent to a satellite to turn power on and off to subsystems and scientific instruments, to point the detectors on scientific instruments to their intended targets, to switch from primary hardware to redundant hardware and to patch on-board programs if a bug is discovered after launch. The standard used for most command processing systems is the Consultative Committee for Space Data Systems (CCSDS) Command Operation Procedure (COP), COP-1 Enhanced Service. COP-1 fully specifies the closed-loop protocol executed between the sending (ground) and receiving (spacecraft) entities. The COP consists of a pair of synchronized procedures: a Frame Operation Procedure (FOP) that executes within the sending entity; and a Frame Acceptance and Reporting Mechanism (FARM) that executes within the receiving entity. The FOP transmits telecommand transfer frames to the FARM. The FARM returns telemetered Command Link Control Words (CLCW's) within the telemetry transfer frame trailers to the FOP. The FOP provides return status about the acceptance of the frames by the spacecraft. COP-1 operates on the principle of sequential frame acceptance and retransmission, with frame sequence numbering. The FOP initiates the transmission of TC Frames whose sequence numbers are arranged in upcounting sequential order. The FARM only accepts frames if their sequence numbers match the expected upcounting order. As soon as a sequence error is encountered, the FARM rejects all subsequent frames whose sequence numbers do not match the expected order. The FOP monitors the CLCW to determine if frames are being rejected, and if so, backs up and retransmits the series of frames beginning with the frame whose sequence number matches the number that the FARM is expecting. Adherence to the CCSDS standard and the implementation of a common telecommand database supporting object frameworks for the spacecraft and ground system reduces costly mission-specific modifications to the ground system. IP is currently used for ground transport and IP networks will be implemented on spacecraft in the near term. There are current experimental activities to bridge the gap between space and ground elements with IP to enable full ease of routing throughout the space architectures.

3. The Challenges of Goddard's Missions in the 21st Century

Numerous revolutionary new space missions are in the concept phase of development at the NASA Goddard Space Flight Center. Most are uniquely different from previous missions in complexity, number of spacecraft, configuration, and interaction. The most noteworthy new focus is on missions comprised of multiple miniaturized spacecraft, often flying in formation, enabling multi-point observations from unique vantage points and enabling temporal differentiated measurements. This shift from traditional single point observations to multi-point observations will be dramatic and will require a broad array of innovative new technologies to provide the needed functionality and affordability. The five specific goals in the area of real-time mission control systems are as follows:

1. Affordable autonomous ground and flight systems that manage both constellations and single missions in real-time - Loading issues and priority schemes will need to be addressed to support multiple missions simultaneously
2. Real-time data processing on-board and the ground of both science and engineering data, including automated science feature identification
3. Downlink and uplink bandwidths for processing commands, anomalies, telemetry in real-time
4. Attitude control systems that maintain relative positions of spacecraft within a constellation or formation in real-time
5. Real-time data storage for large-scale constellations that require download of large data sets

Innovative new operations concepts and supporting technologies will also be necessary to allow these constellations to be operated in an effective and affordable manner. Displays and user interfaces appropriate for managing a constellation of satellites instead of just one will need to be developed.

Other unique concepts are under study to enable radical new missions in the far term. The Earth Science Vision Team, chartered by the NASA's Earth Science Enterprise, is developing advanced ideas, such as "Sensor Webs" of advanced, smart instruments capable of coordinated multi-point observations. Advanced instruments capable of inter-communicating will enable collaborative arrays of sensors to perform passive monitoring and active exploration for improved science data acquisition. Routine autonomous operations, data collection and data synthesis are required to make mission operations manageable and cost effective. Innovative data access, analysis, and visualization tools are needed to facilitate science analysis and understanding. Current systems have some basic automation, notably being able to page key individuals in the event of pre-specified anomalous conditions, but are not yet at the level of sophistication to fully eliminate the "person in the loop". On board processing of data may require a change in the way data is downlinked and processed. None of the current systems today have the security and reliability, and in some cases the processing power, that will be required for automatic or even remote commanding of instruments.

In order to meet its unique mission needs within its constrained budget, NASA commenced a new initiative to radically re-engineer its engineering process and toolset. The initiative, called the Intelligent Synthesis Environment (ISE), will enable geographically distributed groups of people, such as engineers, designers, scientists and technology developers to work together collaboratively on a totally electronic design of the space mission or system. ISE will leverage computational intelligence, which will be built into the design environment, to guide the utilization of the vast resources of knowledge and predictive capability that the environment will access. Advanced modeling and simulation capabilities will allow scientists to interact with simulated vehicles and missions to study science payload, mission performance and interaction of science requirements with vehicle and mission engineering. Collectively, this advanced engineering environment is targeting a significant reduction in the cost of formulation and development of future missions and systems.

Underpinning all of these new complex missions and visionary advanced engineering environments are information technologies necessary to provide the capability or functionality to accomplish these objectives. With an increasing role and dependency on next generation information systems, development of "no-surprise software" in less time and at reduced costs is becoming an important element for all future system development.

4. NASA's Strategic Drivers

Within NASA, there is renewed focus on developing new technologies to enable missions that would otherwise not be possible. The Agency is making technology investments for generic classes of challenging missions in advance of the formulation of specific missions. Missions will have firm cost caps and will not be approved for development until the enabling technologies have matured. For this reason it is essential to identify and mitigate the largest technological risks and cost drivers early in the technology development lifecycle. To achieve this goal, some strategic drivers defined by the Agency include the following:

1. Leverage external technologies and developments
2. Focus on "first of a kind" technology development
3. Shift from "Technology derived from missions" to "Missions enabled by technology"
4. Significantly reduce mission development lifecycle and costs

5. Key Challenges

Some of the key challenges involved in Mission Control Systems for the next generation missions are as follows:

5.1. Fast pace of emerging information technology

The rapid evolution and revolution of information technologies requires an acute awareness of the latest advances, the ability to continually refresh a system's technology base and an agility to quickly change direction based on technology shifts. The challenge of how to ensure a dynamic "information refresh" capability within a system, given growing cost constraints, becomes a critical factor in developing mission critical systems that will be used for a number of years.

5.2. New push to partner with industry and academia

As a means of fostering transfer of technologies and knowledge between NASA, private industry and academia, NASA has been encouraging its workforce to develop working partnerships with industry and university leaders. The desired partnership model, which creates the most interesting challenges, is one in which NASA, private companies and universities bring resources "to the table" and jointly invest in a technology project. These partnerships raise issues of intellectual property rights, which become even more challenging for software. A software product is not tangible and the understanding of what is intellectually protected is still in its infancy. The situation then arises of how to craft the legal agreements to protect the government employees' rights, the private company's proprietary rights, and the taxpayer's rights to NASA information (e.g., via the Freedom of Information Act.) This challenge becomes even more daunting when you consider the speed with which software technology becomes obsolete, and yet, the legal profession is not generally recognized for its expediency.

5.3. Meeting current commitments

As NASA strives towards increasing its level of new, advanced technology initiatives, the challenge of balancing the requirement to meet current customer commitments against the need to increase the amount of new technology opportunities creates tensions due to the seemingly diametrical pressures. With the agency's push to "do more with less," a challenge arises as to how to increase the productivity level and quality of support to current customers, while beginning to shift some resources to new R&D initiatives.

5.4. Competition in the marketplace

At one time NASA did not have to be particularly concerned about retention of its workforce. If you desired employment in aerospace, the ultimate employer was NASA. There is still a certain aura associated with being a NASA employee. However, the increase in commercial companies in the development of telecommunications and satellites, combined with today's demand for IT professionals, has made it challenging for NASA to attract and retain top professional talent.

5.5. Security requirements versus desires for open access

It is extremely important that a satellite receive only the commands intended for it and that these commands be received error free. It is also important that data from the satellite be received by the appropriate scientists without errors. With custom built, centralized systems involving point-to-point communications, this can be achieved. However, future missions plan to reduce costs by using commercial data transmission systems, sharing data lines and even space-to-ground transmission systems with hundreds of other users. Also, scientists and engineers want to be able to access spacecraft data and even command a spacecraft from anywhere in the world. These functions are now possible thanks to the Internet, but NASA will not allow commanding to a spacecraft or direct data downlink to a user via the Internet until secure systems can be designed that reliably minimize unauthorized access or data tampering.

5.5. Standardization

"Plug and play" is an industry standard promoted by Intel and Microsoft and others that allow users to add and remove various hardware devices without making specific modifications to their systems. The concept works because vendors comply with a standard specification. Now that many vendors supply mission control systems, a similar standard specification is desirable. The Space Object Technology Group (SOTG) is a consortium formed for the purpose of developing a reference architecture and interface standards between the components in the reference architecture. Members of the SOTG include NASA, the National Reconnaissance Office, Computer Sciences Corporation, Raytheon Corporation, Altair Aerospace Corporation, and others. For communication between plug and play ground system components, the Common Object Request Broker (CORBA) architecture was selected because it can support heterogeneous platforms and is not proprietary. The SOTG is developing standard interface definitions between all the basic modules that comprise a mission ground system, including data acquisition, commanding, orbit and attitude determination and science scheduling. These definitions will be turned over to the Object Management Group (OMG) in December 1999. The challenge ahead for the OMG is to establish the SOTG findings as a standard and compel vendors to either modify their current products or market new ones that are compliant with the standard. As the SOTG standard evolves over the next decade, the next generation of off-the-shelf data distribution products will more than likely replace the current version of CORBA. Standards for data transmission protocols and data formats will evolve from the current CCSDS standard. Some discussion is underway at NASA Goddard Space Flight Center and the Jet Propulsion Laboratory as to the replacement of some of the CCSDS layers with the Internet protocol allowing spacecraft and instruments to communicate as nodes on a space network or the Internet.

5.7. Dynamic allocation of resources

In the 21st century, there will be many more satellites in orbit, frequently in constellations or groupings, and many more users desiring access to them. A fixed communications architecture, with centralized control, will not be effective in this environment. Like Web access, the optimum system is one that is completely distributed, secure, and allows dynamic allocation of resources. A user connects to the Internet only when needed, and accesses any node on the Internet, not a centralized access point. Users should be able to access satellites in a similar manner.

6. GSFC Mission Information Systems Strategic Technology Plan

In our Strategic Technology Plan we identified three mission information system technology thrust areas: Rapid Mission Formulation, Design and Execution, End-to-end System Autonomy, and Advanced Scientific Analysis Tools and Systems. For each of these areas, we identified the following long-term visions:

Rapid Mission Formulation, Design & Execution: Enabling revolutionary mission concepts through rapid mission formulation, implementation and execution
Vision: Mission scientists and engineers seamlessly evolve science objectives into mission concepts through virtual models to an operational science system.

End-to-End System Autonomy: Enabling effortless science collection through autonomous mission systems
Vision: Mission scientists operate, maintain and reconfigure systems from anywhere in order to optimize an on-board observation and maximize science return.

Advanced Scientific Analysis Tools & Data Systems: Enabling science knowledge discovery through seamless and transparent access to information
Vision: Academic and research community has continuous and transparent access to data and information for scientific research.

We then defined a snapshot of a phased progression of technology capabilities, which, from today's perspective, are necessary to achieve each focus area vision.

All on-going and proposed technology projects require review and assessment against the vision and technology roadmap to determine their alignment with the strategic directions. A full inventory of technology initiatives is maintained and placed on a review cycle to reassess and check on progress and continued relevance. It is during this reassessment phase that decisions to continue, redirect or terminate projects are made.

7. Examples of ISC Technologies Responsive to the Technology Plan

The following are examples of advanced technologies under development in support of ISC's new technology vision. Collectively these critical space technologies are laying the foundation to enable innovative and less costly missions opportunities for the 21st Century.

Advanced Scientific Analysis Tools & Data Systems

- Scientist's Expert Assistant: Develop and infuse a tool to assist scientists in developing a proposal specification for Hubble Space Telescope. The tool will be used to determine potential capabilities, limitations, and implementations for the next generation space telescope.
- InVision: Develop and deliver data visualization products in support of science and engineering needs. Research advanced IS technology concepts in data visualization.
- Pico-POCC: Develop hand-held or wearable mission control systems for direct use by scientists
- Space Weather Modeling: Support integration of environmental models into a common computational architecture. Provide real-time S/C data streams to initialize modeling environment.

Rapid Mission Formulation, Design & Execution

- Operating Missions as Nodes on the Internet: Prototype and infuse a secure end-to-end system embodying the concept of building an architecture in which a spacecraft is considered a node on the Internet, which can be operated by a scientist via the Web.
- Instrument Remote Control: Develop, infuse and transfer an advanced system for directly commanding remote instruments, and subscribing to data from remote instruments.
- JAVA Server Web Interface for Telemetry and Command Handling (Jswitch): Provide a generic, secure command and control interface via the Internet to both legacy and future NASA missions.
- Scaleable Integrated Multimission Simulation Suite (SIMMS): Provide standard, non-mission specific simulation models and tools that enable scaleable, multi-level fidelity simulation systems.

End-to-End System Autonomy

- ComPASS (Common Planning and Scheduling System): Develop, infuse, and transfer an advanced planning system for future missions to serve as an end-to-end (science to mission) integrated tool for scientists. The tool is targeted to allow science-goal driven, distributed, autonomous on-board adaptive planning and scheduling.
- Agents: Research intelligent agents and apply them in applications for mission operations autonomy and science data analysis and understanding
- Spacecraft Emergency Response Collaborative Environment: Research, develop, infuse, and transfer technology to enable distributed mission control and anomaly resolution

8. Conclusion

NASA is facing an exciting period where revolutionary new missions are under formulation. Innovative, first-of-a-kind technologies are needed to support this revolution. Real-time mission control systems require significant technology development and aggressive plans for validation and infusion to meet the challenges of these new missions.