Utilization of Intelligent Systems Technologies for Manned Mission Operations Support

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With the International Space Station being extended to 2020, there is additional emphasis in the manned spaceflight program to find more efficient and effective ways of providing the ground-based mission support. This search for improvement has led to a cross-fertilization between the advanced software development community and the manned spaceflight operations community. Many mission operations systems and tools have been developed over the past decades as NASA has operated the Mars robotic missions, the Space Shuttle, and the International Space Station. NASA Ames Research Center has been developing and applying its advanced intelligent systems research to mission operations tools for both unmanned Mars missions operations since 2001 and to manned operations with NASA Johnson Space Center since 2006. In particular, the fundamental advanced software development work, and the experience and capabilities developed for mission operations systems for the Mars Exploration Rovers, and Phoenix Lander have enhanced the development and application of advanced mission operation systems for the International Space Station and future spacecraft. This paper discusses the on-going application of a variety of intelligent systems technologies adopted for manned mission operations. We discuss several specific projects between the Ames Research Center and the Johnson Space Center's Mission Operations Directorate, and how these technologies and projects are enhancing the mission operations support for the International Space Station and preparing for the mission operation support of the future human exploration programs.

I. Introduction

NASA is posturing itself for the next major step in the exploration of space, and will require the development of many new capabilities including the design of new spacecraft, new launch services, and new processes and tools associated with the mission operations support. The mission operations support includes the planning of the NASA missions, the training of the crew and flight control team, and the mission execution. While the specific targets for NASA mission operations beyond the ISS Program are currently being assessed, it is clear that NASA will need to infuse new technologies into the new space exploration initiatives. The range and complexity of these exploration missions will require an unprecedented use of automation and robotics in support of human crews. This will require the operations of manned spacecraft in close conjunction with planetary robotic systems.

NASA's current space flight missions are largely segmented into unmanned missions funded by the NASA's Science Mission Directorate, and the human spaceflight missions operated by the Spaceflight Operations Mission

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Directorate. Typically the organizations within NASA that operate the unmanned missions are different from the organizations that operated crewed space systems. The mission operations requirements and needs for the robotic missions have been relatively distinct from those for the Space Shuttle and the International Space Station (ISS).

Developing and validating any new exploration spacecraft and its associated infrastructure may place requirements on operations design for future exploration missions. Separate mission operations processes—and cultures—have evolved to support manned missions and unmanned/robotic missions, each geared to the unique challenges of the two classes of missions[1]. Thus, enabling the technologies and process innovations that benefited the robotic missions to also benefit crewed missions is not simple or straightforward. NASA Ames Research Center has been working with both human spaceflight and robotic systems communities now for several years developing mission operations tools and system, and is helping to bridge the gap between tools for manned and robotic mission operations. The Constellation Program's Mission Operation Project Office has been working with NASA Ames to create new intelligent systems for mission operations[2]. This paper updates the status report provided at the SpaceOps 2008[3] and discusses the possible impacts of a flexible exploration architecture on manned spaceflight operations.

A. Mission Operations Directorate Needs

In collaboration with the NASA's Astronaut corp, the Johnson Space Center's Mission Operations Directorate (MOD) manages and maintains the flight operations of all of NASA's human spaceflights. These include all of the previous manned spaceflights from Mercury through Apollo, and now the Space Shuttle and ISS. The flight operations of the crewed elements of the future exploration initiatives will likely also be managed by MOD.

Manned flight operations support is provided by the combination of several ground mission control centers around the U.S. and the World, primarily focused through the Mission Control Center (MCC) at Johnson Space Center (JSC) in Houston, Texas. The Shuttle flight operations are supported primarily by MCC and the Payload Ops Integration Center (POIC) at Marshal Space Flight Center (MSFC) in Huntsville, Alabama. The ISS is also supported by these two centers, plus the International Partners control centers including the Mission Control Center in Moscow (MCC-M or TsUP), the European Space Agency (ESA) Columbus Control Center in Germany and the ATV Control Center in France, the Canadian Space Agency (CSA) Control Center in St. Hubert, Canada, and the Japanese Experiment Module (JEM) and HTV Control Centers in Tsukuba, Japan.

With the retirement of the Shuttle in late 2010/early 2011, MOD at JSC is preparing for future exploration initiatives, with a stated a goal of reducing the manpower required to support manned space flight operations. MOD has restructured itself to be more efficient in support of the "Plan, Train, and Fly" activities associated with manned flight operations, but is also investigating several technology infusion opportunities as described within this paper which they anticipate will help in achieving this reduction goal.

Most of the effort that goes into supporting crewed flight operations is in the preparation for flight activities (the "Plan and Train" part), and the actual flight/mission support (the "Fly" part) is typically the least manpower intensive. Significant facilities infrastructure is required to accomplish the "Plan, Train, and Fly" activities, from scheduling and analysis tools, to training simulations, and the mission control center itself. Typically, several years prior to a launch or increment activity, MOD works with the program offices to understand the requirements for any given flight/increment. During this early "Plan" phase, MOD must accomplish the mission concept definition, the mission requirements integration, long and short term timeline planning, flight rules development, crew and ground procedures development, and mission analysis and design (consumables, launch and entry analysis, orbit and rendezvous design). The timelines begin as very high-level schedules of crew and ground activities which meet the requirements. These schedules are iteratively adjusted and improved as the flight/increment draws nearer, and it is often adjusted during the mission itself. The schedules are continuously improved from high-level schedules of crew/ground activities to more detailed schedules that account for hourly activities for the mission. While the negotiations for schedule details continue to require collaboration among team members and partners, new applications and tools are increasingly helping automate and adjust the layout of the activities for the missions. Similarly, new applications continue to improve the mission analysis and design processes.

The "Train" phase of the mission preparation includes training both the astronauts and the mission flight control teams. This is accomplished by a combination of classroom training, stand-alone simulations of the flight vehicle

and environment, and integrated simulations where both the astronauts and the flight control team are involved in joint simulations of the missions. During these simulations, vehicle systems failures and flight constraints are scripted to exercise and test the team's abilities to deal with unexpected problems. New applications, techniques and tools that enhance or provide more flexibility in the simulation environments are being assessed to improve these simulation capabilities. MOD is also utilizing more automation in the curriculum design and development process.

The "Fly" phase of the mission includes the real-time flight operations with the Flight Director, Flight Controllers, Ground Controllers (for the facilities), the Engineering support, and in the case of the ISS, the International Partner operations support and integration. Within the MCC, the team is structured such that the Flight Control Room (FCR) is the focus of all mission control, with the Flight Director, CAPCOM, the vehicle systems flight control specialists, and other specialists integrally involved in executing the flight plan, assessing the vehicle systems health, and making the mission decisions in collaboration with the Mission Management Team. For most of the positions within the MCC FCR, there are support flight controllers in the Multi-Purpose Support Rooms (MPSR) within the MCC and in some cases in remote locations (such as the Canadian ISS Robotics Support). The detailed engineering support is provided by the Mission Evaluation Room, and this team can get support as needed from the systems experts at other centers, industry, and International Partners. The Mission Management Team keeps an overview of the ongoing flight activities and provides any Programmatic-level decisions that are needed. Note that while MCC Houston is the lead for overall flight planning and core systems assessments, for the ISS, the POIC at MSFC integrates the payloads, and the International Partner Mission Control Centers are primarily responsible for their own modules. MOD has embraced several new Ames-developed technologies and tools to enhance the real-time mission support environment including better search tools for flight-related information, a more interactive display building environment, and telemetry monitoring and agent-based support tools to off-load the work of the flight controllers. For all these technology improvements to the mission support ("Plan, Train, Fly), MOD is using the current ISS support environment as a test-bed.

Traditionally, past crewed NASA missions have been highly dependent upon earth-based mission operations. Crewed missions hardware and software systems are programmed to be capable of dealing with many unanticipated events, but most of the flexibility of the crewed missions comes from the crew itself and the ability of the earth-based flight controller to adapt and handle any situation. This means that the primary responsibility for handling unforeseen situations always resides with humans, who are either onboard the spacecraft or in mission control.

B. MOD's Flight Operations Improvement Team

In 2006, MOD chartered the Flight Operations Improvement Team (FOIT) to evaluate the processes, structures, and technical approaches that mission operations would need to support the Vision for Space Exploration, and the new Constellation Program.

As part of the FOIT, a team assessed what automation would be required to exist to support mission operations (both earth-based and on-board decisions)[4]. Several areas of automation where determined to be highly valuable, including,

- Solar array sun tracking, antenna/satellite tracking
- Scripted procedures
- FDIR (fault detection isolation and recover after a system failure)

The approach suggested by the FOIT automation team was to aim for full autonomy of future exploration missions from the earth. This means that the spacecraft and crew operate without direct intervention from the ground. This capability is clearly required for future space flight initiatives as spacecraft fly deeper into the solar system and communication delays become significant. This autonomy may be achieved by a combination of automated and manual functions on-board, but requires no cues from the ground. The current MOD plan to support future operations, by necessity, is to evolve their existing operations systems, processes and capabilities to support this future autonomy concept. This means MOD wants to incorporate automation capability within ground operational practices in the near-term, using the ISS Program as a test-bed. Preparing for this improved operations automation must be a staged process where it is necessary to assess what are the components of the future operations that are desired to be either on-board or earth-based[5]. Then, knowing conceptually what are the future operational

models to be striven for, MOD intends to incorporate augmented automation capability within its operational practices.

The FOIT study recommended several conceptual constraints upon future spacecraft, such as "Design a vehicle that can be automated safely." However the most significant recommendations were focused upon the overall operations strategy. This applies equally to the existing ground-based operational infrastructure used by MOD and the future goal of operations. These are (in part);

- Utilize automation where it makes sense… and define up front what makes sense.
- Let flight experience dictate what functions should be automated. Focus automation capability where requirements and vehicle functionality are clear and well understood. Phase in automation of complex operations as those operations mature.
- Define roles & responsibilities up front. Clarify expectations and requirements for all phases of related development, delivery, and utilization. More specifically, clarify the transition points for authority and responsibility between all organizations involved in automation development and implementation.
- Address interactions with other areas of MOD responsibility: MCC, recon, training, procedure development, ops planning.
- Allocate responsibility for developing automation products that are not embedded in flight software to Mission Operations.

For example, to evolve from the existing practices operating the ISS required the assessment of what gaps exist in progressively making ISS more automated. This would initially not require more autonomy from the ground, but would mean that the current ISS operations would be targeted for increase efficiency and automated systems would looked at to reduce flight controller workload. By using the ISS operations as a demonstration and validation ground for the use of new technologies, MOD will be able to assess where, when and how additional advanced software systems will impact future exploration mission operations, and how those will enable the goal of an autonomy capable system for NASA's exploration. The migration of autonomy-based mission support tools from the ground to the spacecraft will be a programmatic decision, but MOD is attempting to assess and support operational use of this technology both for ground operations improvements and for future spacecraft infusion.

The NASA mission community tends to be properly conservative about the use of new technology in mission critical, and life-critical, situations. The automation necessary to support advanced operations is correctly perceived as involving new technology. Consequently, a realistic way to create acceptance of this new technology is to perform a series of analog operations using existing spacecraft, principally ISS, and then to begin using the technology in future exploration missions as soon as practical.

In order to meet these new operational requirements it is critical that advanced operations are assumed from the beginning of any new spacecraft development process. Operations concepts have system-of-systems implications for mission operations design, and tend to become "baked" into mission design, operational models, and culture.

II. Intelligent Systems at NASA

A. Advanced software systems for Operations

NASA Ames Research Center has long been a leader in the development of advanced software technologies and systems for NASA Missions. Through the 1990s this role included leadership of the majority of NASA's automated reasoning and human-centered computing programs. In the first decade of this millennium, Ames has lead all of the advanced software research and development projects for the Exploration Systems Mission Directorate. Ames has exercised these responsibilities to provide the Agency with a notable set of software technology "firsts," including the first autonomy software to be flown by NASA on a spacecraft[6], and the first advanced planning software to daily plan a robotic planetary mission[7]. All current and planned NASA's planetary Mars missions now baseline this same technical capability. Similarly the multiyear partnership with the manned spaceflight operations described in this paper has grown out of a combination of excellent technical work, a focus on NASA's needs and vision of its future, and a portfolio of activities ranging from needs-driven technology development to project-focused tool development.

The partnership between NASA Ames Intelligent Systems and NASA JSC's MOD has begun to address the significant challenges posed by the agency's long-term operations of manned spacecraft. The knowledge, intelligence, and engineering analysis currently provided by MOD mission controllers will need to be automated and accompany the astronauts on future missions to both the ISS and exploration destinations. As ISS becomes a major testbed for systems, mission operations will need to be more adaptable for varied mission scenarios. An ability to rapidly and dependably develop and modify software could provide MOD the means to alter system capabilities on the fly. Following current practices, software modifications to space-based and flight control systems can take in the months or years to make. To modify capabilities between and during missions, revolutionary software development approaches are needed - new approaches that, in the tens of minutes, can result in effective and dependable modifications. Like MOD, in order to achieve these goals Ames must target an evolutionary path to proving out technical approaches. During this evolution it must validate the value for the crewed mission operations community.

B. Human Centered Computing

The lessons learned from NASA Ames developers and the experience they had creating tools for the Jet Propulsion Laboratory's Mars planetary missions, and the past four years of collaboration with MOD have defined a framework for how Ames and JSC determine what opportunities exist for intelligent systems applied to the crewed spacecraft operations for NASA. Principally the discussion of new technologies and tools needs to be framed in a manner that identifies and emphasizes the value to the MOD operational flight controller. It is not about replacing 'man with a machine', but about augmenting the flight controller or operator to do a better job. This overall methodology and approach is often referred to as human centered computing.

Human centered computing looks to the processes and procedures that people do in order to perform any given job. Then with this understanding, attempts to identify opportunities to improve the processes and procedures for people to perform. In particular, for mission operations, this is quantified by specifically identifying how a tool can increase a person's efficiency, enhance a person's functional capability, and/or improve the assurance of person's decisions.

A human centered computing strategy contains the following essential elements:

- Deploy personnel to mission centers to work with the NASA customer(s) to understand the exact nature of their current and future challenges that may be amenable to software solutions.
- Scouting for all relevant approaches or technologies that may address the customer's needs.
- Identify technology gaps left by current software capabilities to seed new R&D.
- Simultaneously conduct carefully-targeted R&D to address the gaps on an ongoing basis
- Evaluate and compare competing results, working closely with the customer to determine the strengths and weaknesses and the cost-benefit of the each candidate solution and improve it on this basis.

This above strategy worked exceptionally well for infusing advanced technologies in the Mars robotic systems, and has proven to work equally well for the human spaceflight community.

III. Advanced Mission Operations Development Projects

At the advent of the Constellation Program, Ames and JSC began discussion about how to leverage each other's strengths and capabilities. Now they have established a set of initial projects that will address outstanding needs within MOD. These projects first started in 2006 and have progressed to several full-scale projects delivering operational flight controller tools in 2007-2010 and continuing into the foreseeable future. Even with the cancellation of the Constellation Program, all of these mission operations development projects are considered relevant to increasing the efficiency of the mission operations flight control team, and significantly support the goal of overall operations manpower reductions. A synopsis status of some of the projects currently underway is presented below.

A. OSTPV Enhancements

The On-Board Short Term Plan Viewer (OSTPV) is a tool used by flight controllers to view and manipulate the International Space Station's Short Term Plan (STP). This plan spans several days to 2 weeks, and describes

activities performed by ISS crew and the status of major ISS subsystems at a time granularity of tens of minutes. These plans are developed using the Consolidated Planning System (CPS), which contains rules that govern the legality of the STP. Flight controllers can manipulate the STP by re-scheduling or deleting activities; however, OSTPV only displays the new schedule, and does not perform any checks for constraints that may be violated as a consequence of plan manipulations.

OSTPV plans will be checked for constraint violations using an application built on the Extensible Universal Remote Operations Planning Architecture (EUROPA), developed at Ames. CPS rules and STPs are semi-automatically transformed into EUROPA's representation for analysis, and a report is generated for use by controllers. This collaboration started in September 2006 and has led to a system which is utilized by flight planners to analyze ISS S-Band communication plans. This project has been expanded in scope by MOD to a Next Generation Planning System (NGPS), which will infuse the Ames technologies and consolidate many of the disparate planning tools being used today[8].

B. Mission Operations Design and Analysis

OCAMS (OCA Mirroring System) is a practical engineering application of multi-agent systems technology, using the Business Redesign Agent-based Holistic Modeling System (Brahms) modeling and simulation tool[9]. The Brahms system combines models of systems (e.g., robots, tools, software) with models of people communicating and moving in a simulated geographic space, revealing how interactions of people, facilities, and tools are productive or gaps that may occur in capabilities and procedures. Brahms simulations can be converted into a runtime system in which software agents mediate work flow operations and communications among people and systems.

The project, initially called MODAT (Mission Operations Design & Analysis Tool) and now called OCAMS, is a collaboration that began in November 2006, leading to a completed workflow automation system which is currently being used by OCA Officers in the MPSR backroom supporting the ISS.

The OCA Officer is responsible for uplinking and downlinking all files to and from the ISS. The Ames OCAMS project team has developed the Agent-based OCA Mirroring System to simulate the OCA Officer's work process in order to identify possible process improvements. Using the newly developed Simulation to Implementation Engineering method, the OCAMS team developed an in-silico work process and practice simulation of the OCA Officer's work in Brahms, based on observations of the actual work in Mission Control. Using statistics generated from this simulation model and collaborative design with the OCA Team at JSC, they then developed an agent-based workflow system that supports the newly designed and improved OCA work process. With the OCAMS system, the time spent by the OCA Officer mirroring files uplinked and downlinked to the Space Station has been reduced to the point that the plan is to merge this console position with another in the Planning MPSR. The next proposed major initiative for OCAMS is to extend this agent support capability to on-board the ISS, providing a more complete interface to the ground OCAMS operations and potentially off-loading both crew administrative activities.

C. Advanced Monitoring Inductive Software System

The Advanced Monitoring Inductive Software System (AMISS) is an Ames developed health monitoring software application that compares current system data with data from previous nominal system operations. AMISS applies data mining techniques to archived telemetry to establish a baseline of normal behavior for groups of data parameters from the monitored system. AMISS then uses that baseline to identify off-normal behavior in real-time telemetry, potentially alerting the mission operations team to problems prior to any caution and warning annunciation for the system. Any deviations from normal baseline behavior will be indicated by AMISS with a non-zero "distance" from nominal. Information is also provided on which data parameters are contributing to the off-nominal readings to help identify the source of the anomaly.

In 2006, Ames delivered AMISS based tools to JSC that allow mission operations users to retrieve archived mission data and run the data offline on AMISS to both "train" the tool on nominal data and to execute the "monitoring" feature. This capability was tested on several ISS Control moment Gyroscope (CMG) data sets,

including data collected during some significant CMG malfunctions. AMISS successfully detected anomalies in CMG behavior in these data sets, sometimes several hours before malfunctions were detected by current MCC systems. These promising results prompted JSC to establish an 2007-08 task to deploy the tool within the MCC environment for evaluation and use in real time by the on-console flight control team. The AMISS tool has been integrated with the MCC real time data system and deployed on the ADCO mission control consoles in the ISS control room to provide real time CMG monitoring. In addition, AMISS has been augmented with fault detection routines that will automatically detect and identify some common CMG faults to assist controllers in diagnosis and recovery activities. AMISS has now been applied to the monitoring of the ISS External Thermal Control System (ETCS) subsystems, and is being assessed by MOD for further utilization by the ISS Flight Control team.

D. Mission Control Technologies

Current MOD mission operations systems are built as a collection of monolithic software applications. Each application serves the needs of a specific user base associated with a discipline or functional role. Designed to accomplish specific tasks, each application embodies specialized functional knowledge and has its own data storage, data models, programmatic interfaces, user interfaces, and customized business logic. In effect, each application creates its own walled-off environment. While individual applications are sometimes reused across multiple missions, it is expensive and time consuming to maintain these systems, and both costly and risky to upgrade them in the light of new requirements or modify them for new purposes. It is even more expensive to achieve new integrated activities across a set of monolithic applications.

These problems impact the life-cycle cost (especially design, development, testing, training, maintenance, and integration) of each new mission operations system. They also inhibit system innovation and evolution. This in turn hinders NASA's ability to adopt new operations paradigms, including increasingly automated space systems, such as autonomous rovers, autonomous onboard crew systems, and integrated control of human and robotic missions.

In order to achieve NASA's vision affordably and reliably, we need to consider and mature new ways to build mission control systems that overcome the problems inherent in systems of monolithic applications. Two keys to the solution are *modularity* and *interoperability.* Modularity will increase extensibility, reusability, and maintainability. Interoperability will enable composition of larger systems out of smaller parts, and make possible the construction of new integrated activities that tie together, at a deep level, the capabilities of many of the components. Modularity and interoperability together contribute to flexibility.

The Mission Control Technologies (MCT) Project[10], a collaboration of multiple NASA Centers, led by Ames, is building a framework (based upon the open-source Eclipse software) to enable software to be assembled from flexible collections of components and services. MCT has been executing in the MCC Operations Test Facility (OTF) for several years, shadowing ISS mission operations. It is now being deployed into the MCC Consolidated Development Environment (CDE) to expand the user base that can evaluate the cyclic deliveries of this capability and to develop, gather, and analyze measurements to evaluate the performance and usability of MCT, from a flight controller's perspective. This move also enhances our ability to define and analyze the proper engineering metrics - performance, lines of code, and the potential cost savings. MCT is in full-scale development planned for completion in FY12.

E. Search Tools

The Search Tools for MOD Flight Controllers project focuses on improving MOD access to and retrieval of critical information required to monitor, control, and manage ISS and Space Shuttle[11]. While much of this information (in the form of notes, change requests, action item lists, procedures, documentation, etc.) is currently accessible using a patchwork of disconnected tools and databases, this project is building a unified search capability across these data sources an presenting a unified single Web-based interface for all MOD flight controllers. In addition, the system identifies cross-referenced and other relevant information that flight controllers might otherwise overlook.

The XSearch development, working closely with JSC/DO/DA/DI, began in January 2006 and has been deployed in the MCC environment enhancing the cross-database searches (primarily the mission Flight Notes, Anomally

Reports and Chits) for the flight control team. In addition to search, the XSearch system provides two other important capabilities: cross-referencing and similarity detection. At the request of MOD, XSearch is now being applied to searching MOD Flight Techniques and Joint Operations Panel meeting minutes.

F. Scheduling, Training Administration, and Records (STAR)

STAR is NASA's next-generation training management system for crew, instructors, and flight controllers. It is replacing the existing Training Administration Management System (TAMS) and Flight Operations Curriculum Administration System (FOCAS) with a suite of tools that provide integrated curriculum development and documentation, customized training plans, scheduling of personnel and facilities, training event feedback, and other training resources. All modules are being designed for maximum efficiency and interoperability. In an iterative process, event feedback is being used to help optimize the training plans. Retirement of the oldest MOD training tool TAMS is targeted for the fall of this year, and will reduce the overall sustaining costs for the training applications. New STAR functionality and the retirement of other legacy training tools are planned for the next several years.

G. Solar Array Constraint Engine (SACE)

As the construction of the ISS was being completed, solar arrays added to provide the power required to support additional modules on the larger station. These new arrays had more freedom to articulate, enabling better tracking of the sun and thus increased power production. However, these arrays also had more complex constraints that limit the range of safe orientations, due to structural loads, contamination concerns, and thermal impacts. These limitations on safe array orientations impact power generation, which requires MOD flight controllers to constantly balance multiple complex constraints against ISS power needs. The increased complexity does not only impact pre-planning activities, but has an even more acute effect on real-time operations, in particular when handling unexpected events or changes in operations plans.

The Solar Array Constraint Engine (SACE) project has developed a tool that provides intelligent decision-support capabilities to ISS power systems flight controllers, to assist them with the task of planning and executing solar array operations in a safe and effective manner[12]. SACE provides situational awareness, orientation evaluation and optimization, and array operations planning functionality to flight controllers. The SACE tool is built on the EUROPA engine, which provides constraint management and reasoning, decision-support and planning.

The functionality of SACE is primarily three-fold. First, SACE provides situational awareness to the flight controllers. SACE monitors the telemetry and station events, identifies applicable constraints and power needs, and then presents the flight controller with graphical information about whether there are constraint violations and whether power production meets power needs. In addition, the flight controllers are provided with contextual information that gives them at-a-glance a picture of how alternative array positions would fare in terms of constraints and power production.

Secondly, the SACE tool provides decision-making assistance to flight controllers. Flight controllers are able to specify ISS events and situations, along with candidate solar array orientations, and providing them with information on whether constraints are satisfied and power needs are met. Contextual information, in the form of various graphical maps, is also provided, making it easy for flight controllers to find good candidate solar array orientations for a given event and situation. Furthermore, the tool offers automated optimization, relieving the flight controller of finding the desired solar array orientation, and automatically suggesting it. As the desired optimal orientation differs based on situations and flight controller needs, the flight controller can specify in detail the criterion for the best solution.

Thirdly, SACE provides a solar array plan generation and editing capability. This is critical for pre-planning operations; the current manual approach will become infeasible as solar arrays are added. The tool reads specifications about planned station events, orientations and situations, and automatically generates a safe plan for operating the solar arrays, while ensuring that power needs are met, or, if they cannot, provides the best power production profile possible. The solar array plan support capability also supports on-console operations, by allowing users to modify the plan and have the plan subsequently updated as needed.

The SACE tool enables simple solar array plan generation. SACE includes: (1) separation of plan configuration and generation into separate phases, so that the user can modify the configuration before proceeding with plan generation; (2) improved algorithm for consolidating constraints and user restrictions during the solution of configurations that need to be merged during plan generation; (3) visual indication to the user of configurations merged during planning; (4) reporting of orbital-average power availability for the generated plan, taking into consideration the actual configuration/orientation of the arrays during each orbit; (5) displaying of eclipse and isolation timelines; and (5) displaying the "time to hazard" for longeron shadowing, as line graphs on timelines.

While the current planned development of SACE is complete, there are some sustaining developmental requirements that are being considered. However, SACE is a fully delivered capability enhancing the PHALCON flight control planning and execution of ISS solar array management.

H. Power Planning and Analysis Tool (PLATO)

The ISS Spartan flight control team currently utilizes a complex suite of tools to plan and execute management of the ISS power systems. The PLATO project is a collaboration project intended to consolidate all the ISS power planning tasks into a single application with an easily manipulated interface, a front end appearance similar to OSTPV, and which will automate the sharing of power-related data with other flight control disciplines[13]. It would still maintain the robust capability of the current power analysis toolset, allowing the qualified user to delve into the underlying interface and modify the analysis parameters just as PRO can today with the IPS tools. Ames is providing the technology infusion to this tool development while the MOD team is providing much of the user interface and integration development. As with the SACE project, this project leverages off the Ames EUROPA engine, which provides constraint management and reasoning, decision-support and planning. This project is targeted to complete in 2012.

I. Constraints and Flight Rules Management (ConFRM)

In preparing for mission operations, the MOD flight control team must understand, document, utilize, and account for many operational constraints. A complicated variety of tools and processes are employed today in dealing with these flight constraints, and ConFRM is envisioned as a tool to manage these Ops constraints[14]. ConFRM would provide a database-like storage of ops-related constraints, such as planning constraints, Flight Rules, and flight controller workstation limits, associated with each mission. ConFRM would provide a standardized authoring tool for Flight Rules, and Ground Rules and Constraints with the ability to export into desired formats. It would have the ability to link all related constraints/products, would capture full history/heritage of a constraint (improves Knowledge Management), have the ability to import/export constraint data to/from other MOD Tools (NGPS, MCT, SSM, etc.), and have the ability to identify mismatches between constraints in various input/output products, providing constraint product Quality Assurance. This project is currently in the early stages of development, again leveraging off the Ames EUROPA engine technology.

IV. Flexible Exploration Operations Support

The Flexible Path Scenario for Human and Robotic Exploration was developed to support the Beyond LEO subteam of the Human Space Flight Review panel that was commissioned by President Obama in the summer of 2009[15]. It is an exploration approach targeting frequent, measured, and publicly notable human exploration of space beyond Earth orbit. The Flexible Path exploration approach targets planetary scientific return focused on multiple locations in the inner solar system. The goal is human exploration producing exciting new science each step of the way. The emphasis would be obtaining multi-kilogram samples from a variety of solar system planetary bodies through tele-robotic exploration in concert with the human missions. In the case of the larger planetary bodies of the Moon and Mars, the humans would remain in orbit, deploy probes, and teleoperate surface robotic vehicles, including rendezvousing with sample returns missions sent from the surface. In the case of smaller objects such as Near Earth Objects (NEOs), the crew would explore the surfaces directly and return samples. Later Flexible Path

missions would include human lunar surface exploration at later dates as funding profiles permit, with landings on the Moon and Mars.

In the Flexible Path study, the role of autonomous operations for the crew and spacecraft in deep space was identified as a critical technology development area. To date, the crew and spacecraft are in near continuous communication with the ground-based mission operations staff. Even when there are outages in communication it is for limited time. The current mode of operations presumes that the spacecraft systems, either the Shuttle or ISS are very often operated from the ground by the flight controllers. The crew activities are planned and coordinated on a moment-to-moment basis with flight controllers as well. During flexible path mission outside of cislunar space, the communication time-delay due to distance will require a fundamentally different mode of operations. The spacecraft and the crew will need to operate independently of the flight controllers for longer and longer times, until "real-time" operations by the earth-based flight controllers is impossible. With time-delays of 10s of seconds to several minutes the operations of the spacecraft and crew must migrate on-board and have status downlinks to the ground. As the flexible path missions are further defined and described, the mission operations models and technology requirements for those operational models will provide additional scope to the on-going work between Ames and MOD. The automation projects previously described herein are currently being deployed in the MCC, but extensions of these capabilities as they mature should be considered for infusion onboard to aid the crew for these Flexible Path missions.

V. Conclusion

NASA's Ames Research Center and Johnson Space Center are working together to apply intelligent systems to mission operation tools and systems. This work is critical to the Agency, ISS and any future human exploration programs. Improving the capacity of NASA's main manned mission operations teams to handle more operations per controller, enhancing the capabilities of those teams to handle complex decisions in a timelier manner, and increasing the available knowledge to the flight controller to make safer decisions are the critical motivations for this work.

This paper reports the latest projects in a planned series of efforts to greatly enhance how Mission Operations are performed for human spaceflight within NASA. These efforts will enhance the current mission operations of the International Space Station and prepare MOD for the more automated and autonomous exploration spacecraft in the future human exploration missions.

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