Current Fault Management Trends in NASA's Planetary Spacecraft

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Abstract— Fault management for today's space missions is a complex problem, going well beyond the typical safing requirements of simpler missions. Recent missions have experienced technical issues late in the project lifecycle, associated with the development and test of fault management capabilities, resulting in both project schedule delays and cost overruns. Symptoms seem to become exaggerated in the context of deep space and planetary missions, most likely due to the need for increased autonomy and the limited communications opportunities with Earth-bound operators. These issues are expected to cause increasing challenges as the spacecraft envisioned for future missions become more capable and complex. In recognition of the importance of addressing this problem, the Discovery and New Frontiers Program Office hosted a Fault Management Workshop on behalf of NASA's Science Mission Directorate, Planetary Science Division, to bring together experts in fault management from across NASA, DoD, industry and academia. The scope of the workshop was focused on deep space and planetary robotic missions, with full recognition of the relevance of, and subsequent benefit to, Earth-orbiting missions. Three workshop breakout sessions focused the discussions to target three topics: 1) Fault Management Architectures, 2) Fault Management Verification and Validation, and 3) Fault Management Development Practices, Processes and Tools.

The key product of this three-day workshop is a NASA White Paper that documents lessons learned from previous missions, recommended best practices, and future opportunities for investments in the fault management domain. This paper summarizes the findings and recommendations that are captured in the White Paper.[1][2]

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1. INTRODUCTION

The science objectives for modern deep space missions, and the anticipated goals for these missions in the near future, are driving new requirements for spacecraft fault management. Traditional safing approaches may be insufficient, or inappropriate in certain critical events. In these cases, onboard resources and control logic must be used to manage fault events. We define Fault Management (FM) as the ability of a system to detect, isolate, and mitigate events which impact, or have the potential to impact, nominal mission operations. Note that this capability may be distributed across flight and ground subsystems, impacting hardware, software and mission operations design.

Fault Management is a critical aspect of deep space missions, but recent experiences have highlighted a need to provide a focused assessment of the current state of practice in this area. In particular, the NASA Science Mission Directorate, Planetary Science Division, has experienced a number of technical and programmatic issues related to FM on recent missions. As a result, SMD/PSD commissioned an invited workshop with participants from the government, industry, and academia to assess the state of the art in both practice and research, to identify current and potential issues, and to make recommendations for addressing those issues. The workshop was held April 14-16, 2008 and was attended by 100 engineers, program managers, and researchers. Also, in preparation for the workshop, the workshop organizers conducted a detailed survey of FM practices in the SMD/PSD spacecraft development community. This paper will describe the objectives and conclusions of the workshop and survey, laying out a roadmap for both near and long term actions that could be taken to address SMD/PSD concerns.

The workshop was structured into multiple sessions that included formal presentations of current mission experiences and relevant research. In addition, a significant amount of time was spent in three focused discussion sessions that

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[2] IEEEAC paper #1475, Version 3, Updated January 20, 2009

addressed particular aspects of the FM problem, specifically: FM Architectures, FM Verification and Validation, and FM Development Practices, Processes, and Tools. The results from each of these sessions were presented in terms of "lessons learned", "best practices" and "opportunities for investment". In this paper, we have combined the results from these three sessions along with FM survey responses, into a single set of top level findings and recommendations.

2. MOTIVATION

In recent years, a number of planetary missions have shown an increase in Fault Management (FM) issues during integration and test and flight, along with associated schedule impacts and life cycle cost increases. Some of the issues noted include:

- Changes to the FM design late in the life-cycle, often resulting in a ripple-effect of additional changes in other areas,
- Inadequate understanding of and estimation of system-level FM testing,
- Unexpected results during FM testing requiring additional time for resolution,
- Operational limitations or restrictions placed on the spacecraft based on how the system was tested (in order to "fly-as-you-test").

These issues appeared and were recognized during reviews in almost every mission sponsored by PSD. The issues appeared regardless of the organizations involved, and occurred in both in-house NASA-developed missions, as well as contractor-developed missions. The resulting schedule impacts jeopardized the mission's readiness for launch, which often is a very hard deadline for planetary missions (different launch windows often have severe ramifications to the outcome of the mission). The resulting cost overruns impact NASA's ability to fund other missions.

Because of the pervasive nature of these issues, the deputy manager of Planetary Science Division and the Chief Engineer of the Science Mission Directorate recognized that there were likely systemic problem(s) that could be found to be the root cause(s). They also recognized that the problems could be technical and/or process oriented. To begin to address these issues, the Deputy Director of the PSD assembled a Steering Committee consisting of representatives from GSFC, MSFC, JPL and APL, and directed the Chief Engineer of the Discovery and New Frontiers Program Office to plan and implement a Fault Management Workshop. The direction given was to improve predictability and manageability in the design, test and operation of planetary spacecraft fault management systems. The workshop would pull together FM subject matter experts from government, industry and academia to discuss their experiences on low Earth orbiting and planetary missions and offer their perspective on solving these issues. To achieve a better understanding of the issues, the workshop would address questions like the following:

- How could the FM development and system-level testing processes be more predictable from a cost and schedule standpoint?
- What are the system level design or life cycle process aspects that drive FM changes late in the life-cycle?
- Are different FM approaches more or less susceptible to these issues?
- Are these issues occurring only on planetary missions or are similar issues happening on Earth-orbiters and/or in the human space flight program?

3. WORKSHOP GOALS AND SCOPE

The goal of the workshop was to document key findings and make recommendations to benefit future missions by avoiding the issues expressed in the previous section. By capturing the lessons learned from past missions through an honest and open exchange and documenting best practices that have been used across these missions, the intent was to assist current and future mission developers to minimize FM design and/or testing issues and thereby control schedule overruns and cost impacts. The approach taken to organize the workshop was to assemble key players in the spacecraft FM field across NASA, industry and other organizations to:

- Capture the current state of FM
- Expose the challenges associated with engineering and operating FM systems
- Identify and describe the issues underlying these challenges
- Discuss and document best practices and lessons learned in FM
- Explore promising state-of-the-art technology and methodology solutions to identify potential investment targets.

The programmatic scope of the workshop focused on deep space and planetary robotic missions since the observed challenges had all occurred on deep space missions. However, it was recognized that Earth-orbiting missions also suffered from similar symptoms, although perhaps to a lesser degree, and that there was sufficient overlap in FM architectures and V&V methodologies to warrant strong representation and participation from the EO community. The scope specifically did not include human-rated missions with the acknowledgement that these missions involved additional FM issues that typically are not required on purely robotic missions. However, members of the human spaceflight community did attend with the goal of understanding the issues uncovered during the workshop and

looking for lessons learned and best practices that are relevant to their missions.

The technical scope of the workshop focused on the portion of the spacecraft that handles faults. For the purpose of the workshop and this paper, we define Spacecraft Fault Management using NASA's ***Preferred Reliability Practices*** definition for Fault Protection:

> Fault Management (also known as Fault Protection) = *"Fault protection is the use of cooperative design of flight and ground elements (including hardware, software, procedures, etc.) to detect and respond to perceived spacecraft faults."* ***NASA NO.PD-EC-1243.***

Spacecraft Fault Management (FM) is a critical aspect of deep space missions. It provides the capability for the spacecraft to detect, isolate, and mitigate events which impact, or has the potential to impact, nominal mission operations. This capability may be distributed across flight and ground subsystems, impacting hardware, software and mission operations designs. It often is identified using different terms, such as Fault Protection, Redundancy Management, Health Management, Fault Detection/Isolation/Recovery (FDIR), and safing. In this paper, we use the term Fault Management to capture and represent all of these terms.

4. WORKSHOP ACTIVITIES

The NASA SMD/PSD Fault Management Workshop was held over 3 days (April 14-16, 2008) in New Orleans, Louisiana. Attendance at the workshop initially was limited in order to promote an interactive environment, but interest grew, and the final registration far exceeded the initial estimate: a total of 100 representatives from 31 organizations across government, industry, and academia (see Table 1). The attendees brought expertise derived from a wide spectrum of missions, both in terms of operations, duration and size, and functional roles.

Table 1. Participants and Missions represented at the SMD/PSD FM Workshop

Institutions	
NASA	Ames Research Center, Goddard Space Flight Center, Headquarters, Jet Propulsion Laboratory, Johns Hopkins University/Applied Physics Laboratory, Johnson Space Center, Marshal Space Flight Center, NASA Research and Education Support Services, Stennis Space Center
Other Government	Air Force Research Laboratory, Defense Advanced Research Projects Agency, Naval Research Laboratory
Academia	Carnegie Mellon University, Iowa State University, Massachusetts Institute of Technology, SRI
Industry	The Aerospace Corporation, AI Signal Research Inc., Ball Aerospace & Technologies Corporation, Bastion Technologies, The Boeing Company, Computer Sciences Corporation, Draper Laboratory, General Atomics, Inspace Systems, Interface & Control Systems, Lockheed-Martin, L-3 Communications, Northrop Grumman Space Technology, Orbital Sciences Corporation, Research Institute for Advanced Computer Science, Space Systems Integration, Universities Space Research Association
Missions	
Low Earth Orbit	Global Precipitation Measurement, Hubble Space Telescope, TacSat, Tropical Rainfall Measuring Mission
Deep Space Missions	Cassini, Dawn, Deep Impact, James Webb Space Telescope, Mars Reconnaissance Orbiter, Mars Exploration Rover, MESSENGER, New Horizons, STEREO
Other	Chandra X-ray Observatory, Constellation (Ares, Orion, Altair), Solar Dynamics Observatory
Functional Roles	
Engineers	Software reliability, spacecraft systems, software, technical supervisors, computer scientists, fault protection, avionics, project chief, system health management, fault management, control systems, systems and software chief, sustaining engineering
Managers	Program managers, V&V managers, flight system managers, section heads, group supervisors, division chief engineers, program integration managers, directors
Academia	Program director, professors

All attendees were expected to contribute to the workshop through presentations, posters, and/or active participation in the dialog during the breakout sessions. Participants were encouraged to identify technology issues and process issues that are driving unplanned cost growth and schedule growth in Fault Management system for unmanned, autonomous spacecraft today. The workshop participants also were tasked with capturing best practices to address those issues, as well as opportunities for investment to mitigate or possibly even avoid the issues on future missions. The workshop was not looking to produce a recipe or a set of standards. Instead, the goal was to rise above institutional preferences and evaluate the applicability, strengths, and weaknesses associated with the different approaches.

The workshop was organized five components: (1) case study presentations, (2) Request for Workshop Input (RFWI), (3) targeted round table discussions, (4) invited speakers, and (5) poster presentations. Current FM approaches and techniques were collected using the case study presentations and the RFWI responses. Thirteen case studies were presented that exposed issues dealing with in-flight anomalies, project FM flight experiences, project FM development experiences, and industry FM philosophy and approaches, as well as lessons learned from eight current or past missions. Attendees of the workshop were requested to provide responses to an RFWI describing the use of FM on projects at their institution. Breakout Sessions provided a forum for the targeted round table discussions to enable the participants to discuss the issues presented in the case studies on the previous day, and to suggest additional issues that were relevant to the Workshop. The goal of the Breakout Sessions was to distill the information to uncover the root causes of the issues. We invited three speakers from academia and one from the NASA community to present a different perspective on FM and some insight into future directions. Finally, the poster presentations provided an opportunity for the participants to explore emerging technologies and to discuss future opportunities for investments to improve fault management for future missions.

5. WORKSHOP RESULTS – FINDINGS AND RECOMMENDATIONS

During the Workshop, three key concepts emerged as central themes that are categorized as general observations. First, the implementation of FM within the software domain is generally similar across NASA, JHU/APL, and industry, and can be described at a fundamental level as an "alarm-and-response" system. See "General Observations on FM Architectures" in Appendix C for details on the similarities and differences noted between the architectures from the participating organizations. In an "alarm-and-response" system, the software monitors information from various on-board sensors for conditions that are out of specified bounds and responds to violations by sending a set list of commands designed to fix the problem. Low-level differences in software FMA implementation do occur, in particular in the areas of: how alarms and responses are represented and implemented; whether alarms and responses are arranged hierarchically or in a flat structure; and whether responses can be single or multi-threaded. Each difference represents a trade-off. For example, a multi-threaded approach ensures that the highest priority fault is dealt with first; however, it also allows responses to preempt other responses, which may lead to unexpected interactions that introduce new challenges when testing the system. Overall, the discussions within the groups increased overall understanding since participants could see the results of other organizations' trade-offs and implementations. More sharing of this type should be encouraged.

Second, there was general agreement that FM in current missions was not being limited by technology, but rather by a lack of emphasis and discipline in both engineering and programmatic dimensions. This is not to say that technology advancements related to FM are not required. Indeed, it was also generally acknowledged that current generation technologies and approaches such as rule-based systems are not expected to scale up to meet the requirements of future deep space missions. Regardless of this situation, it is felt that the problems of current generation programs must be addressed in order to enable any real technology advancement in this area.

Third, the in-flight performance of the FM systems on the projects that were represented at the workshop was deemed successful. Among the respondents, FM design flaws have not had an impact to mission success, though some false trips have resulted in unnecessary safing events. Some of the more complex systems did need a number of configuration changes. Most were attributed to deferred testing that uncovered errors during flight, but some reported needing updates in response to false trips.

Table 2 captures the key findings extracted from the Case Study presentations, the RFWI responses and the Breakout Session discussions. These findings are considered contributing factors to the issues identified in during the workshop, and introduce challenges when evaluating, designing, implementing and testing FM systems. Authors and presenters were extremely frank when sharing their experiences, with the understanding that the sensitive nature of the original materials would be respected. Therefore, supporting data have been sanitized to preserve confidentiality.

Table 2. Summary of Findings and Recommendations from the FM Workshop

#	Finding	Recommendation
1	Unexpected cost and schedule growth during final system integration and test are a result of underestimated Verification and Validation (V&V) complexity combined with late resource availability and staffing.	a) Allocate FM resources and staffing early, with appropriate schedule, resource scoping, allocation, and prioritizing. Schedule V&V time to capitalize on learning opportunity.
		b) Establish Hardware / software / "sequences" /operations function allocations within an architecture early to minimize downstream testing complexity.
		c) Engrain FM into the system architecture. FM should be "dyed into design" rather than "painted on."
2	Responsibility for FM currently is diffused throughout multiple organizations; unclear ownership leads to gaps, overlap and inconsistencies in FM design, implementation and validation.	a) Establish clear roles and responsibilities for FM engineering.
		b) Establish a process to train personnel to be FM engineers and establish or foster dedicated education programs in FM.
3	There is a lack of standard terminology of FM systems that causes problems in reviews and discussions.	Standardize FM terminology to avoid confusion and to provide a common vocabulary that can be used to design, implement and review FM systems.
4	There is insufficient formality in the documentation of FM designs and architectures, as well as a lack of principles to guide the processes.	a) Identify representation techniques to improve the design, implementation and review of FM systems.
		b) Establish a set of design guidelines to aid in FM design.
5	Metrics have not been established to evaluate the appropriateness or measure the lifecycle progress of FM systems.	a) Identify FM as a standard element of the system development process (e.g., separate WBS) to promote innovative solutions and realistic estimates of complexity, cost, schedule.
		b) Establish metrics and process specification with milestones that will allow proposal evaluators and project teams to assess the relevance, merits and progress of a particular FM approach.
6	a) Practices, processes, and tools for FM have not kept pace with the increasing complexity of mission requirements and with more capable spacecraft systems. b) Indications of potential spacecraft anomalies exist in test data, but are not always observed or not adjudicated.	a) Design for testability: Architectures should enable post-launch and post-test diagnosis.
		b) Examine all observed unexpected behavior.
		c) Implement continuous process improvement for FM lifecycle.
		d) Catalog and integrate existing FM analysis and development tools, to identify capability gaps in the current generation of tools, and to facilitate technology development to address these gaps.
7	The impact of mission-level requirements on FM complexity and V&V is not fully recognized.	Review and understand the impacts of mission-level requirements on FM complexity. FM designers should not suffer in silence, but should assess and elevate impacts to the appropriate levels of management.
8	a) FM architectures often contain complexity beyond what is defined by project specific definitions of faults and required fault tolerance. b) Increased FM architecture complexity leads to increased challenges during I&T and mission operations.	Assess the appropriateness of the FM architecture with respect to the scale and complexity of the mission, and the scope of the autonomy functions to be implemented within the architecture.
9	FM system is subject to changing priorities of cost and risk over the course of system development.	Define and establish risk tolerance as a mission-level requirement.
10	a) The bulk of existing FM systems (e.g., mission-specific monitors and responses) is not inheritable. Heritage, similarity and inheritance assumptions tend to underestimate budgeting for necessary V&V activities and review milestones.b) Current FM architectures do not support significant re-use.	Examine claims of FM inheritance during proposal evaluation phase to assess the impacts of mission differences.
11	Inadequate testbed resources is a significant schedule driver during V&V.	Develop high-fidelity simulations and hardware testbeds to comprehensively exercise the FM system prior to spacecraft-level testing.
12	Organizations have different and sometimes conflicting institutional goals and risk postures that drive designs, architectures and V&V plans in different directions, causing friction between customers and contractors.	Collect and coordinate FM assumptions, drivers, and implementation decisions into a single location that is available across NASA, APL and industry. Utilize this information to establish / foster dedicated education programs in FM.

6. FUTURE DIRECTIONS

A number of recommendations for emphasis or investment by NASA were discussed as part of the breakout sessions. These opportunities are summarized below, and organized along the three breakout sessions of Architectures, V&V, and Practices/Processes/Tools.

FM Architectures Opportunities for Investment

The following opportunities for investment are derived from the Workshop discussions of lessons learned and best practices for FM architectures. These opportunities represent potential solutions to gaps identified in current fault management architecture practice.

(1) Capture existing FM architectures and requirements on mature programs. Collect design drivers and implementation decisions in a repository to provide a resource that enables future fault management architects to make better trades. Such a resource could also be used as a learning tool for new missions and young engineers

(2) Develop and/or put into practice methodologies for more rigorous architecture specification, to enable formal architecture-level analyses and facilitate architecture review and pattern re-use

(3) Develop visual formalisms that facilitate FM architecture design and review, such that the FMA is understandable by system engineers and non-fault management domain experts.

(4) Articulate a comprehensive list of functional and non-functional properties for use as figures of merit in assessing FM architectures, and compile a mapping from architectural features to the functional and non-functional properties they promote (including examples of such features).

(5) Investigate architectures that inherently support rapid requirements-based testing early in the project lifecycle.

FM V&V Opportunities for Investment

The following opportunities for investment are derived from discussions to determine the lessons learned and best practices for spacecraft verification and validation. These opportunities represent potential solutions to gaps identified in the spacecraft V&V realm.

(1) Develop a means to confine complexity to testable units

(2) Develop an approach to establish complexity containment regions

(3) Develop an evolvable system model, capable of being validated by tests on flight hardware and software that is sufficient to be used for primary scenario and FM V&V.

(4) Develop a design environment/tool to capture desired system and FM behavior, which is capable of dynamically executing the behavioral model.

(5) Develop a tool to choose which subset of tests to run when exhaustive testing is infeasible

(6) Prioritize V&V actions with buy-in across the program

(7) Develop, maintain, and update tools to support the V&V process

- Tools to analyze test data in timely fashion
- Ops tools and ground tools
- Code coverage accomplished during tests
- Configuration management for testing
- Design-time test generation tool
- Tool to highlight high water marks
- Tools to specify and monitor safety properties through development and test
- Success trees and fault trees
- Software simulation

FM P/P/T Opportunities for Investment

The following opportunities for investment are derived from discussions to determine the lessons learned and best practices for FM Practices, Processes, and Tools. These can be grouped into "processes and tools" and "organization and training," each of which is summarized below.

P/P/T Processes and Tools — Processes and tools should be closely linked, but at this point it is apparent that more focus has been placed on the former in most organizations. Tool use was characterized as "viral" in nature – with good tools propagating between projects and organizations in an ad hoc manner as opposed to being standardized and specified relative to a overall desired process and workflow in the FM development process. Tool integration should be facilitated through work on common terminology/taxonomy, metrics, and interface specifications. In particular, there should be work to integrate "top down" requirements development tools such as fault tree analysis, with "bottoms up" design tools such as FMEA.

Complexity analysis tools should be developed for use in concept development and requirements definition. This would allow FM analysis to be incorporated into Pre-Phase A design centers, into mission costing models, and into various trade space evaluation processes. Ideally, tools would be available for behavioral modeling early in system design and these tools would link with FM design, implementation, and test tools. Finally, process templates should be developed that build upon this new class of tools.

It was felt that current knowledge across the community could be collected in an FM process template or handbook. Such as resource might specify different classes of mission with regard to their FM requirements and then define specific design guidelines for each.

Organization and Training — In the area of organization and training, there were two top-level recommendations. First, a recommendation for NASA to address the educational issues associated with establishment of a dedicated FM engineering discipline. This moves beyond the specification of a common taxonomy and set of metrics, to include targeted university programs and texts. The second recommendation is to begin bootstrapping a community dedicated the engineering and science of deep space mission FM. In some ways, this workshop may have served as a first step towards this goal.

Future Plans

Looking back on the original purpose for holding the workshop, we note the observation on multiple missions of an unplanned expenditure during spacecraft Integration and Testing to accommodate unforeseen or unplanned testing time for FM systems. To ameliorate this situation, the recommendations outlined in this paper propose ways to make FM systems a) more predictable in development, in cost, and in schedule, and b) more manageable by identifying work units that are do-able by engineers at a specified level of experience. In this section, we identify a number of potential paths to follow to implement these recommendations. In addition, we strongly recommend the following activities:

(1) Hold additional workshops to identify solutions to the issues raised. It was beneficial to bring the community together to share ideas. The first workshop concentrated on assessing the current state and uncovering the common issues. The next workshop could focus on options and solutions, and include those disciplines that were weakly represented such as Systems Engineering and Operations. Also, additional government and industry organizations should be included in these activities to expand the focus and view what is being done in other industries.

(2) Establish a NASA Working Group for Fault Management that will take ownership of the issues identified, and establish ways to mitigate them within the NASA governance. This Working Group should be populated by all of the NASA Centers that are affected by the FM issues captured in the NASA SMD/PSD FM White Paper.

Table 3 provides a summary of the Recommendations and proposed timeframes when each could be accomplished.

Table 3. Timeframes of Recommendations

	Near Term	Mid Term	Long Term
Taxonomy & Methodology Standardization	• Standard Lexicon • Fundamental Metrics • Standard Mission Types • FM Process Template(s)	• Refined Metrics & Performance Tracking • Process Standardization	
Technology & Tools	• Survey Current Tools • Survey Related Disciplines • Architecture Analysis • Complexity Analysis	• Design Specification & Review • Formal Methods for V&V • Cost/Risk Estimation	• Complexity Management
Training & Education	• NASA Training Courses • Coordinated Conferences	• Reference Handbook • University Programs	

7. CONCLUSIONS

This paper summarizes the findings and recommendations developed at the NASA SMD/PSD Fault Management Workshop, held in New Orleans on April 14-16, 2008. This paper provides the reader with the background necessary to understand the issues identified at the workshop, and documents lessons learned and best practices to assist future NASA planetary missions when planning, architecting, designing, implementing, and testing the Fault Management portion of a deep space system. The scope of this paper covers the motivation that inspired the workshop, the activities and events that took place during the workshop, the lessons and practices that were captured, and the resulting recommendations that emerged from the workshop. An emerging realization from the workshop is the high cost and risk of proceeding with "business as usual" in the area of fault management engineering. For a complete version of the NASA SMD/PSD FM White Paper, visit http://discoverynewfrontiers.nasa.gov/fmw_info.html.

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BIOGRAPHY

Dr. Lorraine Fesq is a Principal Engineer within the Engineering Development Office at JPL. She has over 30 years of aerospace experience that spans industry, government and academia, and has worked all mission phases of spacecraft development including technology research, requirements definition, systems design, hardware/software integration and test, launch and mission operations. Her research interests focus on spacecraft autonomy and the development of new technologies for analyzing spacecraft hardware malfunctions. Most recently, she served as the Technical Coordinator for NASA HQ's Planetary Spacecraft Fault Management Workshop which brought together for the first time over one hundred FM practitioners and experts in the field from across NASA, DoD industry, and academia.