THE TECHNOLOGIES OF AUTONOMOUS SPACECRAFT MAINTENANCE

Murray L. Elowitz and Bill C. Wong
System Data Processing and Operations
TRW Space and Technology Group
Redondo Beach, California 90278

ABSTRACT

Autonomous spacecraft maintenance (ASM) is the term used to describe the capability of a spacecraft to perform its maintenance functions without frequent, regular ground support and interactions. This new spacecraft attribute is needed to enhance the survivability and availability of our satellites, as well as to reduce operational support costs. This paper explains the concept of ASM as it has evolved. Generic requirements are given and explained for a latter 1980's capability. Spacecraft architectural changes are required, involving a mixture of technology adaptation and advances. Technology developments required to meet the requirements are identified and assessed. Significant advances are needed in system and subsystem technology areas to create a posture for building an ASM capability. With WWMCCS increasing reliance on spacecraft for both communication and sensor data, the issues of ASM are of vital importance to this community.

INTRODUCTION

Most contemporary operational spacecraft require regular and frequent interactions with their ground support stations to perform the spacecraft maintenance functions, which include (to varying degrees) stationkeeping, electrical subsystem management, configuration management, attitude stabilization, thermal control, orbit determination, TT&C, data storage, payload management and fault management. In operation, commands and data from the ground are needed by each spacecraft subsystem for it to perform these maintenance functions. This mode of maintenance requires that the ground station must continuously or frequently monitor the spacecraft. The two major concerns about the current mode of operations are:

a. that DoD’s spacecraft support facilities are vulnerable in case of conflict or crisis, thereby endangering the availability of the spacecraft to support military operations;

b. that the proliferation of operational spacecraft, spacecraft ground support equipment, ground support personnel, etc., make it increasingly costly to support operational spacecraft.

The alternative is to develop spacecraft which function with limited ground interaction. Autonomous spacecraft maintenance (ASM) is the term used to describe the capability of a spacecraft to perform its maintenance activities without regular and frequent ground support interactions.

In the special area of WWMCCS support, it is vital to the WWMCCS mission that all spacecraft assets remain operational in stress situations which arise. WWMCCS needs these spacecraft operating, even if ground support facilities are down or degraded.

This paper describes what the ASM capability is. It then discusses the technology areas required and the expectations for available technology to support a new development with ASM beginning in 1985.

WHAT IS ASM?

The autonomous spacecraft maintenance concept defines the spacecraft capability for operating with very limited and infrequent interactions with the ground support function. ASM is an added property of a class of spacecraft affecting system architecture, design and operations planning, which is built into the system from inception. This property is the capability to perform functions in the categories of operations, housekeeping and fault management, as shown in Figure 1.

Autonomous maintenance includes all the operations and housekeeping tasks that have to be performed onboard the spacecraft in order for it to function without any ground interaction. These include all the regular predictable tasks including those that only occur in certain seasons, such as pre-eclipse conditioning of batteries for a synchronous satellite. All these operations are currently performed either by ground support or a combination of ground support and spacecraft, with the ground having control. The largest technology advancement required for ASM is the addition of the ability to perform the fault management activities autonomously onboard the spacecraft.

Fault management is the capability to detect, isolate and remove faults in order to safeguard the spacecraft. These fault handling functions are present to some extent in most spacecraft, but usually for only the most important and dangerous failures. Autonomous fault management is a marked departure from current practice for operational spacecraft wherein the only kind of switching that occurs is done under ground command with the exception of certain “safe haven” type of actions which protect the life of the satellite from

those failures which threaten the spacecraft health. The area of reconfiguration or recovery means that the satellite must be able to follow its autonomous procedures for recovering from whatever failure may have occurred. This can be done with techniques such as switching in redundant components or changing to alternate modes.

The concept may be clarified by comparing the functions between current non-ASM spacecraft and the ASM versions, as shown in Figure 2. Both spacecraft would have an initial period of on-orbit checkout during which the ground has total control. At the end of this period, the spacecraft is considered ready for operational usage. Current programs rely heavily upon telemetry to monitor overall system performance. The health is measured by both direct and indirect means based primarily upon a limited telemetry list. The data received by telemetry are reviewed and analyzed on the ground including things like trend analysis to predict failures in special cases. It is under this ground control that decisions to command reconfiguration in the case of failures occurs. On the other hand, the ASM spacecraft must monitor its own performance and its own health. To do this, it will rely on more direct measurement of health by having many more individual sensors throughout the spacecraft. Data must be analyzed onboard the spacecraft and in the presence of a fault, switching of components must be commanded by the onboard fault monitor function of the spacecraft.

Requirements

The definition of ASM is best summarized as a set of generic requirements and constraints for its inclusion in a new operational spacecraft system. This set is explained further in Reference 1.

1. The ASM spacecraft shall operate for an extended period of autonomy of up to six months with not more than 10% degradation of performance.

2. The ASM spacecraft shall operate autonomously without ground support data for a regular period of up to sixty days with no degradation of performance.

3. ASM spacecraft shall be designed so that one ground track every 60 days is all that is required to meet existing spacecraft performance.

4. The ASM spacecraft shall be able to recover from failure modes which have been defined a priori; probability that a fault was defined a priori shall be ≥ 0.98.

5. If ASM fault isolation and recovery fails, the spacecraft shall protect itself and await ground support.

6. The ASM spacecraft shall meet the same design lifetime and reliability requirements as the comparable non-ASM spacecraft.

7. The ASM spacecraft and its payloads shall meet the same performance requirements as the comparable non-ASM spacecraft.

8. The spacecraft shall process and store sufficient onboard historical ASM data for ground support, and shall telemeter this data upon a ground command during any ground support period.

9. The ASM spacecraft will transmit a flag to the ground at the first opportunity following any onboard extraordinary activity.

10. The spacecraft shall accept ground support commands to override autonomous fault management activities for the system and the subsystems.

11. The ASM function shall be managed by the spacecraft in a hierarchical manner with the spacecraft at the highest level of decision.

12. The ASM spacecraft shall complete on-orbit checkout and initialization in the same duration period following launch as the comparable non-ASM spacecraft.

These requirements translate into the typical set of functions for a spacecraft as shown in Figure 1. To implement all these requirements, new capabilities will be required. An autonomous navigation function and a new or additional capacity for ASM data storage will be required. A fault tolerant central processor will host the added functions of spacecraft management and subsystem redundancy management. In general, the new spacecraft architecture will be much more heavily dependent upon data processing than current design.

System Impact

ASM will significantly alter the integrated space segment. Ground-space interfaces and functions will be altered and exchanged. The command link will routinely be dormant for long periods. Ground support of navigation will consist of intermittent tracking to reinitialize the onboard ephemeris if allowable error bounds are exceeded autonomously (e.g., every six months).

As envisioned, normal operations scenarios will use minimal crews who at times will be totally absent. During the nominal two months “no contact period” crews will prepare a new data load which will include all data necessary for the spacecraft to operate

autonomously for the next period. At the end of the “no contact period,” the ground station will uplink the new data to the spacecraft and it will downlink all status data and any ASM historical data of importance. New algorithms and analysis programs which will use the downlinked data must be developed to enable ground station personnel to determine spacecraft health..

If a “bellringer” message (indicates an abnormal event has occurred in the spacecraft) is received at the ground station, crews must decide what, if any, action should be taken. Rules and procedures need to be studied and defined. Decisions must be made, such as, should the spacecraft ASM logic be overridden or should no ground station action be taken?

If events prohibit the ground crews from performing the support tasks on schedule, the spacecraft will continue its autonomous operations. In general, some degradation of functions dependent on data load, such as navigation, can be expected.

ASM-RELATED TECHNOLOGIES

The development of an ASM capability will build on advances in many technology areas. For the purposes of this look at ASM, we assume a spacecraft program start in 1985. To be able to meet this start date, the spacecraft developer will require technology advances to be made to meet his needs between now and the program start. At this time the areas of need are identified. Table I is a summary of what we can expect in 1985. The last column gives a relative indication of the extent to which the ASM capability is the unique beneficiary of the technology advances. Using this column, technology efforts to support the ASM start can be targeted heavily to the ASM-unique items.

In the same years there will be technology advances supporting each of the spacecraft subsystem areas. In particular, there is a trend for more and more data processing in place of analog hardware. ASM-related technology must be compatible with these advances.

Data Processing Systems

ASM will be implemented as a highly digitized function which will take sensor data as inputs, process it to determine the system state of health and, when a fault symptom occurs, detect and isolate the fault; then execute recovery procedures. Data processing hardware is advancing rapidly and ASM will benefit in the areas of high throughput and memory capacity devices with low power and volume requirements. These are general advances available to designers of the ASM spacecraft.

Fault Tolerant Computing - The fault management strategy will depend on a reliable, fault tolerant computing element. A key principle that has evolved is that the fault-monitoring function must reside in a fault tolerant processor; i.e., highly reliable, internally redundant and self healing. Two computer manufacturers, Raytheon and Litton, have begun development of fault tolerant processors for spaceborne applications. Table II summarizes the characteristics of these computers. Both are developmental projects today. Areas of concern are radiation hardness, reliability and growth. The internal architectures are significantly different; Raytheon made a totally new design to utilize the latest CMOS/SOS LSI technology, and Litton has evolved an architecture based upon its LC-4516 series of production computers. Other manufacturers including Itek are also working on related products.

The fault tolerant central processor and its applications is a critical need for ASM. Spacecraft designers will be dependent on the availability of fault tolerant processors and are maintaining on-going efforts in this area including alternative approaches.

Architectures - An earlier study of data processing requirements for an ASM-type spacecraft performed at TRW indicated that the throughput required will exceed the capacity of the planned fault tolerant computers (Table 2). A more sophisticated architecture than a single fault tolerant computer will be needed for ASM. For example, independent, distributed processors may be used to provide adequate capacity for ASM sensor data handling and algorithm processing. Disadvantages of separate processors include the need to replicate each processor, memory and I/O for reliability, the introduction of hierarchical conflicts and complexity that is hard to test and verify.

A hierarchical architecture combining the fault tolerant central (higher) processor with distributed (lower) processors is called for. The lower processors monitor all sensors in the subsystem, determine health, control regular housekeeping functions (Figure 2) and report to the central processor. The central processor monitors the health of the processors, resolves conflicts between subsystems and regulates fault management activity. For example, battery conditioning may be inhibited in periods of high thermal power demands. In this architecture, the central computer needs to be a fault tolerant device, but the subsystem processors need not; they could be replicated for reliability and fault management. Part of the function of the central computer would be to monitor the health of the distributed processing elements, and control the configuration when needed.

The ASM data processing architecture must address the fault tolerance problem. Many fault tolerant implementations for digital system elements utilize active redundancy and voting logic. Efforts to date have looked at processing elements as individual spacecraft components, where methods such as TMR (triple modular redundancy) or nMR (n modular redundancy) serve to meet most mission needs. For ASM applications, more

sophisticated techniques are needed. Recent research into fault tolerant processors for ground-based systems (References 2 and 3) succeeded in reducing downtime and reducing system errors in the presence of a fault. Extension to the space environment and a mission of five to ten years is much more stringent, and requires continuing R&D.

An analysis of potential architectures to identify advantages and disadvantages and indicate the most promising of these examples and others is needed. Extensive technology development is required prior to 1985.

Software - Software development methodology is not seen as ASM-peculiar. Spacecraft applications require highly reliable software, and development can make use of techniques developed for other applications requiring high reliability, such as ballistic missiles. The new concept of fault tolerant software wherein coding errors or memory changes can be tolerated without loss of function is evolving from current research. At present, it is not known if usable techniques will result in time to support our hypothetical 1985 spacecraft start; the ASM technology development program should monitor advances in this area.

Spaceborne Navigation

Navigation is a basic element of the space system. An autonomous spacecraft will usually require an autonomous spaceborne navigation system. Today, there are a number of programs aimed at improving autonomous navigation without addressing the ASM concept. It appears that ASM will be able to utilize these products without direct involvement in the development, except to influence fault management aspects.

Fault Management

Autonomous fault management represents the highest risk area in ASM. Present technology is capable of performing certain automatic fault detection functions on the ground utilizing telemetry data. Critical fault detection and removal procedures, usually followed by the spacecraft going into safe haven mode, are performed autonomously where the designers felt the spacecraft could be in danger. ASM will require the a priori development of algorithms and procedures for fault detection, removal and recovery in most cases without entering the safe haven mode.

Strategies for utilizing measurements to monitor the health of spacecraft are needed. In its totality, however, the spacecraft contains complex interactions between components, functions, subsystems, etc. Contemporary ground stations utilize automatic data processing for identifying limit violations, illegal modes and similar conditions from telemetry, augmented by highly trained and skilled personnel. The fault isolation part of the problem

remains complex, requiring well-trained engineering personnel. Advances are needed to develop algorithms for fault isolation.

Before replacing a failed component of a spacecraft with an unfailed replica, precautions are needed to protect the replacement from the cause of the failure, e.g., over-voltage. Every precaution exercised by the ground support personnel will have to be paralleled onboard the spacecraft. Protocols and inter-subsystem controls need to be developed to avoid triggering chain failures. This technology area appears to be uncharted and essentially a new systems development area.

Systems Engineering

ASM represents a system attribute and must be built into the spacecraft from inception. Two key technology areas are testing methodology and spacecraft architectures. New methods are needed to test in the presence of autonomous fault management capability. The testing methods include simulation and stimulation of various fault conditions. An engineering design methodology which leads to testable ASM designs needs to be developed. Testing and test data processing (analysis) methodology also need to be developed. ASM represents a unique aspect to this technology. Increasing spacecraft complexity in the future will require improved approaches to overall testing methodology.

Spacecraft architectures will be strongly affected by the addition of the ASM function. The integration of fault management, ASM onboard data processing and navigation into the design will require new design methodologies to be developed. Many of the new developments will occur for other than ASM, especially the advanced digital processor capability. In another sense, spacecraft architecture represents specific project development vis-a-vis a general application technology. For ASM, an effort is needed to develop approaches to and requirements statements for architectures that best fit with the ASM function.

REFERENCES

1. Jet Propulsion Laboratory, CIT, Feb. 1, 1981, “Final Report of the Autonomous Spacecraft Maintenance Study Group,” JPL Publication 80-88.

2. Avizienis, A., October 1978, “Fault Tolerance: The Survival Attribute of Digital Systems,” Proceedings of the IEEE, Volume 66, No. 10.

3. Siewiorek, D. P., et al, October 1978, “A Case Study of C.mmp, CM*, and C.vmp: Part II - Experience with Fault Tolerance in Multiprocessor Systems,” Proceedings of the IEEE, Volume 66, No. 10.

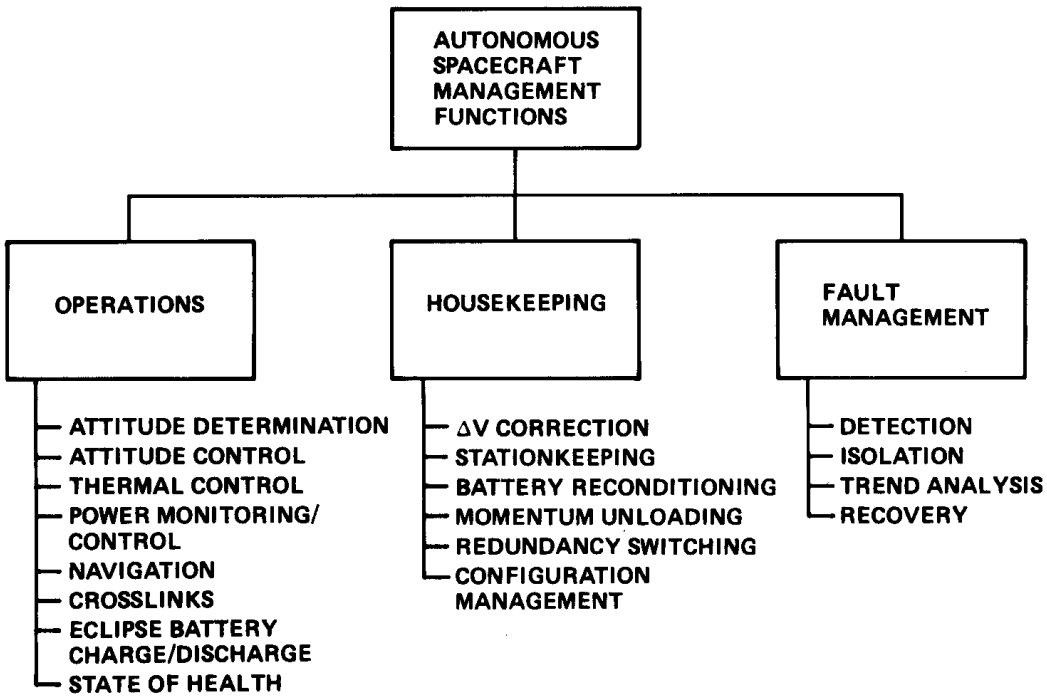

Figure 1. ASM Functions

CURRENT	ASM
HANDS-ON ON-ORBIT CHECKOUT	HANDS-ON ON-ORBIT CHECKOUT
PERFORMANCE MONITOR VIA TELEMETRY	SELF PERFORMANCE MONITOR
HEALTH MONITOR VIA TELEMETRY	SELF HEAL MONITOR
INDIRECT MEASUREMENT OF HEALTH -LIMITED TELEMETRY LIST	MORE DIRECT MEASUREMENT OF HEALTH -ADDITIONAL SENSORS INDIVIDUALLY MONITORED
DATA REVIEWED AND SWITCHING COMMANDED BY GROUND CREW	DATA ANALYZED AND SWITCHING COMMANDED BY ON-BOARD FAULT MONITOR
TREND ANALYSIS PREDICTS FAILURES	SOME TREND ANALYSIS POSSIBLE
SAFE HAVEN MODE	HIERARCHY OF RESPONSE UP TO SAFE HAVEN

Figure 2. Current Versus ASM Approach Summary

TABLE I. Spacecraft Technology Assessments

AREA	PRESENT STATUS	PROJECTED 1985 STATUS	ASM UNIQUENESS
DATA PROCESSING SYSTEMS			
HARDWARE	MEMORY AND THROUGHPUT INCREASING RAPIDLY, LSI AVAILABLE	LSI MATURE FOR SPACECRAFT, VHSIC DEVELOPING	LOW
COMPUTATIONAL POWER	LARGE SIZE CAUSES NEW PROBLEMS OF DESIGN, VERIFICATION	TECHNIQUES WILL BE MATURED FOR LSI; VERIFICATION GOOD, NOT PERFECT	LOW
FAULT TOLERANT	RAYTHEON EFFORT FOR DEVELOPING CENTRAL COMPUTER ENDING	UNCERTAIN	HIGH
	LITTON DEVELOPING OTHER APPROACH	NEED TO CONTINUE DEVELOPMENT	
ARCHITECTURES	MIXED CENTRAL/MICROPROCESSOR SYSTEMS BEING BUILT	MATURE	MEDIUM
	NEED TO DEVELOP FAULT TOLERANT FEATURES	NEED EXTENSIVE STUDY PROGRAM	HIGH
	FAULT TOLERANT BUSES INTERFACES BEING DEVELOPED	EXPECTED TO BE AVAILABLE	MEDIUM
SOFTWARE			
DEVELOPMENT TECHNIQUES	TECHNOLOGY FOR HIGH RELIABILITY DEVELOPMENT AVAILABLE MUCH MORE EXPENSIVE THAN GROUND SOFTWARE (PER INSTRUCTION)	MORE MATURE TOOLS AND TECHNOLOGY	LOW
FAULT TOLERANT	CONCEPTS EVOLVING; DEFINITIVE WORK IN PROGRESS	MAY BE DIFFICULT TO APPLY, NEEDS EXTENSIVE STUDY	MEDIUM
NETWORKING	BECOMING "COMMON"; STANDARDS ARE EVOLVING	STANDARD METHODS WILL BE AVAILABLE; PROBLEM OF FAULT MANAGEMENT NEEDS STUDY	LOW
SPACEBORNE NAVIGATION			
INSTRUMENTS	REQUIRED INSTRUMENTS ARE APPLICATION-DEPENDENT	NEED TO CONTINUE DEVELOPMENT	LOW
	THERE ARE A VARIETY OF STUDIES IN PROCESS	REDIRECT TO SUPPORT ASM	
COMPUTATIONAL	GROUND PROGRAMS TEND TO BE TOO LARGE FOR SPACEBORNE PROCESSORS	NEED STUDIES TO REDUCE REQUIREMENTS	LOW
SYSTEM INTEGRATION	AIDED NAVIGATION CONCEPTS WELL UNDERSTOOD	TECHNOLOGY NEEDS TO EVOLVE WITH ABOVE	LOW
FAULT MANAGEMENT			
FAULT DETECTION	COMBINATION OF ON-BOARD SENSING AND GROUND-BASED ANALYSIS; DRIVEN BY SAFETY	NEED EXTENSIVE DEVELOPMENT EFFORT FOR AUTONOMY	HIGH
FAULT ISOLATION	MOSTLY GROUND-BASED ANALYSIS	NEED EXTENSIVE DEVELOPMENT EFFORT FOR AUTONOMY	HIGH
FAULT REMOVAL	ON-BOARD CAPABILITY FOR SAFETY; OTHERWISE, GROUND-BASED	NEED EXTENSIVE DEVELOPMENT EFFORT FOR AUTONOMY	HIGH
FAULT RECOVERY	GROUND-BASED PROCEDURES ARE DEVELOPED	NEED EXTENSIVE DEVELOPMENT EFFORT FOR AUTONOMY	HIGH
SYSTEM ENGINEERING			
TESTING METHODOLOGY	AUTOMATIC FAULT MANAGEMENT LOGIC COULD MASK FAILURES DURING TEST	NEED TO DESIGN FOR TESTABILITY ENGINEERING; METHODOLOGY NEEDS DEVELOPMENT	HIGH
SPACECRAFT ARCHITECTURE	LIMITED ELEMENTS OF ASM FUNCTION, BECOMING MORE DIGITAL	ASM INTEGRATED INTO TOTAL ARCHITECTURE AND DEVELOPMENT IMPACT NEEDS STUDY	MEDIUM
GROUND SYSTEM ARCHITECTURE	DESIGNED FOR NEAR CONTINUOUS MONITORING AND CONTROL OF SPACECRAFT	NEED OPERATIONS CONCEPT STUDY	MEDIUM

TABLE II. Fault Tolerant Computers*

PARAMETER	RAYTHEON	LITTON
NAME	FTSC	LC 4516 FT.
WORD SIZE	32 SITS	16 SITS
TYPE	FIXED AND FLOAT	FIXED AND FLOAT
USABLE MEMORY	60 K	64 K (TO 265 K)
THROUGHPUT (GIBSON MIX)	200 KOPS	270 KOPS
WEIGHT	50 LBS.	36 LBS.
VOLUME	1,728 CU. IN.	721 CU. IN.
POWER	45-60 W	110W
DEVELOPMENT	FUNDED R&D	IR&D
AVAILABILITY	1985	1984
MISSION LIFE/RELIABILITY	5 YRS/.95	10 YRS/.98
HERITAGE	NEW	PRODUCTION + REDUNDANCY
REDUNDANCY LEVEL	CIRCUIT	FUNCTION

* BASED ON MANUFACTURER'S INFORMATION