Onboard Summarization and Spacecraft-Initiated Operations Technology

Task Leader

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Product Description

We will be working primarily in TRL levels 2-3 to produce prototype systems that enable the spacecraft to control *when* interactions with the ground will occur. Typically, this will be done through a combination of a low bandwidth signal (e.g. beacon) and telemetry, but the telemetry will be highly summarized onboard to minimize data analysis by ground operations personnel. This approach is currently being demonstrated on Deep Space One, but is only the first step in a roadmap for robust onboard data summarization technology. This form of adaptive operations is baselined for several upcoming deep space missions and has broad applications to earth orbiters and distributed systems. We propose to extend onboard summarization in novel ways to support Mission Data System missions and others, especially spacecraft with substantial onboard autonomy. In addition to playing a role in reducing cost, robust summarization technology is essential for also reducing mission risk.

The research in FY00 is approximately 80% technology push since the deliverables are new technology and the incorporation into MDS is just beginning. The main reasons why this work has not yet been incorporated into the MDS architecture are, 1) the MDS thrust through the beginning of CY99 has been to develop the control architecture more so than the telemetry management approach, and 2) the focus of our past research in this area was almost entirely focussed on successfully demonstrating an early version of this technology on the Deep Space Mission. Funding constraints and the dynamic replanning required when supporting a flight mission resulted in not much time being available to work with future customers.

This is continuing work because it uses deliverables made to the Deep Space One Beacon Monitor Operations Experiment as a starting point and also because we leverage the research interests of the team that has been built over the past two years. It is important to understand that new AI methods will be employed and new summarization products will be developed. We are not proposing to provide incremental improvements to software that has been previously developed. Instead, we intend to develop new capabilities for more autonomous systems and to leverage our lessons learned from experience flying summarization on a real mission. The table below highlights performance metrics for our research.

Metrics	Current Missions	MDS/Outer Planets Missions	Fleet Missions	Unattended In-Situ Explorers
Operations Team Size	>40	<10	<10 (entire fleet)	<<10
Routine Tracking Frequency	>12 hrs/wk	4-8 hrs/month	Event-driven Only	None
Onboard Fault Recovery	0-25%	50%	75%	90+%
Onboard Summarization Applicability	None	Cruise Operations	Routine Operations	Entire mission

Benefits

This work should be funded because it his highly relevant to stated NASA technology goals and future mission needs and is the only known work in this area within NASA. Benefits from this technology fall into four major categories: 1) cost reductions in mission operations, 2) mission risk reduction, 3) decreased loading of the overconstrained Deep Space Network, and 4) increased science return for some missions. The exact cost savings is mission-specific and depends on many factors, such as spacecraft operability, mission duration, and the mission risk policy. The above-mentioned savings, however, are real and measurable and can easily be estimated for any mission considering this technology. Typically, missions can use this approach to cut telemetry tracking from daily to weekly, or weekly to monthly. Spacecraft-initiated signaling can also reduce mission risk, make up for shortcomings in spacecraft link margin and overall operability that are common in today's faster, better, cheaper missions. Onboard summarization can reduce operations staffing by half or more by decreasing the time spent analyzing bulk telemetry. Decreased antenna loading is a cost savings to the flight project if full-cost accounting is used and when proposing a new mission. This is also quite valuable to the Deep Space Network because there is a large oversubscription of these NASA resources.

The proposed research does not directly compete with other technology development efforts. Our products are based on AI methods for fault detection and automated data analysis, of which there are many available techniques. However, we do not view other analysis methods as competition, but rather potential methods that can be leveraged for future onboard data summarization systems. Our technology is unique in that we have designed our software to date, and plan to continue designing it such that the software design is amenable to incorporating other known methods for automated data analysis. Indeed, other methods will be investigated in FY00 for possible inclusion into the summarization system design. There is no other known work in our area, which consists of developing and applying automated data analysis methods for the purpose of summarizing spacecraft telemetry and developing associated operational concepts for spacecraft-initiated operations.

Technical Approach

We plan to develop advanced methods for onboard engineering data summarization and the associated operational concepts for deep space missions. In addition, we will also be developing summarization prototypes that address monitoring requirements for fleet systems (rovers or spacecraft). Throughout the planned life of the project we will also continue to maintain our ties to the earth orbiter community to support efforts in leveraging our technology development efforts to create lower-cost methods for operating earth orbiters.

We plan to use the lessons learned from the DS1 Beacon Monitor Operations Experiment, but not the actual software, as a starting point for doing the proposed work. A novel software architecture will be developed that is integratable into MDS deliveries. We will work closely with MDS to deliver deployable technology products that can be used by MDS customers who have baselined our operational concept and have requested our technology products. The emphasis in the new software will be in summarizing autonomous system behavior to a sufficient degree to provide the necessary information to ground operators for troubleshooting unexpected events or otherwise to summarize system behavior to provide assurances that the spacecraft is functioning as expected. Tighter integration of spacecraft fault protection approaches to the summarization system is needed and will be developed to maintain consistency in anomaly detection and reporting. For autonomous systems, it is also critical that the summaries capture the exact sequence of actions and relevant information around the time of episodes since these insights into autonomous system behavior are not available in normal telemetry. In general, the emphasis of our research in the coming year will be to develop summarization concepts and prototypes for MDS flight systems with a greater degree of onboard autonomy than what missions are currently flying.

To understand our future directions, it is important to describe the current status of onboard summarization technology development. Software previously developed for use on DS1 determines the culprit and causally related sensors for episodes encountered since the last downlink and stores the relevant sensor data at a high sample-rate. Low-sample rate data is gathered to "fill-in" the gaps between episodes and high-level spacecraft state and mode summaries are also generated. The software currently employs two AI methods, one providing the ability to use adaptive, or learned alarm limits via the ELMER (Envelope Learning and Monitoring using Error Relaxation) technology and the other is the use of empirical transforms that have heritage in AI research at JPL in selective monitoring. For DS1, ELMER training was performed on the ground. For future missions, more precise anomaly detection will be achieved if ELMER training is performed onboard. This task will investigate the feasibility of putting neural net capabilities onboard the spacecraft for determining ELMER adaptive limits.

In the coming year, our research will involve investigations into model-based methods for capturing causal relationships among sensors onboard, advanced methods for anomaly detection using ELMER (Envelope Learning and Monitoring using Error Relaxation) and evaluation of another JPL-developed technology product called BEAM that is currently being targeted at ground applications. New empirical and possibly model-based transforms will be developed based on lessons-learned from DS1 flight experiences. The new software design will be partially derived from the "technology components" just described. The flight software products developed under this research will benefit from the substantial software system engineering lessons learned from developing flight software for DS1. Additionally, the strong research base in AI should enable deep understanding of the technical issues associated with deploying more autonomous flight systems, such as is being developed for MDS. Ground tools will also be developed, and serve as a practical means for viewing data as well as precursors to possible automated diagnosis of summary data at a later date. Ground visualization and automated diagnosis of summary data is a rich area for further research and will be evaluated in FY00 for possible inclusion in FY01 deliverables. Advances in beacon signaling software go hand-in-hand with advances in onboard summarization techniques. Increasing the ability of the spacecraft to assess it's own state have direct benefit to reducing mission risk by performing more intelligent spacecraft-initiated signaling. In FY00, we will also be delivering advanced beacon signaling software that is tightly coupled with event detection methods used for determining events in onboard summarization software. The table below summarizes the key capabilities that will be developed over the next two years. Progress will be made in each of these areas in FY00.

Key Capabilities	Current State-of-the-Art	After FY01
Long-range archive capability	Does not exist	Created and maintained automatically onboard
Long-term trending	Ground-based	Autonomous, onboard
Sensor causal relationships	Engineered manually by humans	Computed and updated automatically onboard
Summarization of fleet behavior	Does not exist	Entire fleet behavior summarized in a single downlink
Summarization transfer among fleet elements	Does not exist	Efficient knowledge sharing among fleet elements
Summarization/fault protection I/F	Mostly decoupled or non-existent	Tightly integrated
Threshold detection	Mostly static alarms	Adaptive alarms that are inherently mode-sensitive
Training of adaptive limits	Ground-based	Onboard
Transform capability	Empirical and mostly ground-based	Empirical and model-based, computed onboard

We plan to leverage the JPL Autonomy Lab and the Flight System Testbed for developing software components and making them available to MDS and mission customers. We will also leverage other Thinking Systems tasks, including research under Tony Barrett and Dennis Decoste. A potential collaboration with NASA ARC will be investigated for using the Livingstone engine as a ground tool for automatically diagnosing the significance of dowlinked summaries to focus operator attention.

Status and Milestones

This work follows the successful execution of the DS1 Beacon Monitor Experiment. We have just achieved 100% validation of the onboard summarization and tone monitoring systems. This experiment has afforded us tremendous lessons learned. Developing research products that actually fly on a mission enables creation of highly practical new technology components. We've learned how to system engineer new software technology for flight and have resolved many challenging, yet generic, technical issues that enable us to provide more reliable software products for less cost in the future. Being involved in the spacecraft design process, operations planning, and in actual operations have been incredibly valuable in understanding the major cost drivers in both design and operations. We have capitalized on the high-payoff items and can re-apply this knowledge on MDS and other missions. In short, flight experience has enabled us to create technology products of much higher value than would have been possible if just developing a prototype and we can now carry this insight into future endeavors.

Another key milestone has been the decision by the DS1 project to use our experimental system to the extent possible in the planned 2-yr extended mission. The system will be used to perform tone tracking instead of 4-hr carrier/no-carrier tracking to check spacecraft health. Spacecraft-selected tone monitoring reduces risk over carrier/no-carrier tracking. The DS1 project also plans to scale-back weekly 8-hr telemetry tracks, using both the beacon and summarization to reduce workload on flight project staff. In making this decision, the DS1 mission has shown that our approach to operations is both viable and valuable.

FY00 Milestones:

- Trade studies on potential summarization methods
- Summarization software design for inclusion into MDS
- Prototype 1: Summarization software prototype
- Prototype 2: Onboard long-term summary archive proof-of-concept prototype
- Design for ground tools for automated diagnosis and visualization of summary telemetry
- Early fleet operations concept

FY01 Milestones:

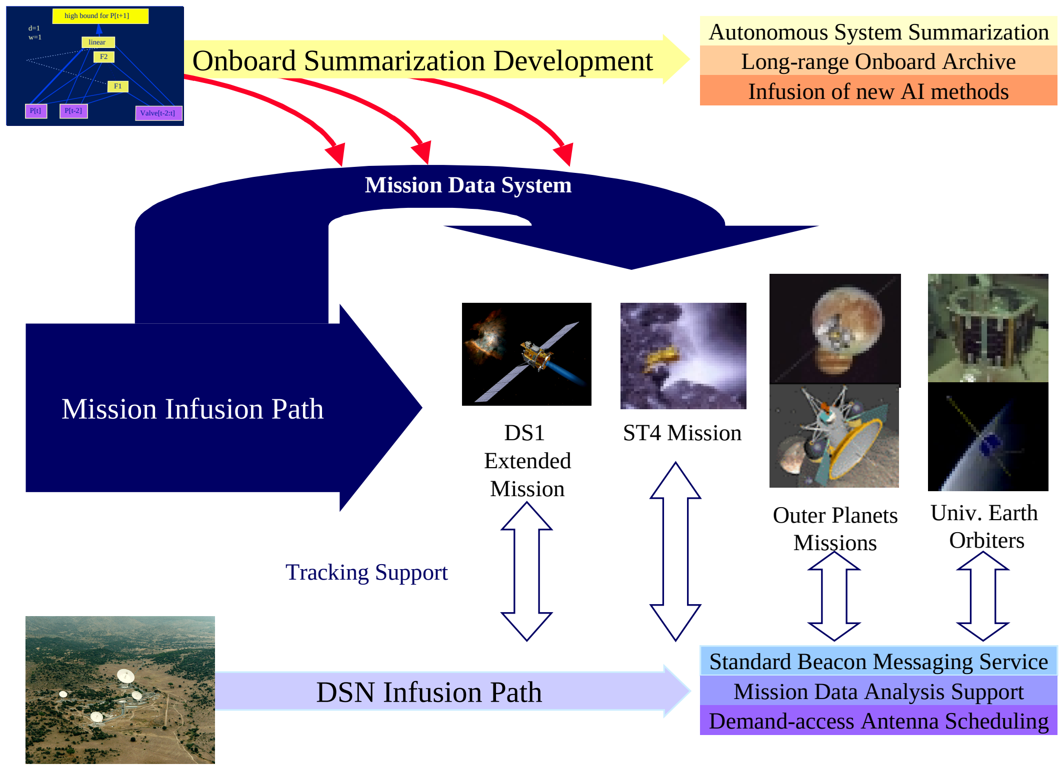
- Delivery to Europa Mission in November 2000 (current date for major MDS delivery to Europa)
- Upgrades to onboard summarization software
- Prototype ground tools for automated diagnosis and visualization of summary telemetry
- Proof-of-concept prototype for fleet summarization (inter-fleet data sharing + downlink summarization)

Customer Relevance

This research applies to the Space Science, Earth Science and HEDS since methods for automated summarization of data has broad applications. The table below shows the relationship to NASA enterprise technology goals:

NASA Enterprise	***Level 1 Technology Requirements***	***Relevance of summarization and Spacecraft-initiated communication***
Space Science	S2 Structure & Evolution of the Universe	Relevant to inter-spacecraft communication for formation flying
	S3 Exploration of the Solar System	Responds to operability, communications, and possibly in-situ requirements
	S4 Sun-Earth Connection	Part of autonomous, survivable spacecraft systems
Earth Science	E2 Sensor Webs	Facilitates transfer of information bewteen spacecraft
	E3 Access to knowledge	Spacecraft technologies for data delivery
	E4 Information Synthesis	Fault detection, adaptive learning, and neural net
HEDS	H1 Autonomous Operations	Intelligent agent for facilitating human reasoning about fault conditions

The technology is now baselined on the Europa mission, Pluto mission, ST4, and discussions are ongoing on how to best incorporate it into MDS. Endorsements of the technology have been obtained from Outer Planets/Solar Probe Program, DS1, the University of Colorado, Stanford University, and Santa Clara University. All of these organizations plan on directly using our products or leveraging our research for their space missions. Currently, key individuals representing ten missions have endorsed this research. The figure below shows the basic roadmap for the summarization technology (top portion), along with the mission infusion path and ground support infrastructure.



Collaborations with the University of Colorado, Stanford, Santa Clara University, and NASA GSFC will serve to transfer lessons learned and in some cases, technology products into earth orbiter missions. These universities have both adapted our operational concept to earth orbiter missions. It is important that the conduit between our work and university research continue and it is imperative that this relationship also be extended to include GSFC so the technology can be infused into NASA earth orbiter missions. We believe funding collaborations through this program and our task is the best way to nurture these inter-center and university collaborations.

Dialog is ongoing with the following organizations and key contacts are listed along with topics being discussed:

- Outer Planets Program (John Carraway): Plan to use our technology on Pluto, Europa and Solar Probe missions and have levied requirements on MDS to support both summarization and beacon signaling software that we are developing
- Mission Data System (Bob Rassmussen, Dan Dvorak, Al Saks): Discussions have started on how to incorporate our products into MDS deliveries.
- Deep Space One (Phil Varghese): Baselining onboard summarization and spacecraft-initiated signaling to decrease extended mission risk, staffing cost, and telemetry tracking.
- ST4 (Polly Estabrook): Require spacecraft-initiated signaling due to operability constraints during the mission

- JPL Telecommunications and Mission Operations Directorate (Chad Edwards and others): Co-funded development of the DS1 experiment and plan to deploy a tone detection system as an operational service in time to support Europa and Pluto missions.
- Applied Physics Lab (Bob Bokulic) – discussions ongoing to apply our adaptive operations technology to the Contour mission to receive assurances of spacecraft health during a 6-year mission in which the spacecraft is mostly dormant. APL is also interested in providing a tone detection service for use on their missions
- University of Colorado (Elaine Hansen) – longstanding relationship sharing experiences in developing adaptive operations technology which they have successfully adapted to earth orbiter missions
- Stanford University (Bob Twiggs) – adapting spacecraft-initiated operations and summarization to their earth-orbiter missions
- Santa Clara University (Chris Kitts) - adapting spacecraft-initiated operations and summarization to their earth-orbiter missions
- NASA Goddard Space Flight Center (Bob Connerton) – discuss inclusion of summarization into New Millennium and other earth-orbiter missions
- NASA Johnson Space Center (James Ortiz) – conduct periodic informal collaboration and discussing partnering between our research in summarization and the JSC Operator Assistant project for space station monitoring.

Technical References

http://eazy.jpl.nasa.gov/beacon Web page contains recent presentations and papers on current research into adaptive operations and onboard summarization

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