Using Model-Based Reasoning for Autonomous Instrument Operation – Lessons Learned from IMAGE/LENA

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Abstract

Model-based reasoning has been applied as an autonomous control strategy on the Low Energy Neutral Atom (LENA) instrument currently flying on board the Imager for Magnetosphere-to-Aurora Global Exploration (IMAGE) spacecraft. Explicit models of instrument subsystem responses have been constructed and are used to dynamically adapt the instrument to the spacecraft's environment. These functions are cast as part of a virtual Principal Investigator (VPI) that autonomously monitors and controls the instrument. In the VPI's current implementation, LENA's command uplink volume has been decreased significantly from its previous volume; typically, no uplinks are required for operations. This work demonstrates that a model-based approach can be used to enhance science instrument effectiveness. The components of LENA are common in space science instrumentation, and lessons learned by modeling this system may be applied to other instruments. Future work involves the extension of these methods to cover more aspects of LENA operation and the generalization to other space science instrumentation.

Introduction

Multiprobe missions are an important part of NASA's future. Consider the missions of the Sun-Earth Connections (SEC) theme, which include missions such as Magnetospheric Multi Scale (MMS, five spacecraft, launch 2006) and the Magnetospheric Constellation Draco (50-100 spacecraft, launch 2010). Members of NASA's Solar Terrestrial Probe line, these missions are part of a series of technologically ambitious projects that build towards the placement of a distributed sensor web that can accurately measure the mesoscale structure and dynamics of Geospace. Geospace is the region of space wherein the Sun and Earth interact to produce Space Weather. To make such missions robust, reliable, and affordable, ideally the many spacecraft of a constellation must be at least as easy to operate as one spacecraft is today.

This level of performance is to be achieved in spite of full suites of scientific instruments, limited communication opportunities perhaps separated by weeks, and limited ground operations resources. Downlink bandwidth limitations reduce the coverage and resolution of the science products that missions may produce. Furthermore, understanding many important phenomena requires

simultaneous measurements from multiple spacecraft. Operations techniques that require communication with the ground incur communications latencies and suffer bandwidth limitations that inhibit a mission's ability to react to science of opportunity, to coordinate collective behaviors across the constellation, and to deal with faults.

The advantages of spacecraft autonomy have been perceived for some time, and for early missions such as Ranger 6 [1] and the early Mars and Venus Mariners [2] an amount of autonomy was a matter of course due to low communication rates and limited commandability. Advances in space borne computers and communications technology led to spacecraft that could more readily be configured and commanded. Part of this trend has continued as computer technology has presented opportunities first to automate, and then to add flexibility and fault tolerance to different segments of the mission [3]. Increasing numbers of increasingly complex spacecraft have led to the recent study and application of even more sophisticated approaches.

One recent approach that is relevant to science missions is the Remote Agent Executive (RAX) experiment that operated Deep Space One with some success during an asteroid flyby [4]. One module of RAX maintains a set of models that correspond to spacecraft systems and makes plans and resolves conflicts by reasoning based on these models [5]. A key driver of RAX resource requirements is the complexity of constructing mission plans that maintain system constraints. One way to reduce this complexity is to delegate responsibility for operation to spacecraft subsystems, leading to the concept of subsystem or instrument-based autonomy [6].

To reduce the complexity of the problem we feel it best to aggressively attack and reduce system complexity at each level of a system's hierarchy. Reducing system complexity at the lowest levels may dramatically reduce the complexity of the overlying control functions. This eases the burden of spacecraft level autonomy, e.g. at the level of a spacecraft agent like RAX. By moving instrument operations as far to the instrument as possible, including the autonomous production of data products, communication resource requirements can be dramatically reduced while at the same time dramatically improving the quality and quantity of the science obtained [7].

We have tested these ideas in the context of the Low Energy Neutral Atoms (LENA) experiment that is flying on the Imager for Magnetosphere-to-Aurora Global Exploration (IMAGE) observatory [8]. IMAGE is a NASA/SEC mission designed to obtain a global picture of the Earth's magnetosphere using a variety of remote sensing techniques. LENA, being a particle detector, can be impaired or may fail because of excessive particle fluxes or environmental radiation [9]. We have constructed an explicit model of LENA's response. The instrument uses this model to dynamically adapt its response to autonomously maintain instrument health and safety and improve science return. We call the reasoning system that uses the model to determine how to configure LENA the Virtual Principal-Investigator (VPI) because of the responsibility it holds for instrument operations. By implementing these functions at the instrument level, it was possible to bring these advanced behaviors into the very constrained computing environment of the LENA Flight Model. Furthermore, these enhancements were realized with no deleterious impact on other IMAGE systems.

In this paper we are focusing on a proposed approach to achieve autonomy for scientific instruments. We begin by considering some autonomy options and by presenting an overview of the model-based approach to autonomous instrument operations that is currently under investigation. Then we discuss the application of these ideas to LENA followed by a discussion of lessons we have learned during the work. We close with a discussion of challenges to generalizing our model-based approach to other instruments.

Model-based Autonomous Instrument Operations

The focus of this paper is on future autonomy for spacecraft instrument operations. A current study, reported on in this paper, focuses on a model-based reasoning approach to instrument autonomy and its application to the autonomy of the LENA instrument on the IMAGE spacecraft.

Figure 1 depicts the major concepts associated with this study. The basic idea is quite straightforward. The ground-based Principal Investigator (PI - we use PI both in a singular and collective sense) has a mental model on the instrument and its designed behaviors, inputs, outputs. This model is formalized and codified and becomes the model that an onboard intelligent process uses to guide the operations of the instrument and to aid in diagnosing instrument faults and taking corrective actions. From our perspective and in our LENA-related work a model is some representation of reality that is used to support an understanding of that reality and to make decisions about the behaviors associated with that reality. As Kaposi and Meyers [10] put it: "A good model is not an arbitrary representation, but a systematic, purposeful simplification of its referent. Such a model focuses attention on selected attributes which hold the key to the solution of the given problem and suppresses features which, for the given situation, are less crucial or irrelevant."

There are several ways to deal with models. Three major classifications of use are:

- Internal representation (model embedded in code as a procedure). In this case the model is implicit, thus difficult to readily modify or adapt.

- External representation (model expressed in an external knowledge representation processed by some procedural code). In this case the model is explicit and thus easily modified or adapted to a changing environment.

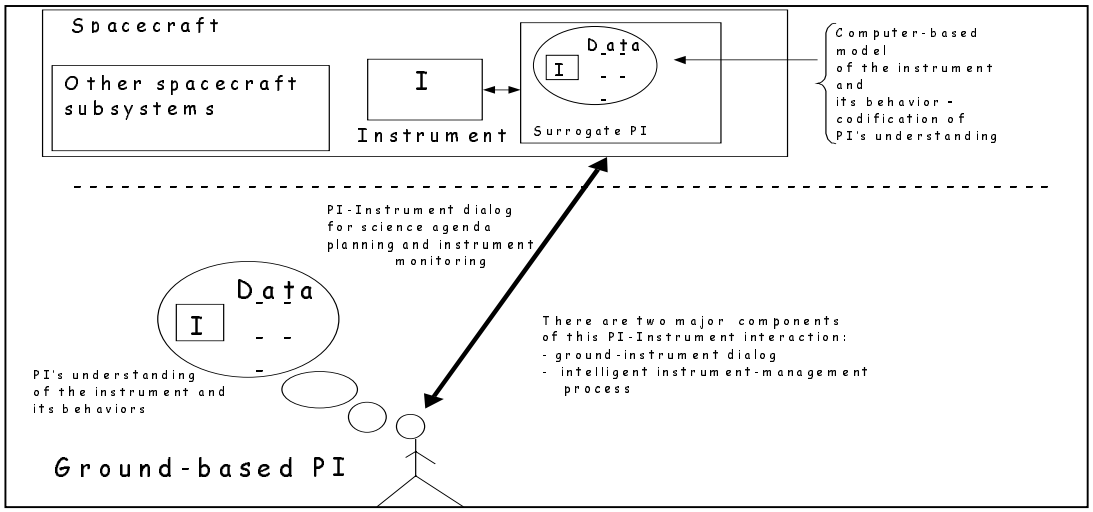

Figure 1 – Major Autonomy Concepts

- Hybrid representation (a combination of the two).

In this phase of the LENA modeling work, use has been very successfully made of the internal representation approach resulting in on-board software automating various LENA functions. The intent is to graduate to the external representation approach. The following section will discuss what we have achieved so far in applying this autonomy concept to LENA.

Model-Based Reasoning Applied to IMAGE/LENA

The IMAGE observatory is a spin-stabilized spacecraft that was launched in March 2000 into an elliptical polar orbit with an apogee altitude of 7.2 earth radii (45,922 km) and a perigee altitude of 1000 km. It is the first satellite dedicated to imaging earth's magnetosphere. LENA, one among the suite of 6 instruments on the payload uses high-voltage electrostatic optics and time-of-flight mass spectroscopy to image fast neutral atom flux and measure its composition and energy distribution.

LENA Implementation

Simulated particle trajectories are plotted in Figure 2.
Neutral particles (1) enter the instrument through a collimator (2) which filters charged particles. The tungsten surface (3) converts neutrals to negative. Negative ions from the surface are then collected by the extraction lens (4), which focuses all negative ions with the same energy to a fixed location. The ions are then accelerated by a high voltage optics potential prior to entering the electrostatic analyzer (5). Finally, the ions pass into a time-of-flight/position sensing section (6) where ion mass, energy, and angle are determined [11].

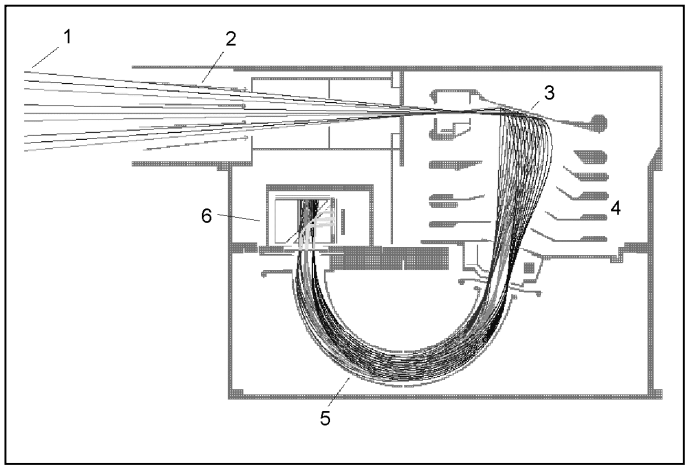

Figure 2 – Neutral Atom Ray Tracing

The electrostatic potentials required to conduct the experiment are derived from 5 commandable high-voltage power supplies: 2 collimator supplies, an ion optics supply and 2 microchannel plate (MCP) supplies. These supplies and the TOF subsystem are controlled by an 8-bit 8051microcontroller-based command and data handling system.

The 8051 executes all data processing. Throughput is less than 1 million instructions per second (MIP). Code space is 32 kbytes and data space is 64 kbytes. These constraints strongly influence the autonomy strategies and realizations implemented onboard.

IMAGE is operated as a lights-out mission—the spacecraft is out of ground contact except for once during each 14.2-hour orbit. To support this operations paradigm, the IMAGE central instrument data processor permits queued commands to be routed to LENA at predetermined times. This allows the instrument to be configured in response to predictable conditions. It is important,

however, that LENA also have the capability to react immediately to conditions that could threaten the health and safety of instrument systems—autonomous real-time command capability.

Autonomous Operations Virtual Principal Investigator (VPI)

The ground-based PI's ability to configure the instrument in response to dynamic conditions is hindered by limited observability of LENA parameters. The downlink bandwidth allocated to LENA renders it unfeasible to telemeter parameters at a sample-rate high enough to ensure that transient behavior will be captured. Communications latency further constrains real-time responses. We address these issues by conveying a subset of LENA's command authority from the ground to a Virtual Principal Investigator (VPI) onboard the instrument (Figure 3).

The VPI provides the capability to respond in real-time to predicted (e.g. radiation belt) and random (e.g. solar storms) conditions. Actions that can be initiated onboard are consistent with the command authority granted by the ground-based PI (Table 2).

The VPI is primarily tasked with monitoring and controlling three critical LENA behaviors: instrument over-stimulation, high-voltage health and safety and radiation-belt induced collimator effects. Potentially damaging event rates could result from high-flux environments. They could also be indicative of high-voltage discharges that could degrade electrostatic surfaces and damage electronic components. In either case, the start or stop channel gains must be reduced to limit the resultant count rates. Operation of the high-voltage systems is also monitored. The status of each high-voltage supply is thereby derived. The state of the electrostatic surfaces can also be indirectly inferred since excessive currents or unregulated voltages may be indicative of anomalous conditions on these surfaces. Control of these behaviors is granted authority level I.

Table 2 – Onboard Authority Level

Authority Level Granted	Reasoning Locale	Possible Onboard Actions
I	onboard	Initiate commands Inform ground of actions taken
II	Onboard/ ground	Submit recommended actions to ground
III	ground	none

The VPI operates within a model-based framework. The behavior of the instrument is decomposed into a family of behavioral models with each model mapped to a subsystem. A model captures the electrical response function of the targeted system. The models are typically excited with the same stimuli as the systems they represent. The resultant responses are routed to the VPI, which considers whether the current instrument state is desirable, and if not, initiates corrective actions.

High Voltage Power Subsystem (HVPS). The HVPS models incorporate components of varying complexity. The degree of complexity is consistent with information the VPI requires to ascertain and control the state of system. A first-order polynomial appropriately codifies the voltage response of the HVPS to commands. Power supply currents, however, are not accurately predicted over the operations range of the power supplies because of disturbance effects and component variations that are not modeled in LENA's present implementation. Therefore the VPI uses simple current threshold tests to verify this aspect of HVPS operation. Each power supply current is appropriately modeled as a constant range (Figure 4).

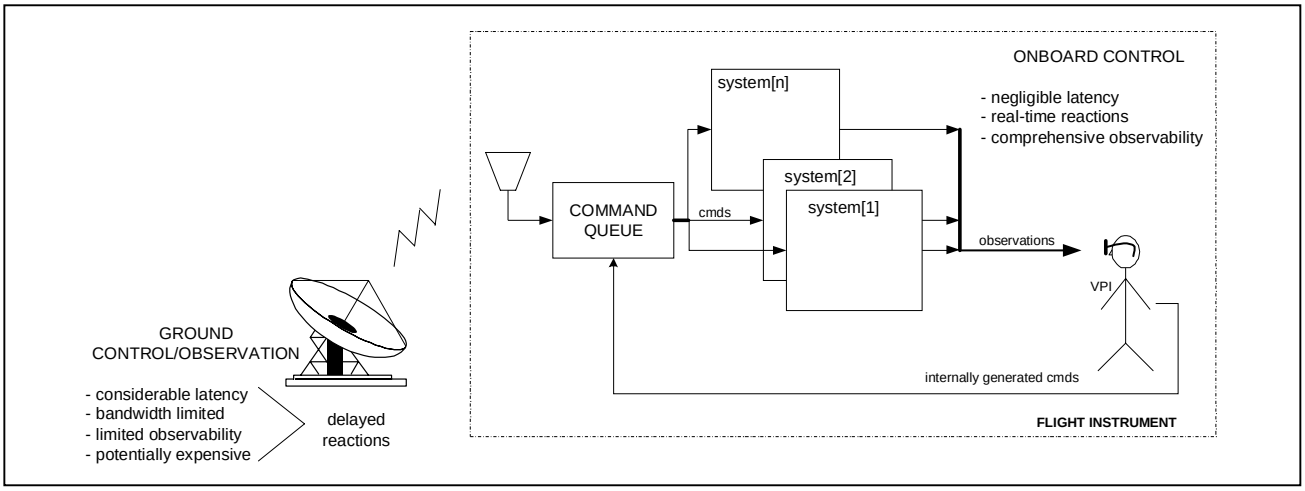

Figure 3 – Ground Based vs. Onboard Control

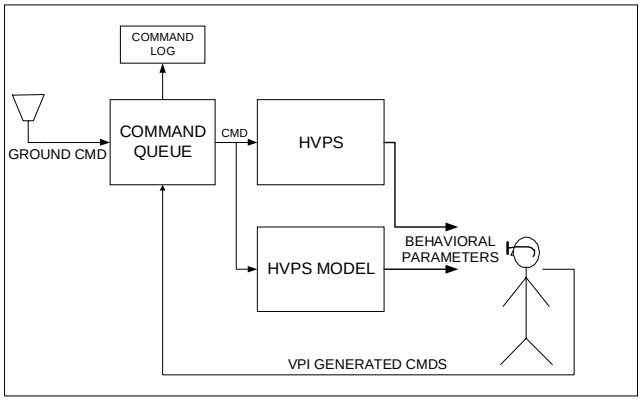

Figure 4 - Virtual-PI HVPS Control

The VPI uses the model outputs to maintain or correct the state of LENA. Measured and modeled parameters are updated and reaction commands are executed on a time-scale consistent with the dynamics of the targeted system and the control objectives of the VPI. For example, HVPS reasoning is implemented as follows: compare the voltage response of the power supply with the expected response. If the deviation exceeds P_1 volts for longer than P_2 seconds, take P_3 action. Here, P_n are parameters that can be varied under ground control. Furthermore, compare measured currents and voltages to the threshold levels P_4. If a threshold is exceeded for longer than P_5 seconds, take action P_6, where again P_n are ground commandable parameters.

Time of Flight (TOF) Subsystem. Overstimulation of the start or stop MCP channels can compromise the TOF system. Excessive rates could result from the periodic radiation passes or from energetic solar ions.

The effective gains of the TOF channels are proportional to the MCP-start and MCP-stop potentials. While science return is maximized when these voltages are at their nominal levels, high count rates are also likely to occur. The goal of the VPI is therefore to maximize nominal-level operations, but reduce voltages as required to maintain instrument health and safety.

Time-tagged commands could be used to decrease the gains during the periodic radiation passes. The drawback of this approach, however, is that count rates cannot be predicted as a function of time with great accuracy. Therefore, fairly conservative time boundaries are typically used to define when instruments should safe themselves. This approach compromises science return.

A more robust approach is to react directly to count rates. Gains are reduced only when required. This approach has the advantage of not only reacting to events that result from the periodic radiation encounters, but to unpredictable energetic particle events as well.

After the VPI has configured the instrument to protect itself in response to a high-rate scenario, it must determine when normal operations can resume. Since the operational voltages have been reduced, measured count rates cannot be used directly in this determination. Instead, a model of each channel is used to predict when the voltages can be increased to nominal levels without violating an overstimulation criterion.

An occurrence when the flight system was overstimulated is shown in Figure 5.

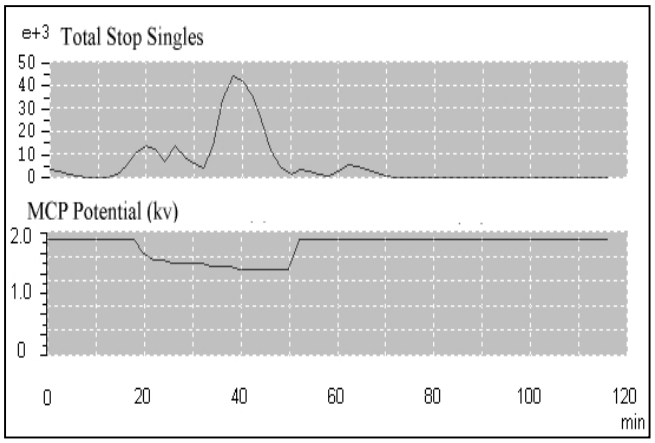

Figure 5 – Stop MCP Channel Overstimulation Response

The stop singles response shown in the upper plot is a function of the incoming particle flux and the corresponding stop MCP voltage shown in the lower plot. The VPI detected instrument overstimulation and subsequently reduced the voltage from the nominal operating point as shown in the lower plot.

An MCP gain model is used to predict when the nominal operating voltage can be restored (Figure 6).

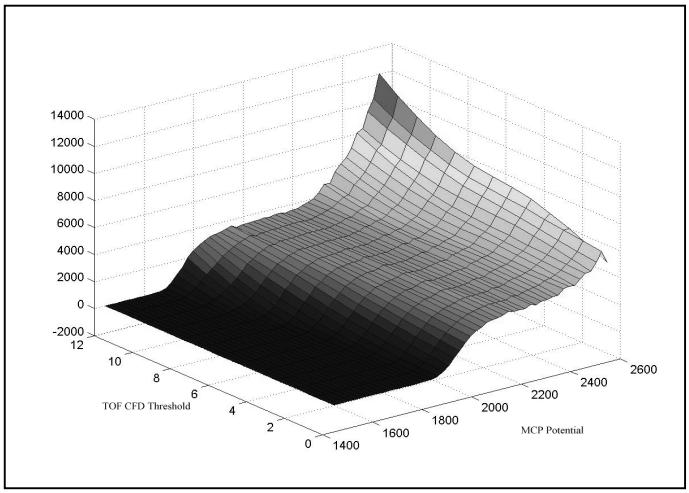

Figure 6 – MCP Gain Model $M(\tau,v)$

The model, codified as a 2-dimensional lookup table is parameterized with respect to MCP HVPS voltage and a signal detection threshold τ used in the TOF electronics. The model acts upon the measured flux to predict the count

rate R that would be measured at the nominal operating voltage v_{nom},

$$R \text{ (predicted)} = k \bullet \text{flux}_{measured} \bullet M(\tau, v_{nom}),$$

where k incorporates various scale factors resulting from the electronics signal processing path. The VPI restores nominal operations when the predicted rate does not exceed the overstimulation criteria.

Collimator Radiation Effects Mitigation. IMAGE's elliptical trajectory traverses the inner radiation belt each orbit. The high-energy particles captive in this region can compromise the long-term performance of the collimator system if the system is active during these passes. Time-tagged commands could be used to disable it before entry to these regions and re-enable it after exit. Rather conservative tags would have to be used however, since the times of passage through the belt are not predicted with great accuracy. This would disable the collimator longer than necessary. Science return would be compromised as a result, since the instrument is nominally configured with the collimator system enabled.

A better approach is to identify and react to the TOF response induced by this region of space. Particles typically enter LENA via its aperture whereas particles in the radiation belt have energy sufficient to penetrate LENA's chassis. These high-energy particles generate a TOF response that is largely isotropic. A typical Start MCP event response and a radiation-induced response are both plotted as a function of LENA spin sector in Figure 7.

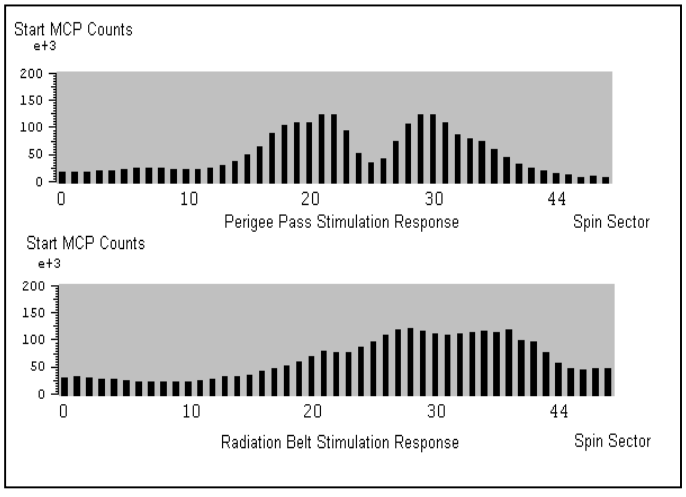

Figure 7 - Start MCP Responses

The VPI compares the TOF response with a radiation response each orbit. If this signature is identified, the VPI concludes LENA is within the inner belt, and disables the collimator. It is re-enabled when the signature is no longer detected.

Lessons Learned- Development Through Current Operations

LENA has not only enabled discovery in the area of neutral atom imaging. It has also shed considerable insight into methods of controlling a space-flight instrument autonomously. Following are some of the lessons we have learned.

The VPI Should Evolve. *The VPI should not only evaluate the performance of the instrument, but should also evaluate its own performance in controlling the instrument. Although this evaluation could be performed on the ground, an onboard implementation may increase VPI effectiveness.*

If the magnitude of residuals between modeled and observed behavior exceeds commandable thresholds, the VPI initiates control actions. The default thresholds were based on ground-based tests and early post-launch observations. They were selected to be sensitive enough to detect and react to potential problems but conservative enough to minimize occurrences of false alarms.

Based on long-term analysis of ground data, we determined that some thresholds could be set more aggressively, thereby increasing VPI sensitivity to potential problems without significantly increasing the probability of false alarms. The statistics required to determine these levels were computed onboard. This reduced the impact of this enhancement on ground-support systems. But more importantly, it facilitated VPI learning by providing a means for directly routing measured performance metrics to the VPI.

Change Will Happen. *Therefore ensure that the autonomous strategies are extensible. The autonomous framework, from both systems and implementation perspectives, should not hinder evolution of science requirements.*

Autonomous control strategies are usually designed and implemented before launch. Their design is often based on incomplete information, given the limitations of ground-based tests relative to the actual flight environment. Furthermore, system requirements may evolve based on science observations. Nonetheless, once on orbit, the VPI must meet the ground PI's prelaunch science objectives and be readily adaptable to evolving post-launch requirements. The control strategy and the implementation architecture, both software and hardware, must be adaptable to unforeseen scenarios.

We initially underestimated the effect of the radiation belts on LENA stimulation on the TOF subsystem. Our initial strategy was to count rates and disable the appropriate MCP power supply if a count rate threshold was exceeded. After deployment, a reasonable threshold was routinely exceeded during each radiation belt encounter. As a result, the power supplies were disabled on a regular basis; this was not our intended strategy.

Our revised strategy decreased the radiation-induced count rate by reducing the MCP gains at the onset of overstimulation. We used predictive techniques to restore nominal gains as soon as threat of overstimulation has passed, thereby maximizing science return. The extensibility of the autonomous control strategy and flight software reduced the implementation risk, cost and difficulty.

Optimize Globally. *Optimal subsystem performance may result in suboptimal system performance. All processes, both ground and space-based should be considered when designing autonomous control strategies for the onboard instrument subsystems.*

The critical objective of the LENA experiment is to increase scientific knowledge by analyzing the data gathered by the instrument. Therefore, data analysis methods used by the science community should influence the design of the autonomous control strategies.

The amplitude of the neutral atom flux measured by LENA is a direct function of instrument efficiency. An efficiency value is typically mapped to each LENA state. Therefore, control strategies that reduce the number of attainable instrument states simplify the flux computations. Conversely, the instrument operating precision generally scales with the number of subsystems states. Therefore, a global optimization approach should be used to address these and other potential conflicting issues.

The LENA MCP HVPS control demonstrates this issue. This power supply can be set with 9.4 volt resolution. Although control *accuracy* is required for good science return, high control *resolution* increases the number of supply states and typically yields little additional science benefit. Therefore, the VPI does not use the full power supply resolution; the default minimum control step is 75 volts. Although the VPI may not control this subsystem in an optimal manner, e.g., the supply potential may be decreased more than necessary in response to an overcount condition, the resultant state-space simplification yields considerable data analysis benefits.

System Autonomy Can be Realized Incrementally. *Given the inherent risks in automating control of a spacecraft instrument, there is good reason to follow a cautious, incremental approach. Through software extensibility, good PI-developer communication, and steady confidence building, a system requiring essentially no external commands was built on-orbit.*

LENA instrument autonomy was developed under a policy in which instrument capability was incrementally enhanced. As with most spacecraft software, incremental enhancements were a planned part of LENA operation strategy. These enhancements were to adapt the LENA control software and operational strategy to account for the actual on-orbit performance of the deployed instrument. The PI and instrument developers observed the behavior of the deployed instrument and then determined what modifications were advisable to better meet mission goals. Thus there arose the opportunity for a well-informed negotiation between the stakeholders in the instrument development.

The modifications to LENA software were designed to meet mission needs as understood by mission personnel after observation of LENA's deployed performance. The development of these modifications was aided in great part by the control software's extensibility. This extensibility also enabled the opportunity for enhancements to the software that went slightly beyond strict mission needs. Good communication between instrument developer and PI allowed the assessment of risks associated with enhancements to the modifications and outright experimentation. At every stage of development, mission goals were addressed by techniques for which a track record had been demonstrated during preceding instrument operations. As trusted routines were controlling the instrument, onboard tests were being performed on enhancements that formed the basis for future modifications. In this way, LENA went from an instrument that required commanding for significant behaviors to one that requires essentially no external commands. An important component of the course of this development is that the developer was intimately aware of the goals and wishes of the PI, a fact that enhanced the developer's ability to negotiate the acceptance of the risk entailed by enhancing the autonomy of LENA. This risk was also ameliorated by the development of the aforementioned track record that allowed both the PI and developer to build confidence in their approach and their ability to extend the original control software

A High-Fidelity Test Environment is Essential. *The software development environment must facilitate thorough test of incremental performance enhancements.*

The cost of failure on flight systems is high. Errant systems can cause measurable losses: e.g. multimillion-dollar spacecraft and the flight operations and data analysis positions that would have supported the launch. Losses that cannot be easily measured are significant as well: e.g., lost science opportunity. When new approaches are responsible for failure, long-term loss of confidence in these approaches can significantly hinder opportunities to implement them in future missions. Therefore a thorough test program is a necessity.

Although simulators can be used to validate software, problems may go undetected if the fidelity of the simulator is not high. Therefore the LENA team uses a copy of the LENA flight hardware for final validation of all software revisions. Although this approach may be more expensive in the short term, the long-term benefits are substantial.

Full Autonomy Issues in a Space Instrumentation Context

Four dimensions along which the path towards near-full autonomy that can be pursued are:

- automation of additional planning, scheduling, and control functions
- explicit model representation
- self-modifying behavior
- generality

Control of the power subsystem to ensure health and safety is the primary concern of LENA autonomy. For other instruments, planning and scheduling functions are essential for realizing science goals—for example, instruments that are positioned by command rather than by pre-determined pattern. Autonomous planning and scheduling would not only reduce the burden on personnel; it would also enable instruments to take rapid advantage of unforeseen opportunities. Clearly such functions would interact with health and safety controls.

Evolving the software towards a more explicit representation of the instrument is a many-sided issue. In general, the more explicit the model, the easier it is to evaluate the software's correctness and to modify it as needed. However, there are tradeoffs involving processing time and memory. Interpreting a declarative model in real-time usually exacts a performance price. This can be significant when processor cycles are limited. An alternative is to "compile" the model into code in advance, but there are still binding-time choices to be made.

For example, compilation can occur during development. In that case, the explicit representation serves as a tool for developers of the instrument software. The benefit can be extended to operations personnel by postponing some compilation to software load time. This would not only aid in interpreting engineering data received from the instrument, but also in human-initiated modification of the model. However, instrument self-tuning and learning then become problematic since the model must be kept consistent with the operating software. Furthermore, late binding and compilation raise issues for validation and verification before upload to the instrument. These tradeoffs are highly dependent on the resources allotted to the instrument, both on-board (time, space, weight, and power consumption) and on the ground (time, cost, and complexity of development and operational tasks).

Self-modifying behavior (e.g., machine learning) can provide greater flexibility and precision, but full autonomy in this area is risky. For spacecraft with sporadic or slow communications with the ground, some degree of autonomous learning may be a hard requirement. Self-modifying behavior ranges from tuning of parameters on the basis of observed trends, as is currently performed by LENA, to more fundamental changes realized through machine learning. If at all possible, an incremental path through this space is desirable in order to manage the risks.

Finally, the model can evolve towards generality across many instruments. Eventually we would like the model for LENA to be an instantiation of a generic machine-processable instrument model. Here too there are cost and performance tradeoffs. Adaptation of a generic model to a particular instrument is closely related to the issues of model representation and learning.

Challenges

There are potential uses of machine learning that go beyond the refinement of thresholds for LENA or other instruments. For example, empirical data could be used to refine LENA's model for predicting when normal operations can be safely resumed. More generally, unsupervised learning could be used to infer significant states of the instrument (e.g., passing through the radiation belt) and the protective actions that are appropriate to them. This would be especially useful for instruments that, unlike LENA, must initiate protective measures *before* a dangerous phenomenon occurs (such as pointing directly to the sun) rather than in reactive response. In addition, as instruments age, they often degrade or develop undesirable states that may be identified by learning techniques.

Issues that arise in considering such a role for machine learning include the required accuracy of the learned models, and the amount of data and time required to train the system to reach a suitable level of accuracy. For example, suppose LENA autonomously refined its model for predicting when nominal operating voltage can be restored. Could there be a scenario in which the system restored nominal voltage, discovered that high count rates still occur, dropped the voltage again, restored it again, and continued to thrash in this manner indefinitely? What learning mechanisms must be in place in order to prevent this from happening?

A related issue concerns the delegation of authority to evolve a model. Would there be value in applying machine learning to recommend a refined model, but leaving the approval of the change to human authority on the ground? How would such recommendations be represented in order to be comprehensible (and the implications clear) to a human?

Related to this question, in turn, is the allocation of resources to perform a learning algorithm. Can linear statistical methods be used to advantage, or is a more complex inductive or connectionist learning method necessary? Should the computations be performed on the spacecraft or on the ground? Could the computations be time-sliced over a relatively long interval to take advantage of down-time in the instrument processor?

These issues are among the challenges facing us in our attempt to realize a true model-based approach to autonomous instrument operations. The success we have experienced so far puts us in a very good position to make progress on these issues.

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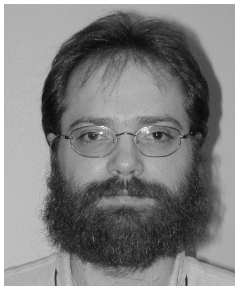
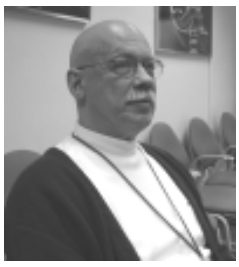
Michael A. Johnson is a senior electrical engineer in the GSFC Microelectronics and Signal Processing Branch. He has served as the lead electrical engineer for numerous flight systems at GSFC, including the IMAGE/LENA Electronics Systems, the Cassini/CAPS Spectrum Analyzer, and the Triana/PlasMag Electron Spectrometer Controller. His current research interest involves developing and deploying autonomous control strategies onboard spaceflight instruments that have severely constrained resources.

Prior to coming to Goddard, he was a lead electrical engineer at MIT/Lincoln Laboratory responsible for the design and development of space and ground-based systems. He received his B.S, M.S and Electrical Engineer degrees from MIT.

Michael L. Rilee is a scientist with Emergent IT supporting the GSFC Laboratory for Extraterrestrial Physics and the Science Computing Branch of the GSFC Earth and Space Science Computing Division. For NASA's Remote Exploration and Experimentation project he has led development of the Plasma Moment Application and the Radio Astronomical Imager, which are science data analysis applications designed for space borne supercomputers. He is currently researching a High Performance Computing System that may fly on Magnetospheric Multi Scale (launch 2007). At GSFC he has been active in Nano-Satellite technology development and the application of parallel computing to data analysis and astrophysical fluid simulation (PARAMESH). He received his Ph.D. and M.S. in Astrophysics (Plasma Physics) from Cornell University, and his B.A. in Astrophysics and Mathematics from the University of Virginia in Charlottesville, VA.



Walt Truszkowski is currently the Senior Technologist in the Advanced Architectures and Automation Branch at NASA's Goddard Space Flight Center. In that capacity he is responsible for managing the agent technology research for the Branch. Currently work is underway to establish an agent-based system for the ESA/NASA satellite SOHO. He also serves as the Lead of the Information Technology Research Group in the Branch. In that capacity, he is leading an effort to create a repository of information on technologies of importance to researchers in the organization. He is also leading the research in the areas of human factors of website design/use and the application of agents for the intelligent access and management of web-based information.



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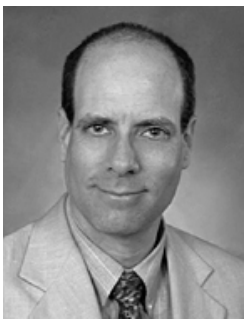
Sidney C. Bailin is founder and President of Knowledge Evolution, Inc., a firm that develops and promulgates innovative knowledge sharing technology.



Prior to forming Knowledge Evolution he was a Vice President of Engineering at Computer Technology Associates, where for 12 years he played a leading role in that company's software technology program. His software experience, which spans 22 years, has ranged

from the development of production real-time communications systems to research and development in automated reasoning and in information agents. He was one of the originators of Object-Oriented Analysis. He has been active in the software reuse community for the past 14 years, and is best known in that community for introducing the KAPTUR methodology, which links reuse to rationale capture. His most recent work concerns the dynamic negotiation of ontologies between agents. Dr. Bailin has published roughly two dozen papers on various aspects of software engineering. He currently sits on the Editorial Board of the Encyclopedia of Software Engineering, where he oversees the topics areas of Software Reuse and Artificial Intelligence in Software, and shares responsibility for entries concerning Object Oriented Design. He is the principal author of a recent book on the LIBRA approach to knowledge sharing, published by the IEEE Press.