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Autonomous Science on the EO-1 Mission

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Abstract

In mid-2003, we will fly software to detect science events that will drive autonomous scene selection onboard the New Millennium Earth Observing 1 (EO-1) spacecraft. This software will demonstrate the potential for future space missions to use onboard decision-making to detect science events and respond autonomously to capture short-lived science events and to downlink only the highest value science data.

1. Introduction

In 2003, the EO-1 spacecraft will demonstrate several integrated autonomy technologies to enable autonomous science. Several science algorithms including: onboard event detection, feature detection, change detection, and unusualness detection will be used to analyze science data. These algorithms will be used to downlink science data only on change, and will detect features of scientific interest such as volcanic eruptions, sand dune migration, growth and retreat of ice caps, and crustal deformation. These onboard science algorithms are inputs to onboard decision-making algorithms to modify the spacecraft observation plan to capture high value science events. This new observation plan will then be executed by a robust goal and task oriented execution system, able to adjust the plan to succeed despite run-time anomalies and uncertainties. Together these technologies enable autonomous goal-directed exploration and data acquisition to maximize science return (See Figure 1.). This paper describes the specifics of the EO-1 experiment and relates it to past and future flights to validate and mature this technology.

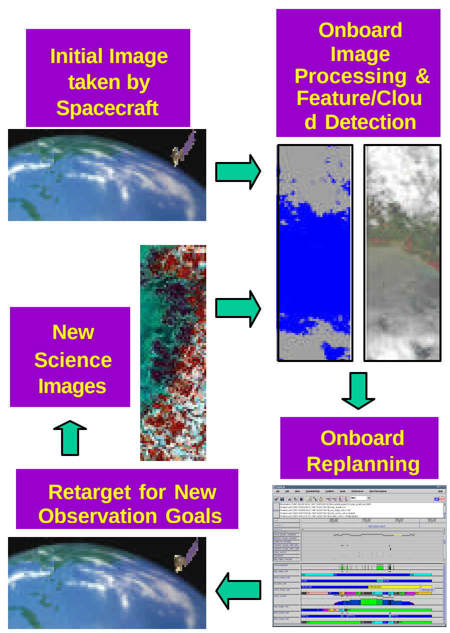

Figure 1: Autonomous Science Mission Concept

· 0 - Now at University of Colorado, Boulder, 1 - MitreTek, 2 - Microtel LLC, 3 – the Hammers Company, 4- Honeywell, 5 – CSC, 6 – Now at Smithsonian Institute

2. The EO 1 Mission

Earth Observing-1 (EO-1) is the first satellite in NASA's New Millennium Program Earth Observing series. EO-1's primary focus is to develop and test a set of advanced technology land imaging instruments.

EO-1 was launched on a Delta 7320 from Vandenberg Air Force Base on November 21, 2000. It was inserted into a 705 km circular, sun-synchronous orbit at a 98.7 degrees inclination. EO-1 is flying in formation 1-minute behind Landsat 7 in the same ground track and maintaining the separation within 2 seconds. This close separation has enabled EO-1 to observe the same ground location (scene) through the same atmospheric region so that paired scene comparisons between the two satellites can be made. This orbit allows for 16-day repeat tracks, with 3 over flights per 16-day cycle with a less than 10-degree change in viewing angle.

For each scene, over 20-Gbits of scene data from the Advanced Land Imager (ALI), Hyperion, and Atmospheric Corrector (AC) are collected and stored on the onboard solid-state data recorder at high rates.

EO-1 is currently in extended mission, having more than achieved its original technology validation goals. As an example, over 5,000 data collection events have been successfully completed, against original success criteria of 1,000 data collection events.

The Autonomy Experiment described in this paper uses the Hyperion hyper spectral instrument (although investigations are underway to determine feasibility of analyzing ALI data onboard in follow-on experiments). The Hyperion is a high-resolution hyper spectral imager capable of resolving 220 spectral bands (from 0.4 to 2.5 µm) with a 30-meter spatial resolution. The instrument images a 7.5 km by 42 km land area per image and provides detailed spectral mapping across all 220 channels with high radiometric accuracy.

The EO-1 spacecraft has two Mongoose M5 processors – one for command and data handling functions and the other part of the WARP (Wideband Advanced Recorder Processor) a large mass storage device. Each M5 runs at 12 MHz (for ~8 MIPS) and has 256 MB RAM. Both M5's run the VxWorks operating system. The autonomy software operates on the WARP M5.

3. Autonomy Software Architecture

The autonomy software on EO -1 is organized into a traditional three-layer architecture (See Figure 2.). At the highest level of abstraction, the Continuous Activity Scheduling Planning Execution and Replanning (CASPER) system is responsible for mission planning functions. CASPER schedules science activities while respecting spacecraft operations and resource constraints. CASPER operates on the tens of minutes timescale. CASPER scheduled activities are inputs to the Spacecraft Command Language (SCL) system, which is responsible for the detailed sequence commands corresponding to CASPER scheduled activities. SCL operates on the several second timescale. Below SCL the EO-1 flight software is responsible for lower level control of the spacecraft and also operates a full layer of independent fault protection. The interface from SCL to the EO-1 FSW is at the same level as ground generated command sequences. The science analysis software is scheduled by CASPER and executed by SCL in batch mode. The results from the science analysis software result in new observation requests presented to the CASPER system for integration in the mission plan.

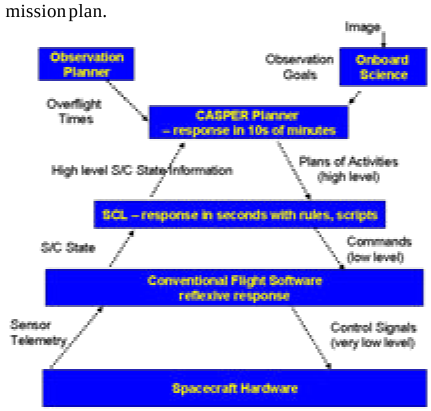

Figure 2: Autonomy Software Architecture

4. Onboard Science Analysis

The first step in the autonomous science decision cycle is detection of science events of interest. In the complete experiment, a number of science analysis technologies will be flown including:

- Thermal anomaly detection – uses infrared spectra peaks to detect lava flows and other volcanic activity. (See Figure 3.)
- Cloud detection – uses intensities at six different spectra and thresholds to identify likely clouds in scenes. (See Figure 4.)
- Flood scene classification – uses ratios at several spectra to identify signatures of water inundation as well as vegetation changes caused by flooding.
- Change detection – uses potentially multiple spectra to identify regions changed from one image to another. This technique is applicable to many science phenomena including lava flows, flooding, freezing and thawing and is used in conjunction with cloud detection. (See Figures 5 and 6.)
- Generalized Feature detection – uses trainable recognizers to detect such features as sand dunes and wind streaks.
- Anomaly detection – uses Gabor filters to classify the data and selects outliers to return as higher probability of science interest [Burl 2000].

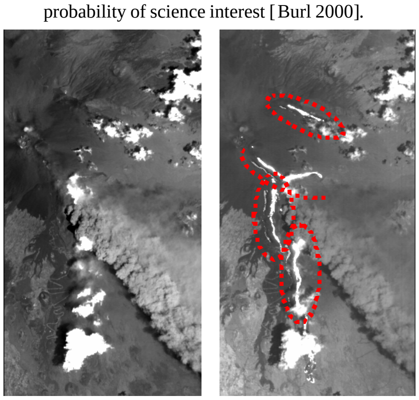

Figure 3: Thermal Anomalies associated with volcano activity at Mt. Etna, visual spectra at left and Infra-red at right.

The first series of experiments will demonstrate use of thermal anomaly detection techniques to detect sites of active volcanism. Initial experiments will also use the cloud detection triggers. In the event of high cloud cover, data collections will be rescheduled. These techniques have been scheduled first because of the maturity and simplicity of the algorithms.

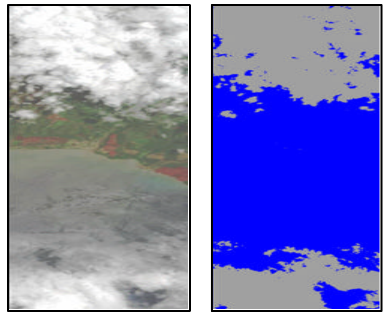

Figure 4: Cloud Detection of a Hyperion Scene – visual image at left, grey in the image at right indicates detected cloud.

Later flights will validate as many science analysis algorithms as resources allow. These fights will begin by validating change detection on multiple science phenomena, feature detection on Aeolian features such as sand dunes, sand shapes, and wind streaks, and the Discovery algorithm. Validating this portfolio of science algorithms will represent a valuable step forward to enabling future autonomous science missions [Davies].

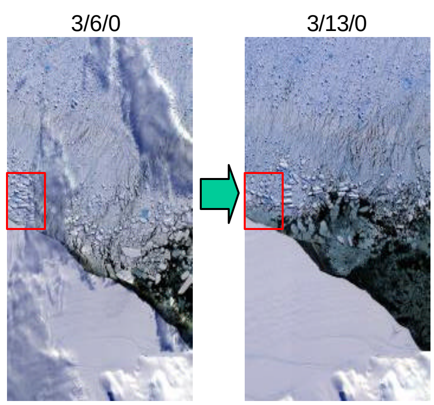

Figure 5 Change Detection Scenes indicating Ice Breakup in the Larsen Ice Shelf, Antarctica. Advanced Land Imager Data, red box indicates detailed Hyperion scene.

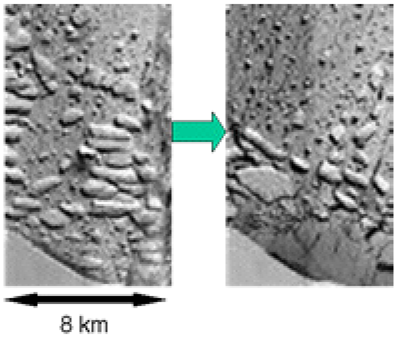

Figure 6: Detailed Hyperion scene indicating change on Larsen Ice Shelf.

5. Onboard Mission Planning

In order for the spacecraft to respond autonomously to the science event, it must be able to independently perform the mission planning function. This requires software that can model all spacecraft and mission constraints. In the EO-1 Experiment, this function is performed by the CASPER [Chien 2000] software. CASPER represents the operations constraints in a general modeling language and reasons about these constraints to generate new operations plans that respect spacecraft and mission constraints and resources. CASPER uses a local search approach [Rabideau 1999] to develop operations plans.

Because onboard computing resources are scarce, CASPER must be very efficient in generating plans. While a typical desktop or laptop PC may have 2000-3000 MIPS performance, 5-20 MIPS is more typical onboard a spacecraft.

CASPER is responsible for long-term mission planning in response to both science goals derived onboard as well as anomalies. In this role, CASPER must plan and schedule activities to achieve science and engineering goals while respecting resource and other spacecraft operations constraints. For example, when acquiring an initial image a volcanic event is detected, CASPER plans a response. This event may warrant a high priority request for a subsequent image of the target to study the evolving phenomena. In this case, CASPER will modify the operations plan to include the necessary activities to re-image. This may include determining the next over flight opportunity, ensuring that the spacecraft is pointed appropriately, that sufficient power, and data storage are available, that appropriate calibration images are acquired, and that the instrument is properly prepared for the data acquisition.

In the context of the EO-1 autonomy experiment, CASPER reasons about the majority of spacecraft operations constraints directly in its modeling language. However, there are a few notable exceptions. First, the over flight constraints are calculated using ground-based orbit analysis tools. The over flight opportunities and pointing required for all targets of interest are uploaded as a table and utilized by CASPER to plan. Second, the ground operations team will initially perform management of the momentum of the reaction wheels for the EO-1 spacecraft. This is because of the complexity of the momentum management process caused by the EO-1 configuration of three reaction wheels rather than four. In the proposed follow-on experiment we will examine the possibility of migrating this function onboard.

6. Onboard Robust Execution

EO-1 will fly the Spacecraft Command Language (SCL) [Interface & Control] to provide robust execution. SCL is a software package that integrates procedural programming with a real-time, forward-chaining, rule-based system. A publish/subscribe software bus allows the distribution of notification and request messages to integrate SCL with other onboard software. This design enables either loose or tight coupling between SCL and other flight software as appropriate.

The SCL "smart" executive supports the command and control function. Users can define scripts in an English-like manner. Compiled on the ground, those scripts can be dynamically loaded onboard and executed at an absolute or relative time. Ground-based absolute time script scheduling is equivalent to the traditional procedural approach to spacecraft operations based on time. In the EO-1 experiment, SCL scripts will also be planned and scheduled by the CASPER onboard planner. The science analysis algorithms and SCL work in a cooperative manner to generate new goals for CASPER. These goals are sent with a messaging system.

Many aspects of autonomy are implemented in SCL. For example, many constraint checks redundant with fault protection are implemented in SCL. Before each command is sent from the autonomy software to the C&DH software by SCL, it undergoes a series of constraint checks to ensure that it is a valid command. Any pre-requisite states required by the command are checked (such as the communications system being in the correct mode to accept a command). SCL will also verify that there is sufficient power so that the command does not trigger a Low Bus Voltage and that there is sufficient energy in the battery so as to retain safe margins. Using SCL to check these constraints (while included in the CASPER model) provides an additional level of safety to the autonomy FSW.

7. Flight Status

The EO-1 Autonomy Flight Experiment was initially proposed in August 2002 and was approved in November 2002. The experiment was originally conceived as a rapid deployment 8-month effort. This initial effort is currently being strongly considered for expansion due to the incredible opportunity provided by the EO-1 platform of opportunity.

The EO-1 autonomy software was integrated under the flight version of VxWorks in December 2002, and have been undergoing testing and integration with the WARP M5 software. Based on the results of this testing, the EO-1 software is planned for upload in the late-Spring timeframe for approximately one month of shadow operations to provide additional confidence. At the successful completion of this period and patching of any discovered issues, a baseline of approximately 35 experiment observations will be acquired. This experiment phase should complete by the end of Summer 2003. If the option to augment the experiment is chosen, and additional 100+ experiment observations will be scheduled.

8. Related Work, Discussion, and Conclusions

In 1999, the Remote Agent experiment (RAX) [Ames] executed for a few days onboard the NASA Deep Space One mission. RAX is an example of a classic three-tiered architecture [Gat 1998], as is the EO-1 experiment. RAX demonstrated a batch onboard planning capability (as opposed to EO-1's continuous planning) and RAX did not demonstrate onboard science. PROBA[ESA] is a European Space Agency (ESA) mission that will be demonstrating onboard autonomy and launched in 2001. However, ASE has more of a focus on model-based autonomy than PROBA.

The Three Corner Sat (3CS) University Nanosat mission will be using the CASPER onboard planning software integrated with the SCL ground and flight execution software [Chien 2001]. The 3CS mission was scheduled for launch in late 2003. However as it was scheduled for launch in the Space Shuttle, it has been delayed indefinitely. 3CS will use onboard science data validation, replanning, robust execution, and multiple model-based anomaly detection. The 3CS mission is considerably less complex than EO-1 but still represents an important step in the integration and flight of onboard autonomy software.

More recent work from NASA Ames Research Center is focused on building the IDEA planning and execution architecture [Muscettola 2002]. In IDEA, the planner and execution software are combined into a "reactive planner" and operate using the same domain model. A single planning and execution model can simplify validation, which is a difficult problem for autonomous systems. For EO-1, the CASPER planner and SCL executive use separate models. While this has the advantage of the flexibility of both procedural and declarative representations, a single model would be easier to validate. We have designed the CASPER modeling language to be used by domain experts, thus not requiring planning experts. Our use of SCL is similar to the "plan runner" in IDEA but SCL encodes more intelligence. The EO-1 science analysis software is defined as one of the "controlling systems" in IDEA. In the IDEA architecture, a communications wrapper is used to send messages between the agents, similar to the software bus in EO-1. In the description of IDEA there is no information about the deployment of IDEA to any domains, so a comparison of the performance or capabilities is not possible at this time.

The EO-1 Autonomy Flight Experiment will demonstrate an integrated autonomous mission using onboard science analysis, replanning, and robust execution. EO-1 will perform intelligent science data selection that will lead to a reduction in data downlink. In addition, the EO-1 experiment will increase science return through autonomous retargeting. Demonstration of these capabilities onboard EO-1 will enable radically different missions with significant onboard decision-making leading to novel science opportunities. The paradigm shift toward highly autonomous spacecraft will enable future NASA missions to achieve significantly greater science returns with reduced risk and cost.

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