Demo: Onboard Re-scheduling Prototype for an Earth Observing Spacecraft

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Abstract

Prior space missions have not routinely used onboard decision-making. The Autonomous Sciencecraft (ASE), flying onboard the Earth Observing One spacecraft, has been flying autonomous agent software for the last decade that enables it to analyze acquired imagery on board and use that analysis to determine future imaging. However ASE takes approximately one hour to analyze and respond.

This paper describes the Earth Observing Autonomy (EOA) project to increase the responsiveness of spacecraft flight software for onboard decision-making as well as to increase the capabilities such flight software. Specifically, we target onboard Image analysis and response within a single orbital overflight at low Earth orbit (about eight minutes). We demonstrate prototype flight software that simulates acquisition of imagery, onboard spectral analysis of the imagery, replanning of imaging to include reimaging of detected phenomenon, and then execution of this response imagery-all within this eight minute single overflight including the spacecraft response time (e.g. To re-point the spacecraft, acquire the image, etc.). We demonstrate generated videos of the simulation of the spacecraft operations.

Introduction

The Earth Observing Autonomy (EOA) project targets the development of a spacecraft autonomy capability to enable a spacecraft to image, analyze the image, and re-image based on that analysis within a single overflight, imposing a responsiveness constraint of 5-8 minutes. While this software is applicable to a wide range of spacecraft, we assess this software against Orbview Class spacecraft (such as Worldview-3) [1,2,3]. This would represent a dramatic improvement over the current state of the art, ASE[4], which responds within roughly 1 hour.

We have developed a software prototype of the EOA capability that includes several autonomy components:

1. *Onboard science processing algorithms.* Science analysis algorithms process onboard image data to detect science events and suggest reactions to maximize science return. Specifically we investigate the use of the Mixture –tuned Match Filter (MTMF) [5] for onboard spectral analysis of acquired imagery (however ASE has already demonstrated other types of onboard analysis - thermal analysis for volcanoes and wildfires [6], spectral analysis for flooding [7], spectral analysis for cryosphere study [8], as well as spectral unmixing for mineralogical analysis [9]).
2. *Onboard planning and scheduling software.* The Continuous Activity Scheduling Planning Execution and Replanning (CASPER) [1] combined with the Eagle Eye Mission Planning Software [2] system generates a baseline mission operations plans from observation requests. This baseline plan is subject to considerable modification onboard in response to data analysis from step 1. The model-based planning algorithms enable rapid response to a wide range of operations scenarios based on models of spacecraft constraints.
3. *Robust execution software.* The JPL core flight software [12] (CFS) expands the CASPER activity plans into low-level spacecraft commands and includes a powerful and expressive sequencing engine. The CFS sequencing engine monitors the execution of the plan and has the flexibility and knowledge to perform improvements in execution as well as local responses to anomalies.

One challenge to spacecraft autonomy is *Limited computing resources*. An average spacecraft CPU offers 200 MIPS and 128 MB RAM – far less than a typical personal computer. For the EOA prototype, we baseline a Rad 750 or Leon processor for all of the autonomy capability.

EOA demonstrates an integrated autonomous mission using onboard science analysis, replanning, and robust execution. EOA performs intelligent science data analysis, and spacecraft retargeting, leading to a reduction in data downlinked and an increase in science return. These capabilities enable radically different missions with significant onboard decision-making allowing the spacecraft to take advantage of novel science opportunities without the ground in the loop. The paradigm shift toward highly autonomous spacecraft will enable future NASA missions to achieve significantly greater science returns with reduced risk and reduced operations cost.

Autonomous Science Scenario

The demonstration will simulate an EOA mission scenario. During this demonstration EOA will command a software simulation of a Worldview-3 like spacecraft to image science targets, process and analyze onboard image data, and re-plan operations based on science results.

For this demonstration we assume several baseline mission parameters:

Parameter	**Value**
Orbit	950 km Sun synchonous
Initial Science Images	31-38° lookahead from nadir
Response image	Nadir to 31° lookahead
Spacecraft slew rate	4° per second, instantaneous start and stop, no settle time
Imaging time	Total dwell of 2s per image

We use Google Earth to visualize the operations of the spacecraft (see https://drive.google.com/file/d/0B4gKIo5pZb30Q0xsaUlKb1BZZFk/view?usp=sharing).

The demonstration will highlight the following capabilities of EOA as shown in Google Earth:

1. *Autonomous Initial Plan Generation*. Eagle Eye/CASPER will generate a mission plan using an uplinked set of high-level goals requesting science observations and data downlinks. CFS will convert these plans to sequences of spacecraft commands and issue these commands to the Worldview-3 simulation. The initial schedule is shown by the light blue rectangles.
2. *Plan Execution*. As each scene in the initial schedule is imaged, the rectangle turns green.
3. *Onboard Image Analysis*. The onboard science analysis algorithms are run on each acquired initial image. If the onboard image analysis detects a feature/region/event of interest it will generate a request to re-image the site with a pre-specified priority.
4. *Onboard Replanning*. CASPER/Eagle Eye modifies the onboard schedule to respond to the science analysis recommendations to insert new observations and delete low-value future planned observations.
5. *Re-imaging of the targets*: targets that are re-imaged as responses are shown in yellow. Images that were in the initial schedule but are pre-empted due to contention with response images turn from light blue to red.

A key aspect of the agent software is geometric analysis of the relative position of the illumination source (the sun), the target, and the observer (the spacecraft). For the initial image and followup image the angles to the illumination are constrained and the angles to the observer are also constrained (e.g. looking to far ahead, to the side, or behind hampers image quality). Furthermore the spacecraft pointing and slewing must be carefully scheduled to maximize the utility of scheduled images.

Two onboard re-scheduling software prototypes have been constructed. One is a standalone scheduler that operates with target information specified in the along/across spacecraft track coordinate frame of reference. The second uses the CASPER/Eagle Eye framework to operate in a lat/lon altitude frame of reference.

The standalone scheduler re-schedules the observation schedule from scratch each time a new request is received. This scheduler greedily schedules in a priority-first fashion, with each request being scheduled at the earliest possible start time. No backtracking across priority levels is performed therefore this algorithm is O(n lg n) where n is the number of requests that must be considered (the requests between nadir and the horizon).

The CASPER/Eagle Eye scheduler first generates an initial schedule by greedily scheduling in priority first order among all of the requests. When satisfying each request, is schedules the individual requests at the earliest possible start time. When rescheduling, CASPER/Eagle Eye takes the new request and searches the current plan within the valid time interval when the new request can be scheduled. It greedily replaces the earliest observation that can be replaced with valid slews to the preceding and following observations. Note that this algorithm presumes that the initial plan is packed tightly so that the new observation cannot be inserted in between currently scheduled observations without modification to the existing preceding and following observations. This rescheduling algorithm is O(n) where n is the number of requests in the valid along track viewing window for the new image request (a smaller number than the n used above but of the same order).

This image analysis software and response software was first implemented in a linux/workstation environment and then was ported into a VxWorks software simulation. In the future we plan to bring the software into a Rad 750 Hardware testbed which is the closest level to a flight testbed.

Current timing benchmarks show the image analysis, slewing, pointing, and re-planning within 0.5-2.0x real-time based on hardware and software assumptions. Because we have not optimized many of the computations this estimate is considered strong evidence that the performance of the current software prototype is close to flight worthy from a timing standpoint.

Summary

We have demonstrated onboard operations scheduling, image analysis, and re-imaging within a realistic flight software operating system and flight hardware performance environment. This prototype demonstrated the feasibility of performing such functions autonomously within a low earth-orbiting environment (roughly 5-8 minutes overflight time). Future efforts will further mature this concept and software by bringing the prototype into a relevant flight hardware testbed.

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