Revolutionary Deep Space Science Missions

Enabled by Onboard Autonomy

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Abstract

Breakthrough autonomy technologies enable a new range of space missions that acquire vast amounts of data and return only the most scientifically important data to Earth. These missions would monitor science phenomena in great detail (either with frequent observations or at extremely high spatial resolution) and onboard analyze the data to detect specific science events of interest. These missions would monitor volcanic eruptions, formation and movement of aeolian features, and atmospheric phenomena. The autonomous spacecraft would respond to science events by planning its future operations to revisit or perform complementary observations. In this paradigm, the spacecraft represents the scientists agent – enabling optimization of the downlink data volume resource. This paper describes preliminary efforts to define and design such missions.

1. Introduction

Recent developments in data mining, pattern recognition, and autonomous systems technologies present a unique opportunity for space science. Future space missions have the capability to detect and recognize science onboard. These missions will also have the capability to respond autonomously to these events by planning and carrying out observations to capture short-lived science events and rare phenomena. These capabilities will allow the spacecraft to acquire and downlink the most valuable science data. In this new paradigm, rather than acquiring data painstakingly pre-determined on the ground, the spacecraft will use onboard intelligence to search for data of interest to the science community.

How will such a revolutionary mission be achieved? Several critical technologies synergistically combine to enable this radical shift in space missions: Science analysis algorithms, onboard mission planning, and robust execution, close the response loop onboard to enable autonomous science.

Science analysis algorithms analyze instrument data onboard and use a range of techniques to detect science events. For example, automatic feature recognizers can be trained on the ground by scientists using previous mission data. These recognizers can then be uploaded to the spacecraft to give it the

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capability to automatically recognize features such as: sand shapes, sand dunes, impact craters, or lava flows [Burl 2001].

The spacecraft could also be tasked to monitor a specific geographic region with repeated overflights to search for changes. In this scenario the spacecraft compares imagery from consecutive passes and interprets the images to detect change as an indicator of science events. Such a technique could be used to detect phenomena such as: volcanic activity from fresh lava flows or plumes, flooding, thermal events, crustal motion, movement in ice formations, and atmospheric events.

This onboard knowledge of science events will be used to drive further operations of the spacecraft. When a trigger event is detected, onboard mission planning software would have the ability to plan appropriate responses. Onboard feature detection, change detection, and unusualness(anomaly) detection software will analyze science data. The conclusions of these algorithms will be used to downlink only when scientifically interesting events happen, and to detect features of scientific interest such as volcanic eruptions, sand dune migration, growth and retreat of ice caps, and crustal deformation [Davies et al. 2001]. Based on the output of these onboard science algorithms, the autonomous spacecraft will replan its activities in order to capture high value science events. This new observation plan will then be executed by a robust goal and task oriented execution system, capable of able to dynamically adjust the plan in order to achieve the goals despite run-time anomalies and uncertainties. Together these technologies enable autonomous goal-directed exploration and data acquisition to maximize science return.

The remainder of this paper describes several such mission concepts under study as well as upcoming flights to validate and mature this technology.

2. Mission Scenario

In the autonomous science paradigm, the spacecraft is not just commanded from the ground-based science team to make pre-planned observations. Instead, the science team specifies a set of watch sites and reactions. In this paradigm, the science team is in effect specifying a set of goals, i.e., "what to look for" rather than a precise sequence of activities ("look here at this specific time") Figure 1 shows this new mission paradigm. The spacecraft is monitoring a set of targets and analyzing the science data onboard. When specific events are detected from this analysis, the spacecraft has the capability to plan and execute an appropriate response. This response may be as simple as "downlink the observation", "a notice of the event", or "some summarization of the data." On the other hand, the event may trigger a whole new series of observation requests which now need to be appropriately integrated with the current operations plan such that spacecraft resources, operations constraints, scheduled data downlinks, engineering activities, and observation priorities are taken into consideration.

3. Science

Onboard science event detection methods can be classified into several families of algorithms:.

Change detection: In this approach, an area is imaged frequently (e.g. once daily) but only downlink when specific science events occur (e.g. creation of a fresh impact crater) or downlink summary of change. Alternatively, detection of a change could trigger a reaction to image a related area. For example, recognition of a flooding event could trigger

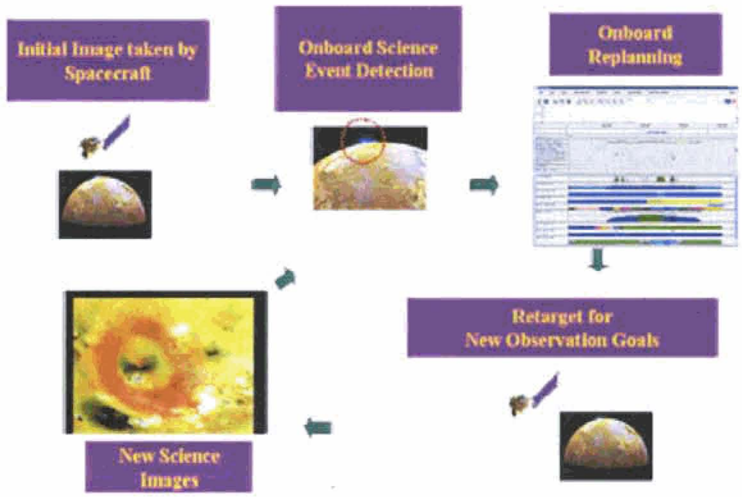

Figure 1: Autonomous Science Mission Concept

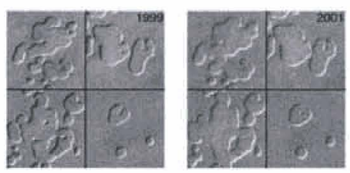

Figure 2: Change in Martial Polar Ice captured by MGS-MOC

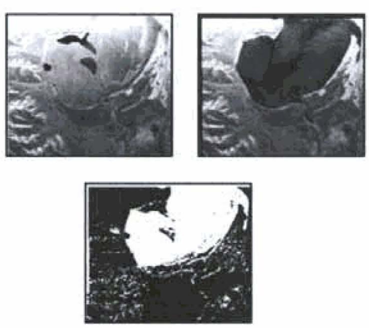

Figure 3: Change in Aksai Chin Lake X-SAR Image data, change detected shown at bottom.

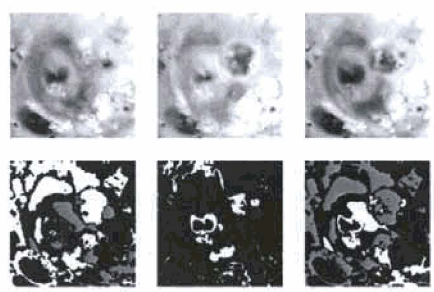

Figure 4: Change caused by Io Volcanism captured in Galileo Imagery. Detected change at bottom.

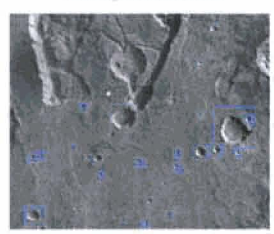

Figure 5: Craters detected in MGS-MOC imagery by DiamondEye feature recognition algorithm.

observations upstream and downstream from the original detection to determine the extent of the event. Figure 2 shows change in the Martian Polar caps as captured by Mars Global Surveyor Mars Observer Camera (MGS-MOC) imagery. Figure 3 shows freezing and thawing of a lake in the Himalayan area as captured by synthetic aperture radar (SAR) and analyzed by change detection software. Figure 4 shows change detection software tracking volcanism on Io, using data from the Galileo spacecraft.

Feature Detection and Tracking: These approachs detect and track (previously identified) science features such as volcanoes, lava cones, sand shapes and downlink images of science items or track dynamic phenomena involving these features (sand shape migration). Figure 5 shows impact craters on Mars detected in MGS-MOC imagery by the DiamondEye Feature recognition system [Burl 2001]. Figure 6 shows sand spots automatically detected, again by the DiamondEye. Figure 7 shows dark slope streaks in MGS-MOC imagery and Figure 8 shows dust devil tracks in Odyssey THEMIS imagery. Both dark slope streaks and dust devil tracks are prime targets for feature recognition and tracking.

Unusualness Detection: This technology detects science patterns or features that do not regularly occur in the tracked dataset. This algorithm performs by classifying the areas of the image and then identifying outliers [Burl 2000]. Figure 9 shows this "visual discovery" algorithm identifying sand dune features in MGS-MOC imagery. The image on the left shows the original image with boxes marking the "outlier" regions. The image on the right shows the outlier regions pulled from the original image. These outlier areas might be considered areas with higher chance of scientific interest. If only identified areas are downlinked, downlinked data may be comparable but science return can be enhanced.

These science analysis algorithms then trigger onboard data processing to reduce data volume to the minimum required to track the phenomena of interest or mission re-planning to retarget the spacecraft on subsequent orbits to track in further detail the phenomena of interest.

4. Mars Orbiter Mission Concept

We have begun preliminary mission studies for a number of deep space missions leveraging this new mission concept. Among these, the best understood is a Discovery Class Mars Orbiter. In the Mars orbiter mission concept, a spacecraft uses an imaging SAR to track surface features on Mars. This mission has several *campaigns*.

Track the growth and retreat of the Martian ice caps (and other surface volatiles).

Track the polar region soil seasonal freeze and thaw. In both cases the onboard data analysis will detect the regions of change and can downlink only changed areas, downlink a line segmentation of the regions (e.g. region boundaries), or downlink whole images based on change over a threshold.

Track aeolian features (e.g., sand dunes) sand shape including determining seasonal variation in distribution, size, and orientation. In this campaign feature detection software is used to classify sand shapes and extract shape and orientation information. Another option is to track features (such as dust devils) across multiple images to extract trajectory information.

In all of these cases, the spacecraft acquires a large quantity of data and downlinks only a small relative proportion (or summarized information). Compared to a conventional mission the total amount of data acquired is significantly greater, but the amount of data downlinked is roughly comparable. However, the science content per returned byte has been

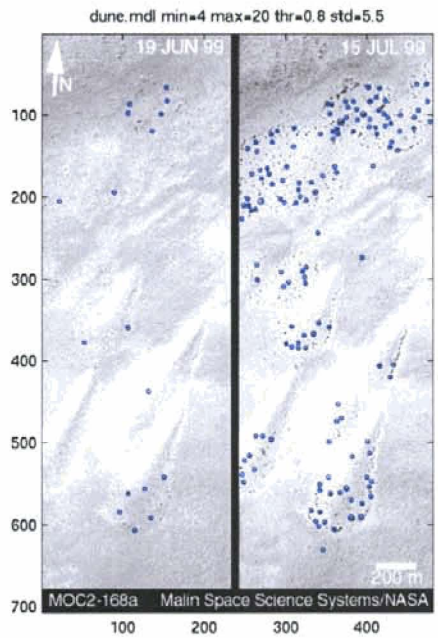

Figure 6: Sand Spots automatically detected by DiamondEye in MGS-MOC imagery

Figure 7: Dark slope streaks – manually identified in MGS-MOC imagery

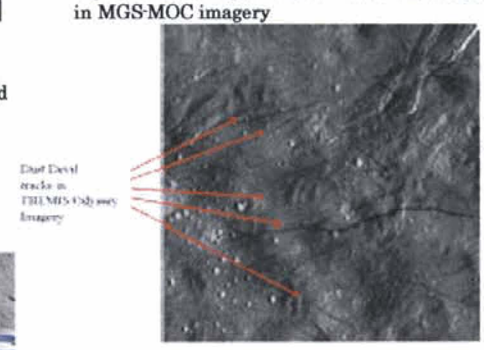

Figure 8: Dust Devil Tracks manually identified in THEMIS Odyssey imagery

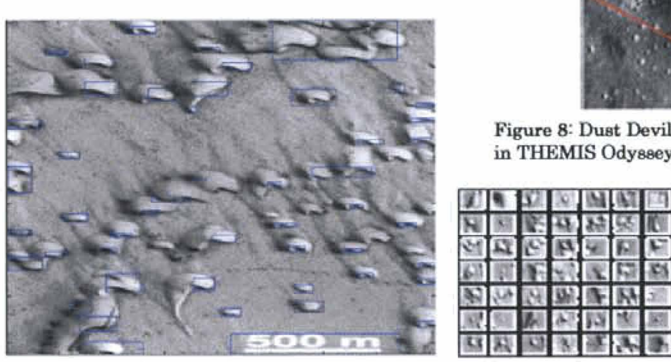

Figure 9: Outlier patterns automatically extracted from MGS_MOC imagery.

greatly increased.

4.1 Scenario feasibility

We have been developing this mission concept with mission designers, including aspects of trajectory, spacecraft design, etc. We describe best estimates as to mission feasibility below.

The Mars Orbiter mission concept borrows from the successful Mars Global Surveyor (MGS) [Beerer et al, 1996] and Mars Odyssey [Mase et al, 2002] missions in that our concept uses similar orbit design and instrumentation. We thus maximize the change detection capabilities of the mission by enabling comparisons between newly acquired data and data from MGS and Odyssey. Our suggested mission places the spacecraft in a near-polar, near-circular sun-synchronous orbit. The low altitude (approximately 300 km) of the orbit facilitates high-resolution imaging and mapping and also results in an orbital period providing regular coverage of most sites each Martian day. To provide ample opportunity for seasonal change detection, we plan for at least two martian years, or four earth years, of data collection.

The spacecraft orbit is designed as follows. The orbit is sun-synchronous, near-circular, near polar, low altitude orbit. Surface coverage roughly twice per martian day, once in sunlight once in shadow. Daily coverage under nearly the same lighting conditions – this happens every ~13 orbits. (For example, everyday the spacecraft could pass over the surface at 4 am and 4 pm in local true solar time.)

Repeat coverage is a function of latitude. The following table indicates the percent coverage of the given latitude over one martian day (based on STK analysis). The first part of the table indicates coverage for a 45° half-cone (90° cone) angle sensor. This translates to the percentage of the given latitude's targets that would see the spacecraft at or above 42° elevation.

	Mars Orbiter
Science Instrument	Imaging SAR
Resolution	SAR: 3 m (1e-5 rad
Pointing Accuracy	10 mrad in each axis; less than 1 mrad drift in 1 sec, 3 mrad in 12 sec
FOV	SAR: 0.5 deg
Orbital Altitude	250x320 km
Overflight Frequency	Roughly twice per martian day
Launch Date	October 2009
On-orbit Mission Duration	4 years
C&DH	128 MB RAM; 22GB MSM; Rad 750
Communications	128 k bps X band downlink 1 k bps uplink
ACS	Star camera, 3 reactions wheels + 1 spare; IMUs; 3 orthogonal gyros; 3 orthogonal accelerometers.
Pointing	Control to 10 mrad in each axis (MGS/Ody). Less than 1 mrad drift in 1 sec. Less than 3 mrad drift in 12 sec (MGS/Ody).

45° half-cone	
Target Latitude (deg)	Percent Coverage
0	44
30	74
90° half-cone	
Target Latitude (deg)	Percent Coverage
0	17
30	37
60	65

4.2 Mission Science Rationale

In order to understand the evolution of Mars, and the current Martian environment, the presence of and cycles of volatiles must be understood and quantified. Therefore, Mars science missions currently are driven by the stated NASA goal of "follow the water", a goal that also covers monitoring changes in the ice caps and clouds. Evidence from Mars Global Surveyor indicates the presence of near-surface liquid water [Malin and Edgett, 2000]. An orbiter with SAR and imager, equipped with the autonomous algorithms described above would be used to observe change in ground volatile content as a function of season (especially with ground-penetrating radar), as well as detect areas where water and CO_2 seeps have modified the surface appearance. These high-science-value areas would then be assigned a high priority for data return and for more detailed observation on subsequent passes, and by other resources (other orbiters, surface rovers, aerobots etc.). Additionally, constant surface monitoring would be used to detect signs of active volcanic, fluvial and aeolian processes.

5. Discussion and Conclusions

A number of upcoming missions will be flying onboard autonomy software to improve their science return. Launching in 2003, the Three Corner Sat Mission (3CS) [Chien et al. 2001a] will utilize onboard data validation, replanning, and robust execution to maximize science return. 3CS consists of three identical spacecraft that are not attitude controlled. The spacecraft will attempt to take science images of the earth based on models of the tumble of the spacecraft. Onboard data validation software will try to score each image according to its science value – attempting to pick out images that are mostly of the earth. Onboard re-planning software then plans for more images based on available power, science image scores, and next downlink.

In 2003, the EO-1 Spacecraft will fly software to analyze images onboard to detect cloud cover and potentially other features. Onboard planning and execution software will then replan operations to optimize science return. Specifically, CASPER will plan and schedule science observations, slews, downlinks, and other supporting activities.

These pathfinding missions are a precursor to more ambitious applications of autonomy such as our Mars Orbiter mission concept and will usher in a new era of autonomous space exploration, enabling missions with dramatically increased science return.

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