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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 onboard the spacecraft and return only the most scientifically important data to Earth. These revolutionary 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 and identify specific science events of interest. This includes affording the opportunity to capture transient geologic processes and atmospheric and weather phenomena such as volcanic eruptions, storm-induced catastrophic flooding, formation and movement of aeolian features, advance and retreat of ice sheets and flows, and development and tracking of storms. The autonomous spacecraft would respond to science events by planning its future operations to revisit or perform complementary observations. In this new 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 nontraditional missions.

1. Introduction

Recent developments in data mining, pattern recognition, and autonomous systems technologies present a unique opportunity for space science. Future missions to Earth and beyond will have the capability to respond autonomously to transient geologic processes and atmospheric and weather phenomena onboard, yielding greater scientific returns at a significant reduction in data downlink, by planning and carrying out observations to capture these short-lived science events and other 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 from traditional space missions: Science analysis algorithms, onboard mission planning, and robust execution, close the response loop onboard to enable autonomous science.

Science analysis algorithms examine

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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 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 transient geologic activity and atmospheric and weather phenomena such as: the emplacement of lava and pyroclastic flows, the discharge of plumes from vent structures, storm-induced catastrophic flooding, thermal events (e.g., underground thermal flow and thermal-water mixing), tectonism (impact cratering, faulting and fracturing, and collapse of crustal materials), advance and retreat of ice sheets and flows, and atmospheric events [Davies et al. 2001].

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 described above. 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 will then 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

This onboard science element of the autonomy technology can be classified into change detection, feature detection and tracking, and unusualness detection algorithms:

Change detection: In this approach, an area is imaged frequently (e.g. once daily) but only downlinked when specific science events occur (e.g. newly formed impact crater) or the summary of change can be downlinked. Alternatively, detection of a change could trigger a reaction to image an area effected by the transient process. Examples include recognition of a flooding event that could trigger observations upstream and downstream from the original detection to determine the extent of the event or change in the Martian Polar caps as captured by Mars Global Surveyor Mars Observer Camera (MGS-MOC) imagery (Figure 2). Examples using change detection software include freezing and thawing of a lake in the Himalayan area as captured by synthetic aperture radar (SAR) (Figure 3) and volcanism on Io, using data from the Galileo spacecraft (Figure 4).

Feature Detection and Tracking: This approach is used to detect and track special features of interest such as volcanic constructs and flows, impact craters, faults, mass movements, floods and other features formed by aqueous activity, and aeolian dunes and wind streaks. DiamondEye Feature recognition system [Burl 2001] can be implemented to detect features of high scientific interest, including impact craters and sand spots on Mars using MGS-MOC imagery (Figures 5 and 6, respectively). Other features of special scientific interest may include dark slope streaks in MGS-MOC imagery (Figure 7) and dust devil tracks using Odyssey THEMIS imagery (Figure 8). Both dark slope streaks and dust devil tracks, which record current wind and possibly aqueous [Ferris et al., 2002] activity, 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]. An example of this is shown in Figure 9 where the "visual discovery" algorithm is implemented to identify sand dune features using MGS-MOC imagery. {{this information should be referred to in the figure caption}}.

The major objective of using these science analysis algorithms, therefore, is to trigger onboard data processing in order to capture, identify, and/or monitor (track) transient geologic and climatologic phenomena at a significant reduction of data volume for ground-based analysis. This includes mission re-planning such that the spacecraft retargets the science phenomena of interest during subsequent orbits for further detailed analysis.

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) and seasonal freeze and thaw of the ice-enriched soils in the polar regions. In both cases, the onboard data analysis will detect the regions of change and can downlink (1) the changed areas only, (2) a line segmentation of the regions (e.g. region boundaries), or (3) whole images based on change over a threshold.

In addition, aeolian features (e.g., sand dunes) can be tracked, which include determining seasonal variation in distribution, size, and orientation. In this campaign,

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feature detection software is used to classify aeolian features to extract the 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, while the spacecraft acquires a large quantity of data, it downlinks only useful 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 greatly increased.

4.1 Scenario feasibility

We have been developing this nontraditional 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] and Mars Odyssey [Odyssey] 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. In essence, our planned mission could serve as a long-term (perhaps decades) observational platform that searches, identifies, and monitors transient geologic activity and atmospheric phenomena 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.

	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).

The spacecraft orbit is designed as follows. The orbit is sun-synchronous, near-circular, near polar, low altitude orbit. Surface coverage of a specific location, for example, would occur roughly twice per martian day (e.g., once in sunlight once in shadow). Daily coverage under nearly the same lighting conditions happens approximately 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.

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 recently observed environmental change on Mars [Baker, 2001], as well as the current Martian environmental conditions, the inventory and cycles of volatiles must be understood and quantified. Our mission strategy is consistent with NASA's goal of "follow the water". For example, our mission could monitor for changes in the recently reported icy landscapes of Mars (e.g., ice caps and flows within the polar regions), as well as cloud development. In addition, evidence from Mars Global Surveyor indicates the possible presence of near-surface liquid water [Malin and Edgett, 2000]. Similarly, [Ferris et al. 2002] show that some of the dark slope streaks could be indicative of current hydrologic activity. An orbiter with SAR and imager, equipped with the autonomous algorithms described above, could 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 Martian landscape. 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, our mission design would allow for constant monitoring of the Martian surface for the detection of transient geologic activity, as well as atmospheric phenomena, which includes the emplacement of lava flows, tectonism (impact cratering, faulting, and collapse events), fluvial and aeolian activity, and the tracking and monitoring of dust devils and dust storms.

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 subsequently 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, including lava flow emplacement, catastrophic flooding, and advance and retreat of ice sheets. 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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MGS, Mars Global Surveyor, http://mars.jpl.nasa.gov/mgs/

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Odyssey, Mars Odyssey Mission, http://mars.jpl.nasa.gov/odyssey/