Coordinating Multiple Spacecraft in Joint Science Campaigns

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Abstract

This paper describes technology to support a new paradigm of space science campaigns. These campaigns enable opportunistic science observations to be autonomously coordinated between multiple spacecraft. Coordinated spacecraft can consist of multiple orbiters, landers, rovers, or other in-situ vehicles (such as an aerobot). In this paradigm, opportunistic science detections can be cued by any of these assets where additional spacecraft are requested to take further observations characterizing the identified event or surface feature. Such coordination will enable a number of science campaigns not possible with present spacecraft technology. Examples from Mars include enabling rapid data collection from multiple craft on dynamic events such as new Mars dark slope streaks, dust-devils or trace gases. Technology to support the identification of opportunistic science events and/or the re-tasking of a spacecraft to take new measurements of the event is already in place on several individual missions such as the Mars Exploration Rover (MER) Mission and the Earth Observing One (EO1) Mission. This technology includes onboard data analysis techniques as well as capabilities for planning and scheduling. This paper describes how these techniques can be cue and coordinate multiple spacecraft in observing the same science event from their different vantage points.

1 Introduction

Planning, scheduling and execution techniques have been successfully applied on several NASA missions to coordinate onboard spacecraft behavior with little or no communication with ground. Data analysis technology to support the onboard identification of opportunistic science events is also being applied on several spacecraft including the Mars Exploration Rover Mission. Based on the success of these applications, a new paradigm of space science campaigns is now being investigated where opportunistic science observations are autonomously coordinated between multiple spacecraft. This paper describes technology to support this new paradigm and specifically illustrates how science observations can be cross-cued between a surface asset, such as a rover or lander, and an orbiter.

In this paradigm, opportunistic science detections can be cued by either asset where the second asset is requested to take additional observations characterizing the identified surface feature or event. This type of coordination will enable a number of science campaigns not possible with present technology. Multiple spacecraft assets already exist for Mars and are planned for several other planetary bodies including Titan (where plans call for an orbiter, aerobot and potentially a surface rover or lander) and the moon (where plans currently include several orbiters as well as multiple surface vehicles). Some examples of applications for this paradigm on Mars include the orbital detection and in-situ characterization of ice geysers, trace gases, seismic events, and surface changes, such as new gullies and dark slope streaks (which are shown in Figure 1). These features are not fully understood by scientists and data taken close after their appearance is considered highly valuable. Extensive atmospheric campaigns can also be conducted to characterize dust devils, clouds and dust opacity using simultaneous orbiter and surface asset observations. Figure 2 shows a dust-devil captured by the MER rovers and dust-devil tracks captured by the Mars Odyssey orbiter. Simultaneous observations by multiple

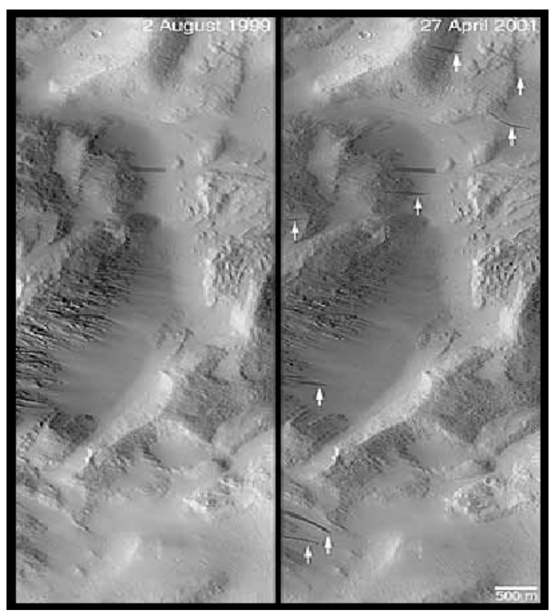

Figure 1. A dust-devil image from the MER Rover Mission and dust-devil tracks imaged by the Mars Odyssey Mission orbiter.

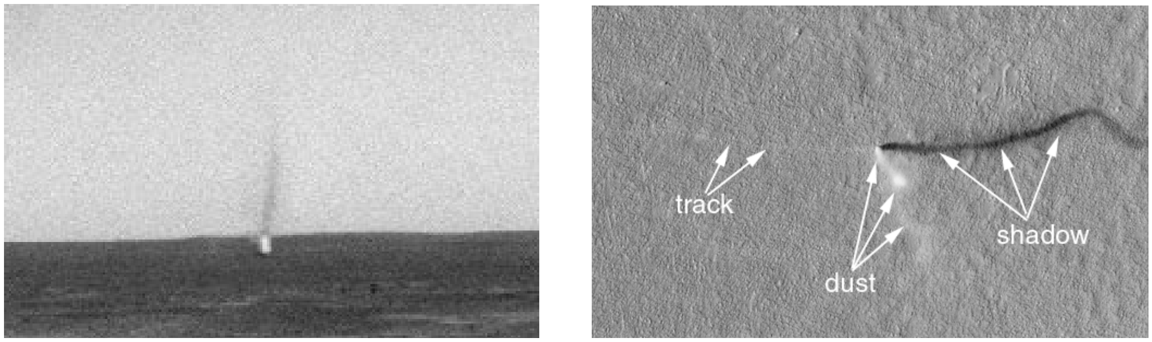

Figure 2. A dust-devil image from the MER Rover Mission and dust-devil tracks imaged by the Mars Odyssey Mission orbiter.

assets have been taken in flight; for example, Mars Global Surveyor TES (Thermal Emission Spectrometer) measurements and MER Mini-TES measurements have been coordinated in the past to take lower and upper atmospheric measurements at the same time. However, these measurements only occurred after labor-intensive manual coordination by the two operations teams. Coordinated asset campaigns are applicable to a number of platforms, including orbiters, landers, rovers, and aerobots.

Technology from several different fields is applied to support this type of coordinated campaign. First onboard data analysis techniques are used to analyze images to recognize key science events or terrain features. An example of such an event would be the identification of an active dust-devil by either a rover or orbital platform. These techniques are currently in use on several current missions including the MER Rovers [1,2] and the E0-1 Earth Orbiter One Mission [3]. Second, techniques for planning, scheduling and execution are used to re-task spacecraft in a coordinated fashion to take additional observations of detected science events within a short time period. These techniques have been extensively used on the E0-1 earth orbiter [3], Sensor web applications [4,5], and the Deep Space 1 (DS1) mission Remote Agent Experiment [6]. Planning techniques have also been used in a large number of demonstrations using the JPL research rovers [7,8]. Last, technology from the Interplanetary Network (IPN) Delay Tolerant Network [9,10] (DTN), which is being developed to provide the next generation of spacecraft relay and networking services, was used to communicate between spacecraft assets. This application ensured spacecraft could be rapidly informed of newly detected science events and that spacecraft could coordinate their responses.

This work has been tested and demonstrated with a set of relevant hardware on two primary scenarios. Demonstrations were held at the JPL Mars Yard using the FIDO MER-class research rover (shown in Figure 3) and two webcams (positioned at a high vantage point) to serve as orbiters. Both webcams were put into different “orbits” where an orbit consisted of a webcam panning to a series of positions so that different portions of the yard were in view for each pan movement. Figure 4 shows an image of the Mars Yard taken from one of the webcams.

One demonstration scenario highlighted a Mars atmosphere science campaign where a dynamic short-lived event (such as dust-devil) is detected and characterized by three hardware platforms, a rover and two orbiters. The scenario was tested in several formats where any of the platforms could detect the event and inform the other two platforms, which would then schedule a response to the event by moving closer to the event of interest and taking a high-resolution science measurement (in the case of the rover) or scheduling a new high-resolution image on the next overflight of the relevant area (in the case of the orbiters). A second scenario used a Mars seismic campaign where observations of a detected seismic event are coordinated between multiple landed and orbiting spacecraft. For this demonstration, multiple seismic sensors were positioned in the JPL Mars Yard. Several seismic events were manually triggered and automatically detected by analyzing data from the seismic sensors. When a seismic event was detected, a rover and two orbiters were quickly re-tasked to acquire new visual data of the area where the seismic event was detected. New data could capture evidence of terrain changes or other effects of seismic activity (e.g., gas vents). Both of these scenarios highlighted how a set of orbital and landed assets could be coordinated to further characterize a dynamic surface event. Though these demonstrations primarily used image data, they could easily be extended to capture other relevant types of data (e.g., spectral, GPR).

2 Data Analysis Technology for Science Event Detection

Data analysis technology was used to support event detections in both demonstration scenarios. For the

Figure 3. JPL FIDO Rover

distinctive albedo (e.g., a dust devil that is bright in a Martian scene that is dark) then the difference of the images produces a large difference in intensity that can be thresholded with confidence. This detection becomes more challenging when the difference in the intensity of the two images, at the location of the change, is comparable in magnitude to the noise of the image. This is the case whenever the dust devil is faint. For such situations, the threshold cannot be selected easily as it will likely consider image noise as change (false positive), actual change as noise (false negative) or both. The approach taken to this issue is that the detection algorithm takes into account the noise of the image and uses the fact that a dust devil is bounded within a portion of the image. To reduce the noise, the MER algorithm detects changes in an image by dampening the intensity of change using the average noise of other images in the same temporal sequence. Assuming that the major component of the image noise is zero-mean Gaussian noise, then the areas with no change tend to zero while the areas with change do not. Thus, although the intensity of the motion information has been damped, the motion can be detected because the areas with no change tend to zero faster than those with change.

Figure 4. View of JPL Mars Yard from one webcam orbiter, which was attached to the Mars Yard viewing platform.

Since dust-devils could not be easily created in the JPL Mars Yard, we instead used humans or a separate robot to create motion during a series of FIDO Navigation camera images or during a series of webcam images. Some tuning was required to rule out noise created by other factors (such as wind) and to enable reliable detection from the different platform viewing angles. However the MER algorithm was successfully applied to consistently detect motion in temporal sequences of both rover images and webcam (i.e., orbital) images.

To detect seismic activity, a new, relatively simple, algorithm was developed that examined a sequence of Real-time Seismic Amplitude Measurement (RSAM) data collected from four seismic sensors placed in different quadrants of the JPL Mars Yard. (RSAM data measures the average amplitude of ground shaking through accelerometer readings). Each sensor package contained an accelerometer and gathered time-stamped data at 100 Hertz that was compressed and sent over a wireless connection to a sink node. The sink node was then interfaced with a computer that could process the data and contained a seismic event detection algorithm. To detect a seismic event, the detection algorithm looks for local maxima (over a certain threshold) in a sliding time window that consists of the N most recent RSAM samples. If multiple maxima are found, a global maximum over that time period is determined. The algorithm then determines at what sensor and time point a global maximum has been achieved. If multiple peaks occur from different sensors in the same time window, the algorithm determines the area with the largest global maximum and signals an alert only from that sensor. Seismic activity was created by placing a steel plate in close proximity to each sensor and physically hitting it with a large sledge hammer. Though simple, this method consistently produced seismic measurements that were detected by the described algorithm.

3 Planning and Scheduling Technology for Event Response and Characterization

Planning and scheduling technology was used to support spacecraft response and coordination in both demonstration scenarios. To support these capabilities, we used the CASPER planning system [11] to handle online spacecraft command sequence modification in response to new science opportunities. Based on an input set of science goals and the spacecraft's current state, CASPER generates a sequence of activities that satisfies the goals while obeying relevant resource, state and temporal constraints, as well as operation (or flight) rules. Plans are produced using an iterative repair algorithm that classifies plan conflicts and resolves them individually by performing one or more plan modifications. CASPER also monitors current rover or

Figure 5. Dust-devil detection result taken during an atmospheric event demonstration in JPL Mars Yard. An ATRV Jr. robot was used to create dust-devil like motion. In this scenario, the motion was detected in a series of FIDO rover navigation camera images. One example from such a series in shown on the left and on the right is a snapshot of the detection result showing the area where movement was detected.

orbiter state and the execution status of plan activities. As this information is acquired, CASPER updates future-plan projections. Based on this new information, new conflicts and/or opportunities may arise, requiring the planner to re-plan in order to accommodate the unexpected events. A separate CASPER module was used for each platform and a planning model of operations was created for both the rover and two orbiters. Both models contained information on science and engineering activities relevant for that platform (such as a traverse activity for the rover and a slew activity for the orbiters). Models also contained a set of relevant states and resources for each platform, such as power and onboard data storage. All spacecraft were scheduled to have scheduled communication passes where they could communicate directly with each other or through a relay orbiter that was simulated at the network level.

To handle opportunistic science, we enabled the various CASPER modules to recognize and respond to science alerts, which are new science opportunities detected by one of the other platforms. When either the rover or one of the orbiters platform detected a science event (e.g., dust-devil activity), that platform sent a message to the other platforms to take additional observations of the science event location. For example, if a dust-devil is detected in FIDO navigation imagery, a science alert was generated and sent to the two orbiters. Each local planner would then handle the alert by attempting to schedule additional imagery of the relevant area on the next orbital pass.

4 Coordinated Science Campaign for Characterizing Dust-Devils

In November 2008 and April 2009, several multi-asset demonstrations were performed in the JPL Mars Yard. Both demonstrations highlighted an atmosphere science campaign where a dynamic short-lived event, (e.g., dust-devil), is detected and characterized by multiple hardware platforms. To showcase the breadth of this type of campaign, two different scenarios were used. One part of the demonstration showed the detection of dust-devil like motion by a rover, which then cued one or multiple orbital testbeds (i.e., webcams) to further characterize the dust-devil motion by taking additional observations of the dust-devil area on their next overpass. A sample detection result is shown in Figure 5 and a sample response image taken by one of the orbiter webcams in shown in Figure 6. A second part of the demonstration showed the detection of dust-devil like motion by one of the orbital platform, which then cued a rover to temporarily suspend its current drive activities, point its mast camera at the location where the dust-devil was last observed, acquire an image of the location, and then resume its drive. Dust-devil like motion was created during these demonstrations by setup an ATRV Jr. robot to drive in a circular formation. This scenario highlights how an orbiter could be retasked to characterize a dynamic surface event on the next over flight of the relevant areas and how landed assets could be cued or awoken when a surface event, such as a dust devil, is coming into range.

5 Coordinated Science Campaign for Characterizing Seismic Activity

In September 2009, a multi-asset demonstration was performed in the JPL Mars Yard that highlighted a seismic activity campaign where a seismic event was detected on the surface and that area was then further characterized by both orbital and rover platforms. As mentioned previously, the demonstration used a set of four seismic sensors distributed in the four quadrants of the Mars Yard. Seismic activity was triggered manually by hitting a steel plate that was located near one of the sensors. When seismic activity over a certain magnitude was detected, science alert messages would be sent to the rover and the two orbiters. Depending on the location of the event, the rover could drive towards the area of activity and take additional observations of the general area where the activity was detected. (For this demonstration, we mainly took rover mast images to characterize the area, but other remote and close-contact instruments could be integrated in the future.) Each of the orbiters would automatically schedule additional orbital observations of the relevant on the next available over flight.

For both the atmospheric event and seismic demonstrations, an application was devised (using Google Earth) that displayed science events as they were detected as well as spacecraft camera field-of-views and acquired imagery. Figure 7 shows a snapshot of that application during the seismic campaign demonstration. Location markers show the locations of science events as well as the field-of-views (FOVs) of the different spacecraft platforms. As events occurred they could be double-clicked to show the image and/or data corresponding with that event. The figure shows the data which triggered a seismic event detection and a corresponding orbiter response image.

6 Conclusions

We have demonstrated an autonomous science system for coordinating multiple spacecraft in coordinated science campaigns. By integrating data analysis and planning capabilities, the resulting system can operate in a closed-loop fashion and enables the rapid response of multiple spacecraft when a science event occurs. Further coordination can occur with little or no communication with Earth. This system was demonstrated with multiple hardware platforms on two key science campaigns inspired by current and/or potential future Mars missions. These campaigns were to dynamically characterize atmospheric events and seismic events from multiple spacecraft, both landed and orbital. This type of capability could dramatically increase the science return and type of science that can be collected by future missions.

Figure 6. Dust-devil response image taken by webcam orbiter, which was attached to the JPL Mars Yard viewing platform.

work was performed by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. The seismic sensor package hardware was designed and built by the Cascade Volcano Observatory, USGS (POC: Richard LaHusen). The seismic sensor package software was developed by Washington State University (POC's: Wen-Zhan Song and Behrooz Shirazi). The Delay Tolerant Network software, which supported communication between hardware platforms, was developed at the Jet Propulsion Laboratory by Leigh Torgerson, Scott Burleigh, Josh Schoolcraft, Amalaye Oyake, Ashton Vaughs, Nuha Jawad, Cindy Wang, and Yan Brenman.

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This work was performed by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. The seismic sensor package hardware was designed and built by the Cascade Volcano Observatory, USGS (POC: Richard LaHusen). The seismic sensor package software was developed by Washington State University (POC's: Wen-Zhan Song and Behrooz Shirazi). The Delay Tolerant Network software, which supported communication between hardware platforms, was developed at the Jet Propulsion Laboratory by Leigh Torgerson, Scott Burleigh, Josh Schoolcraft, Amalaye Oyake, Ashton Vaughs, Nuha Jawad, Cindy Wang, and Yan Brenman.

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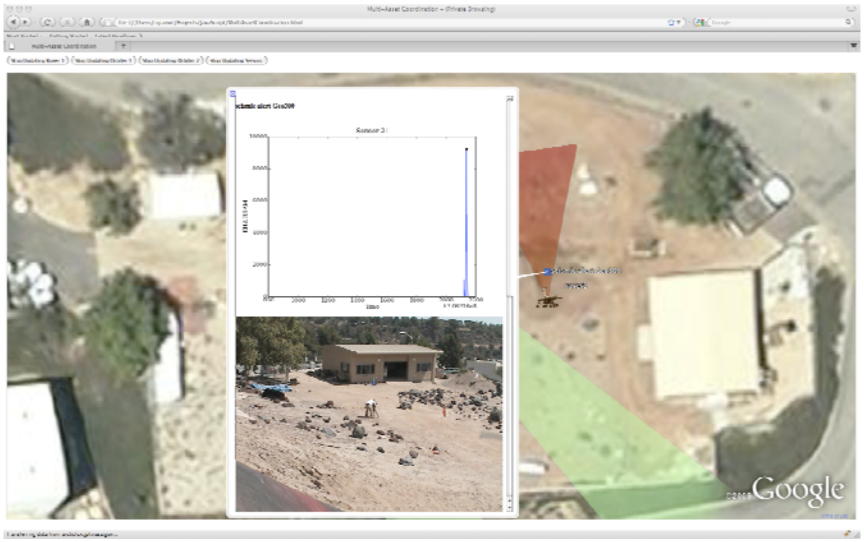

Figure 7. Screen shot of developed application (using Google Earth) to show locations of spacecraft and science events. This application ran in an online fashion where data and taken images could also be displayed

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