Improving Mission Survivability and Science Return with Onboard Autonomy

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ABSTRACT

The ability to autonomously process data to generate information onboard a spacecraft and to make decisions based on the onboard analysis to control and, where necessary, change subsequent spacecraft and instrument operations, is now a reality, having been demonstrated by the NASA New Millennium Program Autonomous Sciencecraft Experiment. Spacecraft autonomy is a necessity for spacecraft survival in a dynamic environment; to operate in the most efficient manner to conserve resources; and to maximise science return through recognition of events of particular scientific value without overwhelming onboard and downlink resources. ASE data classifiers will soon be operating on the Mars Exploration Rovers and Mars Odyssey. Scientists and engineers designing the next generation of spacecraft and instruments should consider incorporation of autonomy at early stages of the design process.

1. TRADITIONAL MISSION OPERATIONS

For much of the era of spaceflight, robotic spacecraft have collected data according to pre-planned operations sequences. After acquisition, the collected data was returned to Earth, and analysed on the ground before the next observation sequence was planned, often of another planetary body, for flyby missions. In the case of planetary flyby missions like *Mariner*, *Pioneer* and *Voyager* the observations obtained were the first high-resolution look at the surfaces, revealing strange new worlds. This was the discovery phase of planetary exploration. All of the data collected were of high value due to their uniqueness, and allowed the planning of the next stage of exploration, reconnaissance missions such as *Viking* and *Galileo* to further investigate planets and satellites. Again, regardless of usefulness, all data collected were returned within the limits of downlink. In the case of *Galileo*, downlink was severely restricted, and a significant amount of data collected was not returned.

Even today, *Cassini* observations, including instrument settings, are pre-planned and firmly established, and unalterable, weeks before encounter.

More and more missions today have moved beyond the reconnaissance phase and mapping phases into a deeper investigative mission role, driven primarily by high-level science goals. Prime examples are the fleet of assets in orbit around and on the surface of Mars, currently consisting of the Mars Exploration Rovers (MER), Mars Odyssey (MO), Mars Global Surveyor (MGS), Mars Express (ME) and Mars Reconnaissance Orbiter (MRO).

Vast amounts of data are being generated by these missions, and it is impossible to return all of the data collected. The use of onboard autonomy, which is capable of processing large data sets, recognizing events of particularly high science value, preferentially returning those data of interest, and retasking of assets to obtain more data of the phenomenon in question, would remove the time delay in the discovery process by removing the need to data downlink, analysis, and re-sequencing of assets from the ground, a process that leads to missed opportunities for higher temporal resolution data, for example.

2. OPERATIONS WITH AUTONOMY: ASE

Autonomous spacecraft operations have been successfully demonstrated by the New Millennium Program Autonomous Sciencecraft Experiment (ASE) flying on the Earth Observing 1 spacecraft (*EO-1*) [1]. This new, flight-tested capability allows operations decisions to be made onboard the spacecraft, including resource allocation and fault detection and mitigation. Sequenced operations commands can be altered as a result of onboard data analysis, with science goals driving mission operations.

ASE routinely detects dynamic events and retasks *EO-1* to obtain further data, and the planner developed for ASE is currently used for routine *EO-1* operations, overseeing over 5000 datatakes, greatly reducing operations cost while increasing system flexibility and allowing rapid, autonomous operations changes [1]. ASE uses classifiers to process Hyperion hyperspectral imaging data to detect dynamic events. Hyperion collects data at 220 wavelengths between 0.4 and 2.5 microns, at 30 m/pixel. ASE is being used to detect thermal emission from active volcanism [2], changes in the cryosphere, for example, where ice is forming or breaking up [3], and flooding events [4], as well as assessing cloud cover [3]. A précis of the most important data is returned in hours, rather than the weeks taken to obtain data with previous 'normal' operations [2]. On a positive detection of one of these processes of interest, an ongoing volcanic eruption, or detection of the onset of ice break up on a frozen lake, the onboard planner reschedules the spacecraft to obtain additional observations at a higher temporal resolution, at the next available opportunities. Having also determined cloud cover, the option exists to repeat observations at a later date if the target is obscured.

With a view to increasing temporal coverage of events, making the best use of other available resources, ASE and *EO-1* have been incorporated into a sensor web [5] that utilizes multiple detection and classification systems to detect events, which then are used to trigger *EO-1* observations. The sensor web is autonomously operating, seamlessly integrated into the *EO-1* operation planner, and affords rapid response to detections of volcanic activity [6], cryosphere changes, and flooding.

3. ASE ON MARS

ASE classifiers are being readied for uplink to Mars Odyssey THEMIS instrument to monitor the edge of the martian ice caps, detect clouds, and search for thermal anomalies [7], and making use of data for which there is insufficient downlink to return. Similar algorithms for detecting dust devils and clouds were uplinked to MER in the fall of 2006 [8]. In the case of the THEMIS experiment, a large proportion of collected data (~40% of nighttime data) are not returned due to downlink constraints. The ASE classifier will process all relevant THEMIS data to determine the position of the edge of the polar ice caps, and returning not the whole dataset but the edited dataset containing the edge information. In this way, at very little resource use, additional science value is returned. The ASE THEMIS data classifiers will also search through the data for pixels of anomalous surface thermal emission on the surface, possible evidence of hydrothermal or volcanic activity. This is a very low-cost operation looking for a very low-probability occurrence, but with a very high potential scientific value if such activity is discovered. In MER Panoramic Camera (Pancam) data, ASE algorithms search for clouds and dust devils, sending down only those images, or even portions of those images, where such phenomena are detected [8]. This allows more images to be taken and only the most valuable to be returned.

4. ENHANCED SCIENCE RETURN EXAMPLE

The benefits of Artificial Intelligence and spacecraft autonomy onboard a deep-space mission can be illustrated by considering how best to detect and monitor a dynamic, unexpected event of high science interest, such as an ongoing, large-scale but short-lived volcanic eruption [9]. The jovian moon Io is intensely volcanic, and although studied extensively by the NASA *Galileo* spacecraft, many questions remain as to the precise nature of the composition of the erupting lavas, specifically, whether very-high temperature ultramafic lavas are present [10, 11]. Ultramafic lava would apply strong constraints on the thermal and chemical evolution of Io's interior [12]. The science objective would therefore be to determine the temperature of Io's lavas and constrain possible compositions.

Given the nature of thermal emission from active volcanism, the best opportunity for detecting high-temperature lavas comes from rare lava-fountain events, where relatively large areas at or close to magma liquidus temperatures are exposed. Even from a great distance away, even from the orbit of Europa, it is possible to determine a lower limit on magma temperature, a very strong constraint on composition. For *Galileo*, engaged in multiple fly-bys of the Galilean satellites, each encounter observation sequence was planned well in advance. Instrument setting and exposure times were pre-ordained. Although lava fountains were observed, in one case at high spatial resolution, observations were planned to image the non-thermally active background and the intense thermal emission saturated both the visible imaging system (SSI) and infrared imager (NIMS). There was no opportunity to quantify the intensity of the thermal emission and change observation sequencing and instrument settings. By the time data had been returned to Earth and analysed, the spacecraft had moved on and the science event was over.

An onboard AI would do things very differently. Onboard data processing would quickly identify an intense thermal source at a great distance, calculate the opportune moment to make observations (with visible and infrared imagers in the 0.4 to 10 micron range to capture the full thermal emission spectrum), and set the appropriate instrument gain state or exposure time to obtain unsaturated data. Additional instrumentation can be brought to bear on the new eruption: an ultraviolet spectrometer would be used to study erupting gas. Subsequent orbits would flag this location for in-depth visible and infrared study to determine composition spectroscopically.

The science content of the returned data is therefore increased from an acquisition queue using preset observation sequencing, the need for communications (data transfer and commands, and accompanying time lag) between spacecraft and Earth for spacecraft re-tasking is eliminated, the use of bandwidth is optimised, and an important science question can be answered by making decisions on the spot.

A mission to Europa, such as the Europa Explorer concept now being studied by NASA, would spend at least two years in the Jovian system. This will allow considerable lengths of time for monitoring Io.

5. EUROPA

Detection of active resurfacing processes on Europa would be a major discovery. Such detections are best accomplished by either detecting plumes or by detecting anomalous thermal signatures on the surface in the thermal infrared [13]. Data classifiers based on the cryosphere and thermal detectors on ASE would fly on the Europa Mission, processing hyperspectral data and data from other instruments to detect such spectral features [13], a low-cost process with a potential huge science return.

6. MISSIONS REQUIRING AUTONOMY

The use of autonomy need not be as aggressive as described in the example in the previous section. The degree of autonomy has to be tailored to the environment in which the spacecraft will operate, and the science goals of the mission.

Some degree of autonomy is a necessity for missions inserted into a dynamic environment. Examples include balloons, blimps (a steerable balloon) or aerobots (rigid flying machines) in planetary atmospheres. A blimp exploring the atmosphere of Mars, Venus [e.g. 14], or Titan [e.g., 15], can process data onboard and return to sites, descending to the surface if necessary, to carry out a closer investigation of a target of interest identified during onboard data processing. This is especially important on missions where the lifetime of the probe is limited, and communications might be sporadic. Onboard autonomy allows continual operations, far removed from remote control, with accompanying time lag.

Another possible operational scenario is that of a Venus Atmosphere/surface blimp or balloon. Detecting a feature of interest from a relatively high, (and cool) altitude, the probe could make a rare descent into the much hotter, hostile environment for a quick high-resolution observation or sample collect before retreating back to safety at higher altitude.

For missions to active bodies such as comets, the level of autonomy can be tailored to the goal of the mission: is it important to head for a plume erupting from a comet to collect a sample, or are plumes to be avoided at all costs? In either case, the plume has to be identified first.

Thusly, these and others missions can benefit from onboard processing to focus on features and processes of greatest interest, allowing modification of instrument and spacecraft goals during monitoring or mapping phases. Another example would be on the aforementioned Europa mission. A spacecraft orbiting Europa has a limited operational lifetime because of the hostile radiation environment. Processing of data onboard can increase the science return by returning products from data that would otherwise not be returned in full, allows rapid identification of high-priority phenomena on the surface (thermal emission signifying possible volcanic activity, for example), and retasking of instruments and resources to gather data of these locations at higher temporal, spatial and spectral resolutions. Detection by a low data-volume instrument could be used to trigger observations by a high data-volume instrument, for example, an imager detecting a new hot spot triggering the spacecraft radar.

The same techniques for identifying and reacting to detections of active volcanism can be used to search for and investigate other phenomena on other planets, for example, on a dedicated mission to the Saturn moon Enceladus (detecting plumes, thermal anomalies on the surface), on Triton in the Neptune system (volcanic plumes and changes in ice caps), and on Titan and Venus missions (searching for volcanic activity and compositional outliers, for examples).

7. INCORPORATING AUTONOMY

The new ASE technology allows a step in the normal planetary exploration timeline to be removed. Now, instead of a discovery being investigated by the next mission, further investigations can be performed on the spot, driven by onboard science data analysis applications controlling resource allocation.

When designing a mission, therefore, it is important to consider how autonomy can enable the achievement of science goals early in the concept and design process. Spacecraft autonomy can enhance what a mission can achieve, as shown by ASE [1-4] but to gain maximum benefit, it is preferable to integrate autonomy into the hardware, software and operational concept design sooner rather than try to bolt it on at a later stage. In particular, data classifier efficiency is a factor of available processing speed and data storage capacity, and data product type, as well as a function of the complexity of the data processing task.

Further information about ASE and contact information for the ASE Team are available at http://ase.jpl.nasa.gov.

8. ACKNOWLEDGEMENTS

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