A Deployable Instrument Package for Paleontological Research

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Abstract

The search for evidence of past life is likely to be an important part of Martian exploration. Unfortunately, the number of potentially fossiliferous outcrops at any landing site may be quite large, and it would be advantageous to have some automated way of ranking those outcrops with respect to their paleontological potential. The Deployable Instrument Package for Paleontological Research (DIPPR) is designed to perform such a function. DIPPR consists of a family of one large and four small rovers carrying arrays of cameras and spectrometers for outcrop characterization. The large rover would be responsible for long-range observations, heavy computational tasks, and transport of the smaller rovers. The smaller rovers would have the capability to approach outcrops closely and perform more detailed scans. Outcrop characterization protocols would involve a progressively updated calculation of "paleontological probability index", a semi-quantitative measure of the likelihood that a particular outcrop may contain fossils. Ultimately, DIPPR would produce a paleontological probability map of the landing site, which could be used by astronauts to determine how best to plan extravehicular excursions for fossil hunting. While designed to be used by astronaut teams working on Mars, DIPPR also could be operated remotely from Earth with relatively minor design modifications.

Introduction

Observations made during the Mars Global Surveyor mission indicate that liquid water has existed on the Martian surface in the past and may exist today in the shallow subsurface (Head et al., 1999; Malin and Edgett, 2000a,b; Zuber et al., 2000). Combined with the documentation of chemical and morphological signatures in Martian meteorite ALH84001 that are suggestive of the operation of organic processes on early Mars (e.g., McKay et al., 1996; Thomas-Keprta et al., 2001), such findings constitute a compelling argument that the search for evidence of fossil life should be one of the principal goals of the first stages of manned exploration of Mars. Unfortunately, the fossil record on Earth is far from completely preserved, and – although we do not have to contend with the ravages of plate tectonics on Mars as we do on Earth – we should not expect that fossils will be easily found on the Martian surface. As the authors of a recent NASA strategy report put it, searching for well-preserved fossils on Mars will be like searching for the "proverbial needle in a hay stack" (Carr et al., 1995).

How do we improve the odds of a successful search for fossils on Mars? Paleontological experience here on Earth suggests that the key is looking in the right places. The first step must be to choose a landing site which exhibits characteristics of an area that might have harbored and preserved life in the past using appropriate space borne remote sensing techniques. While such methods will improve the likelihood of success, a productive search for Martian fossils will require additional tools to help astronaut teams "high-grade" potential study sites at length scales ranging from kilometers to microns. In this report, we describe a concept and design for a mobile, semi-autonomous instrument package. This package could be deployed by Martian astronauts to provide the data necessary to make informed decisions about which potential study areas have the highest probability for containing fossils and thus should be earmarked for more detailed study by astrogeologists. In this manner, the package would promote a streamlined mission plan, minimizing the number of extravehicular excursions necessary for effective fossil exploration and maximizing the efficient use of surface time by astronauts.

Concept

We envision the Deployable Instrument Package for Paleontology Research (DIPPR) as a family of versatile, sensor-bearing rovers. These rovers will carry a variety of instruments designed to collect imagery and compositional data that will permit on-board and remote computers to establish the probability that any potential study site might contain fossils. Based on such information, paleontological probability gradients can be mapped over accessible regions of the Martian surface. This information can then guide astronauts in making decisions about which sites to study in greater detail.

The rovers in the package can be thought of as a family of semi-autonomous vehicles that have specific functions but also work as a team to optimize their versatility, efficiency, and mobility. In a typical deployment, a large rover capable of long-range scanning would collect low-precision data to develop a coarse paleontological probability map. The results would be analyzed using on-board decision-making software, which would help to determine where smaller rovers would be deployed for more detailed work. Although the rover family could proceed with these detailed studies autonomously, the data obtained in long-range scans, including the assigned paleontological probability map, would be transmitted in real-time to astronauts at the Martian base station. Furthermore, the astronauts would have the option of manually overriding the automatic short-range deployment operation, if desired.

At short range, the small rovers would carefully scan outcrops for chemical, mineralogical, and morphological signatures of rocks that have high probabilities of containing fossils. Based on its analysis of the results, DIPPR would then transmit a high-resolution paleontological probability map to the base station. This map would serve as a fundamental resource to guide astronaut investigations of potentially fossiliferous outcrops. Although DIPPR is designed as an aid for *in situ* human exopaleontological research, minor modifications of the design and appropriately deployed communications satellites could permit the remote operation of such an instrument package from Earth.

Most of the sensors on DIPPR are based on established technologies that were used on the Pathfinder Mission (NASA Mars Exploration, 1997a) or are intended for use on the Athena Payload (Athena Project, 2000). What is novel about DIPPR is not the design of the instruments in the package, but rather the way in which data obtained by those instruments are utilized. The ability of the LMR array to respond to its own observations promotes the highly efficient use of astronaut time and energy. Moreover, DIPPR's capacity for routine data interpretation could greatly improve the ability of astronauts who have not had extensive training in paleontology to conduct effective research.

The Science of Mapping Probability Gradients for Fossil Discoveries

The first step toward a successful search for evidence of ancient Martian life will be to identify rock outcrops that are most likely to contain preserved fossils. In general, this excludes exhaustive studies of igneous and most metamorphic rock outcrops. It is tempting to limit the search for fossils to sedimentary outcrops, but this step alone is not sufficient to significantly expedite the process of Martian fossil exploration. The Martian surface displays vast regions with a sedimentary substrate, and our experience on Earth is that relatively few outcrops of sedimentary rocks contain well-preserved fossils. Therefore, we need protocols for identifying appropriate rock types and establishing a ranking scheme for their probability of containing fossils. In addition, these protocols must be based on data that can be obtained using instruments appropriate for deployment on a rover-sized vehicle.

Evaluating the Potential of Outcrops to Contain Appropriate Rock Types

Some DIPPR rovers would be equipped with cameras capable of taking panoramic images of relatively large regions of the Martian surface, or with relatively low-spatial resolution spectrometers capable of crude determinations of outcrop composition. Such long-range information would be evaluated by on-board computer systems to develop a preliminary probability map by comparing the observed outcrop characteristics with a digital catalog of geomorphic and geochemical features that are indicative of sedimentary rock outcrops on Earth. For example, landforms that look like mesas or outcrops that exhibit horizontal features suggestive of stratification would be considered indicative of the presence of sedimentary rocks, whereas narrow conical landforms and outcrops with no apparent bedding would be rejected – or at least given low priority – for further consideration. Crude estimates of outcrop chemistry would aid the site selection process further. While this approach might eliminate some potentially fossiliferous outcrops, the goal is to direct the astronauts toward outcrops that have the greatest likelihood of containing fossils.

Rock Types and their Paleontological Potential

Once the long-range image scans have determined that certain outcrops may have a high potential for containing sedimentary rocks, short-range scans must be used to determine the paleontological potential of rock types actually encountered. Although some igneous materials, such as air fall tuffs, and some low-grade metamorphic rocks display fossils here on Earth, sedimentary deposits are likely to be the most fruitful targets for paleontological research on Mars. Of these, sedimentary conglomerates and breccias have the lowest potential, whereas other siliciclastic rocks and chemical-biochemical sedimentary rocks are more favorable. Fossils are most abundant on Earth in the carbonate rocks limestone and (less frequently) dolomite. Limestone forms most often as a consequence of the direct underwater biochemical deposition of calcite and aragonite at rates ideal for the preservation of organisms. Other carbonate rocks, such as travertine deposited around hot springs, may preserve algae and biofilms. Dolostone typically forms by the diagenetic replacement of limestone and may preserve structures of biological origin that existed in the limestone precursor. It is important to note, however, that there are currently no known carbonate rock deposits on Mars; however, we do not exclude the possibility of finding such deposits due to the low spatial resolution of recent and previous studies.

Chert and evaporite, both chemical/biochemical sedimentary rocks, are also important fossil resources on Earth. Chemically-deposited chert forms from silica gels that may entrap microorganisms during deposition. (The oldest known fossils on Earth were preserved in chemically deposited chert; Schopf, 1999.) Biochemically-deposited chert typically represents the accumulated shells of diatoms and other silica-producing organisms. On Earth, highly consolidated biochemical chert does not typically preserve the structures of these organisms very well. Poorly consolidated biochemical chert preserves fossils well on Earth, but would be eroded away rapidly in an environment similar to Mars. Diagenetic chert usually forms when silica-rich fluids percolate through siliciclastic and carbonate rocks; in some instances, this process does not disturb pre-existing fossils. Evaporite rocks form during protracted periods of evaporation in closed lakes and ocean basins. As with limestone, no evaporites are known on Mars at present, but we do not exclude the possibility of unknown deposits. Although they are generally good at preserving organic material, the highly saline conditions under which evaporites form are not very conducive to life (Dietrich and Skinner, 1979).

Fine-grained siliciclastic rocks such as shales and mudstones are also prime targets for fossil hunting. Making up nearly half of all sedimentary rocks in the stratigraphic record on Earth, fine-grained siliciclastic rocks are, for the most part, representative of sediments deposited in quiet water. Such conditions are particularly well suited for the preservation of soft-bodied organisms, and terrestrial shales typically contain between one and ten weight-percent organic carbon (Boggs, 1992). Sandstones are less likely to contain fossils because sand deposits typically have high porosity, which can encourage the decay of organic material after burial. If the sand was rapidly lithified in a wet environment, however, some fossils might be preserved.

Preservation Considerations

Certain conditions that either enhance or reduce the ability of a rock to preserve fossils are shared among all fossil-bearing rocks. Oxidizing conditions, which are commonly related to dry environments, hinder fossil preservation by oxidizing organic remains to CO_2 and by providing an ideal environment for aerobic microorganisms to participate in decomposition. Reducing conditions, associated with stagnant bodies of water and swamps, tend to improve fossil preservation because such conditions are inhospitable to many organisms that promote decomposition of organic materials (Dietrich and Skinner, 1979). These redox conditions are preserved in sedimentary rocks, and can be used to determine the likelihood of fossil preservation in those rocks.

Identifying and Ranking Potentially Fossiliferous Rock Types

The identification and characterization of Martian rocks is a difficult task, especially without human assistance. Traditional techniques of field geology include visual examination, textural analysis, and the testing of physical and chemical characteristics. While such methods are easily taught to humans, many are surprisingly difficult to automate. Visual examination, for example, involves complex image processing that is effortless for humans, but still imperfectly implemented with electronic apparatus. To a field geologist, the “feel” and “taste” of a rock are important components of rock identification, yet humans are far better at sensory perception than the most sophisticated robot. Even such "low-tech" methods as measuring hardness or testing for the presence of calcium carbonate with hydrochloric acid are difficult for machines, particularly in the Martian environment. On the other hand, automated probes can be built with some capabilities that human's do not have. In particular, various forms of spectrometry may be used for mineral identification. Once a rock's mineralogy is known, it is a relatively simple matter to determine its type with only limited textural analysis that is well within the capabilities of existing optical sensors.

DIPPR's algorithms for classifying the paleontological potential of a given outcrop would be based on a series of mineralogical and textural evaluations as follows. Initial spectral scans would be evaluated for indications of the presence of certain sets of minerals:

- Mafic Minerals – pyroxene, olivine, amphibole, chromite, etc.
- Moderate- to High-Pressure Metamorphic Minerals – garnet, kyanite, coesite, etc.
- High-Temperature Metamorphic Minerals – sillimanite, cordierite, etc.

These mineral groups are only found in quantity in igneous and metamorphic rocks, which do not typically preserve fossils. Therefore, any rocks containing more than ten modal percent of minerals from these groups would be removed from paleontological consideration.

After this preliminary consideration, identification of the remaining candidate rocks would be based on their most common mineral constituents, which are referred to in this report as "primary minerals". DIPPR's working definition of various candidate rocks is based on an abundance of more than forty-five modal percent of primary minerals as follows (Carmichael, 1982):

- Siliciclastic Rock – clay minerals (e.g., kaolinite, illite) or quartz
- Carbonate Rock—calcite, dolomite, aragonite
- Evaporite—halide minerals (halite, sylvite, etc.), or sulfates (gypsum, anhydrite, etc.)
- Chert—cryptocrystalline quartz

In some cases, mineral content alone will not constitute sufficient information for the determination of rock type and short-range imagery must be analyzed for distinguishing features. For example, sandstone and chert both have quartz as a primary mineral but chert is microcrystalline and sandstone is made up of easily discernable grains. Grain size also helps to distinguish fine-grained and coarse-grained siliciclastic rocks that have very different paleontological potentials. Grain shape studies based on close-up imagery will provide a means of evaluating the level of deformation or metamorphism of candidate rocks and further evaluating their potentials; sutured grain boundaries and the presence of contorted microlamination would lead to the assignment of lower paleontological potentials.

The actual ranking of observed rocks for paleontological potential would follow rules based on terrestrial experience. Limestones and fine-grained siliciclastic rocks are most likely to retain fossils, so they would receive high and sub-equal preliminary rankings. Chert is relatively less likely to be fossiliferous and would be ranked lower. Evaporites and sandstones would be ranked lower still. Preliminary scores would be modified based on accessory mineral compositions and other factors that increase or decrease the probability of fossil preservation. For example, the presence of accessory minerals containing oxidized iron and manganese, such as hematite and limonite, would suggest oxidizing conditions and would lower the rock's ranking slightly. In contrast, the presence of minerals like pyrite would suggest reducing conditions and would raise the rock's ranking. Sensor indications of the presence of organic material in any sample would result in the highest ranking. A chert's rank would be increased if it either displayed sedimentary layering or formed nodules in a carbonate or siliciclastic matrix, since such chert on Earth seem more likely to preserve fossils.

The Modification of Rankings Based on Pattern Recognition

Relatively highly ranked materials would be examined for the presence of shapes that might constitute further evidence of fossil content. Protocols for classifying patterns of both possible macroscopic and microscopic fossils would be based on systems used on Earth to classify fossil types. Rock surfaces would be examined for the basic shapes and structures that typically characterize terrestrial fossils:

1) Straight or coiled single cones, tubes, or cylinders
2) Colonial tubes
3) Valves
4) Multielemental or multiplated structures
5) Reticulate and cystose networks.

Rocks with surfaces displaying such features will receive higher rankings. If these features were developed in materials with chemical compositions that frequently characterize fossil replacement minerals, such as silica and apatite, the ranking would be even higher. Progressively higher resolution images could be used to search interesting macroscopic shapes for microstructures indicative of an organic origin and could be used to examine the sample for unicellular and multicellular microorganisms and the dissociated skeletal fragments of macro organisms . Highly suggestive shapes could be compared to digital reference catalogs of terrestrial species to further hone the ranking procedure.

Development of Final Paleontological Potential Maps

Based on these rankings, each studied section of each outcrop would receive a numerical score representing its calculated potential for containing fossils. The score would be entered automatically into a standard geographical information system (GIS) database and thus registered with high-resolution digital elevation data to develop a map of paleontological potential for astronaut use. We anticipate that such maps would be the fundamental resources used by astronauts and Mission Control to plan extravehicular excursions for the collection of appropriate samples and final evaluation of candidate outcrops for their fossil contents.

DIPPR Design

A family of rovers carrying various sets of analytical tools and cameras will collect the data necessary for building paleontological potential maps. In this section, we describe the philosophy behind the family rover design and the general technical specifications of the instruments employed.

The Martian Rover Family Unit

Our Martian rover (MR) family concept grew out of a design developed in the Fall of 2000 as part of an MIT freshman-level subject called "Solving Complex Problems". (The problem was to develop a mission to Mars to search for signs of past or present Martian life. Our complete mission design may be accessed via http://web.mit.edu/12.000/www/finalpresentation/). The MR family, which consists of four little Martian Rovers (LMRs) and a single big Martian rover (BMR), was conceived to minimize potential problems that might be encountered by lone rovers, to improve the quality of data communication across great distances on the Martian surface, and to generally increase the efficiency of rover-based research. The BMR would be capable of long-range satellite communications and could accomplish power-intensive computations. It also would accommodate a larger sensor payload. Most importantly, the BMR would have the capacity to carry the LMRs and act as a charging station. Control of LMR activities typically would be delegated to the BMR, but human control would be possible through relays of commands through the BMR communications system. . This structure improves the likelihood of a successful deployment in a variety of ways. LMRs would be assigned to particularly dangerous tasks (such as close encounters with outcrops or navigation over rough ground) and the loss of a single LMR would not jeopardize the overall success of the mission. Moreover, functional LMRs could inspect a damaged LMR and potentially make field repairs. Communication would be made more reliable by relaying data from the LMRs to the BMR, and redundant data storage on LMRs and the BMR would improve data security.

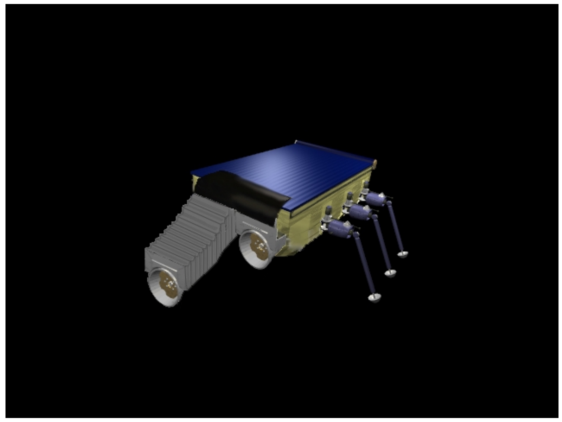

Figure 1: A Little Martian Rover

Little Martian Rovers

Each LMR would consist of a Sojourner-like rover body with some special modifications. For example, the wheels used on Sojourner would be replaced with six evenly spaced legs. Although a legged rover is heavier than a comparable wheel-based design, negative ramifications of the extra weight are mitigated by the relative ease with which a legged rover can negotiate rocky terrain. The legs would consist of two aluminum bars with a foot attached to the longer bar. The hip joints on the legs would be used for rotational motion, and the knee joints would provide lateral motion. A second modification would be the mounting of a fully articulated sensor arm at the front of the rover. This adaptable device would accommodate long-focal length cameras (used primarily for navigation), short-focal length cameras (for mesoscopic and microscopic imaging of outcrops), and narrow field-of-view spectrometers. A third new feature would be a tool mounted on the back of the rover to prepare fresh rock surfaces. Power would be drawn from battery packs that would be recharged by high-efficiency solar cells mounted on the LMR. In the event that these cells are incapable of maintaining sufficient charge for effective operation of the rover, each LMR would have the capability of traveling back to the BMR to recharge The communications system on an LMR would be very similar to the system used for Sojourner, allowing the LMR to communicate with the BMR via basic UHF. The LMRs may move up to 500 meters from the BMR before their signal starts to degrade (NASA Mars Exploration, 1997a,b).

Big Martian Rover

With a total height, width, and length of about 0.75 m, 1 m, and 1.5 m, respectively, the BMR would be responsible for the long-distance transportation of the rover family, as well as long-distance communications and high energy-usage operations of the mission. The BMR would be substantially larger than Sojourner with an enclosed deck. It would have six wheels, each with a diameter of 0.5 m, which would be mounted on a suspension system similar to the JPL-developed Rocker-Bogie system. The LMRs would enter the BMR via a ramp to a rear hatch that would be closed during transport. Power would be supplied by a solar array that would be similar in design and efficiency to the LMR array but which would be much larger. A communications/navigations mast would be mounted on the front of the BMR; it would accommodate a 360-degree camera as well as a satellite uplink and rover-to-base communications systems. The BMR also will be equipped with a navigational camera, a long-range spectrometer, and a device to expose fresh rock surfaces.

DIPPR Payload

Cameras

Panoramic cameras would be employed on the rovers for navigation and long-range outcrop analysis. On the BMR, a camera capable of 360° imaging at high resolution would be required for effective visual analysis of outcrops at multi-kilometer distances from the rover, as well as long-distance navigation and landmark identification. Since the LMRs would not require such an extensive imaging system, a fixed wide-angle camera mounted on the front of the rover would suffice for navigation, obstacle avoidance, and visual analysis of outcrops at distances of several hundred meters or less. An example of a camera system that would meet our needs is the Pancam system, being implemented as part of the Athena payload on the two Mars Exploration Rovers [MERs] slated for launch in 2003 (Athena Project, 2000). The Pancam is a mast-mounted stereo camera system with very high resolution, which includes several filter wheels to provide rudimentary spectroscopic data and color imagery. These characteristics make it ideal for use as the panoramic camera on the BMR, but leave Pancam a bit overqualified for the LMRs. For the LMR camera, a wider field-of-view than the Pancam's 18.4°×9.2° would be preferred, whereas the extensive set of filters would be unnecessary, as would the mast and servomotor control. Nonetheless, Pancam serves as an excellent model for the DIPPR cameras, and further technical details can be found on Cornell's Athena Payload website (Athena Project, 2000).

Microscopic imaging cameras would be employed on the LMRs for use in close-up analysis of the surfaces of rock outcrops. Mounted on the LMR's articulated sensor arm, the microscopic imaging camera [MIC] needs to have a resolving power on the order of 10μm, in order to accurately image mineral grains as small as 100 μm. Its magnification needs to be adjustable up to a resolution of about 100μm, with a field of view that covers several square centimeters. These specifications are based on the need for the ability to determine whether a silica-rich siliciclastic rock is a sandstone, chert, or conglomerate. Identifying mineral grains in these rocks requires both high and low magnification, since grains in conglomerates can exceed several centimeters in size, while sand grains can be as small as 100μm.

A camera with some microscopic imaging capability was part of the ill-fated Mars Polar Lander, and a fully functional MIC is slated for the MERs in 2003 (Athena Project, 2000). While the actual specifications of the Athena payload MIC are unclear, DIPPR's MICs will most likely require a shorter focal length and greater magnification range, given the location where the MER MIC is mounted, looking down from the rover's undercarriage.

Spectrometers

There is a wide array of spectrometers available today which are capable of identifying the mineralogy of a rock sample, including UV/VIS, VNIR, Thermal IR, Raman, and Mössbauer spectrometers. Each has its own particular advantages and disadvantages, which must be taken into account when choosing spectrometers for DIPPR. DIPPR will require two distinct classes of spectrometer: an imaging spectrometer for the BMR and point spectrometers for the LMRs. The imaging spectrometer will need to be able to accommodate a 360° field of view, and to characterize mineral abundances in outcrops up to several kilometers away at 1 meter per pixel or better spatial resolution. The point spectrometer must be able to determine the mineralogy of an outcrop's surface to the level of individual mineral grains, or on the order of 100 μm. Both spectrometers must be able to identify all of the minerals specified previously in this paper. This constraint immediately removes the Mössbauer spectrometer from consideration, since it only identifies minerals containing iron (Athena Project, 2000).

All of the remaining spectrometers, however, have the ability to identify the necessary minerals, thus the field must be narrowed by considering the engineering constraints of the mission and the present technology. UV/VIS spectrometers are very accurate and useful for determining mineralogy on Earth, but have not been fully adapted to use in space yet. As such, they are an unproven technology. Raman spectrometers, however, have been adapted for planetary exploration (Athena Project, 2000). Since Raman spectrometers have no long-range capability, one could not be used for the BMR imaging spectrometer (Lane, 2001). A Raman spectrometer could, however, be used for the LMR spectrometer. However, Raman spectroscopy is still a relatively new technology, and no missions have used it yet. Furthermore, Raman spectroscopy requires precise control of the separation between the instrument and sample, and so only works at distances on the order of 1cm. Therefore, given current engineering constraints and technology, we choose not to use Raman spectroscopy in DIPPR.

VNIR (visible-near-infrared) and thermal IR spectrometers are proven technology in space. Numerous Earth-observing satellites use imaging VNIR spectrometers, and very small, light, and field-portable terrestrial VNIR instruments are in use by geologists around the world (NASA Jet Propulsion Laboratory, 2001; Analytical Spectral Devices, Inc., 1998). Thermal IR spectrometers are also used on Earth-observing satellites, as well as two Mars-observing satellites and the 2003 MERs. In most cases, these spectrometers are combined to some degree, so that a single instrument includes visible, near-infrared, and thermal-infrared bands. Imaging spectrometers in these bands have been built for space applications with very high spectral and spatial resolutions, making them ideal for use on the BMR. Point spectrometers in these bands are extremely small and light, and have sharp spatial resolution and extremely high spectral resolution (Analytical Spectral Devices, Inc., 1998). While DIPPR would require the design of new versions of these instruments, the basic design and engineering work needed to implement them on a Mars rover has already been done.

A model thermal-infrared imaging spectrometer for the BMR is the mini-TES, part of the Athena payload (Athena Project, 2000). It is small and light, with sufficient spectral resolution to identify primary rock-forming minerals that are expected on Mars. Additional resolution and/or spectral coverage might be necessary to characterize the abundances of accessory minerals, but it would be relatively straightforward to upgrade mini-TES's capabilities. Although mini-TES could also work as a point spectrometer, its optics are designed to look at distant outcrops, not nearby mineral grains. Thus, a better model for the LMR spectrometers would be the Analytical Spectral Devices VNIR point spectrometer, which is extremely lightweight and uses little power. It acquires data through a fiber-optic cable, the terminus of which could be mounted on the LMR sensor arm (Analytical Spectral Devices, Inc., 1998). While it is not designed for space use, it could be modified to be space-certified.

Rock Resurfacing Tool

While the LMRs would have the capability to conduct most tests necessary for rock identification and shape analysis without assistance, it may prove necessary from time to time to obtain a fresh surface on an outcrop for detailed work. In such cases, a rock resurfacing tool might be used. Such tools have been designed for the Athena Mission, in the form of the Rock Abrasion Tool (RAT), and we envision mounting a similar design on the LMRs (Athena Project, 2000). The RAT is a small grinding wheel, with a diamond-based abrasive and a stiff wire brush for cleaning. Since any rock resurfacing tool would likely draw a large amount of power for a short time, the LMR batteries would be used to provide power for the tool.

Navigational Aids and Safety Devices

A sophisticated software system would be employed to permit the MRs to navigate potentially hazardous terrain. Receiving input from the navigational cameras, an accelerometer, and three inclinometers, the navigation software would quickly calculate position, orientation, movement direction, and acceleration and adjust the motion of the MR to correct for "stumbles" and choose as clear a path as possible. In general, these systems would be similar for all rovers, but there would be some algorithmic differences. For example, the BMR navigation software would include clauses permitting both long- and short-range navigation, whereas the LMR navigation software would have lower tolerances for obstacle size and use different algorithms for the coordination of leg movements.

In order to produce accurate paleontological potential maps, it would be important for all MRs in the family to be equipped for exact location determination. This would be accomplished by registering all rover movements relative to the Martian base station. (Presumably the position of the base station is known well.) In addition to simply counting wheel revolutions and leg movements using on-board computers, we envision having the ability to triangulate the position of all rovers relative to one another and known geomorphic features using laser rangefinders mounted on each rover. Both locational methods would be augmented by the use of stereoscopic images to evaluate the apparent height and width of distant landforms that have precisely determined true height and width characteristics as determined from digital elevation models.

Data Analysis Procedures

A primary concern in the design of DIPPR has been to maximize overall mission efficiency by progressively minimizing the number of outcrops that astronauts must study in detail. To accomplish this, we have focused much of our effort on determining optimal procedures to assess sites for their potential to be fossiliferous and, on that basis, to assign them relative priorities for detailed study.

Long-Range Data Analysis

Long-range data would consist of panoramic images, a computed position and orientation for the observing rover, an estimation of the distance to a target outcrop from stereographic image analysis and laser range-finding, and generalized mineral abundance information for the outcrop obtained with the thermal emission spectrometer. Combining the rover's positional and outcrop distance information, it should be possible to identify the position of the target outcrop on any available digital elevation model and thus "project" the panoramic image of the outcrop onto a topographic model. The rover positional and outcrop distance information also can be used to project the spectrometer data onto the same model. The original and projected panoramic images would be analyzed in an effort to detect evidence for stratification using contrast and color variation as the primary determinants. We would rely heavily on the effective and well-known Canny edge detection algorithm (Canny, 1986) to develop edge displays that would be used to quantify the degree of stratification for various faces of the outcrop. By the same token, the coarse spectrometric data would be used to establish rock types, which would then be assigned an area-averaged numerical score based on the normalized propensity of each identified rock type to preserve fossils. These two sources of quantitative data would be combined to determine a preliminary paleontological probability index for the outcrop.

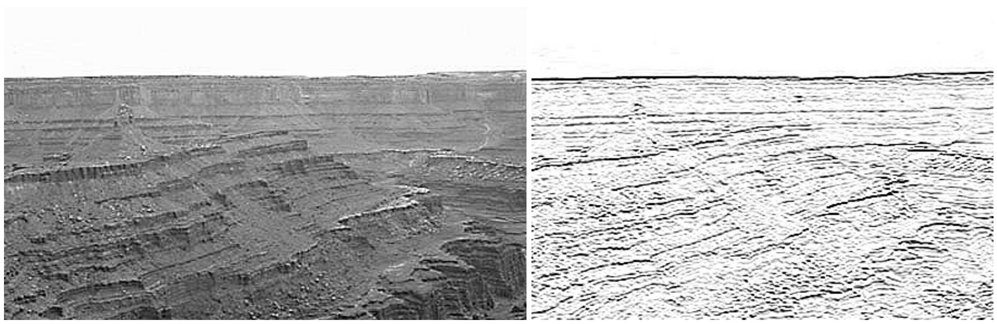

Figure 2: Example of use of Canny edge detection algorithm

Short-Range Data Analysis

Outcrops having sufficiently high paleontological probability indices would be targeted for further study. The LMRs would be deployed for that purpose. Short-range data obtained by the smaller rovers would include close-up panoramic images, higher-resolution images of rock surfaces obtained with other cameras, a detailed topological characterization of the outcrop obtained using range-finding devices and both types of cameras, and mineralogical abundance data with high spatial resolution. A first-pass study of each outcrop would be accomplished using all LMR's in the family, which would be observing at distances of several tens of meters. In a manner similar to that used to evaluate the long-range data, more reliable paleontological probability indices would be determined for various parts of the outcrop. If no high-index areas were identified, the outcrop would be assigned a modified area-averaged index and would not be studied further by DIPPR. If such areas were identified, the LMRs would move in for more detailed study at the scale of meters. In this fashion, progressively higher modified indices would be used to focus study at progressively higher spatial resolutions until promising outcrops had been mapped in great detail. Ultimately, this information would be combined to determine the paleontological probability for the studied region and, after a sufficient number of deployments, such data would form the basis for regional paleontological probability maps.

Rationale

This approach to long- and short-range data interpretation is regarded as a substantially more efficient way to develop paleontological probability maps than is its most logical alternative: a systematic, painstaking study of all accessible outcrops using short-range instrument packages. Continual updating of paleontological probability indices based on positive and negative feedback from sensor and camera data would permit study to be concentrated on the portions of outcrops deemed most likely to contain fossils. Eventually we would expect the best outcrops to contain small (centimeter-scale) surfaces with very high indices. These would be of sufficiently limited dimension to make coring and sample recovery practical, and such samples would be transported first to the BMR and eventually to the base station for preliminary study.

Conclusion and Recommendations for Future Studies

DIPPR is a family of Martian rovers designed specifically to assign paleontological probability indices to specific outcrops based on real-time analysis of sensor observations and to use such information to create paleontological probability maps of the Martian surface to guide human exploration. Deployment of the DIPPR system would be semi-autonomous, guided in real-time by ongoing revisions of paleontological probability index estimates as rovers in the family make progressively more detailed observations.

We believe our approach to the analysis of the data obtained using this technology is novel. DIPPR would be capable of the computational assessment of a broad spectrum of outcrop characteristics – including pattern, texture, and mineralogical variability – in order to make reasonable conclusions about the past geological processes acting on the site and the probability of finding fossils preserved there. On Earth, such conclusions are made exclusively by trained human geologists. The expense and risk associated with Martian surface geology studies is such that tools such as DIPPR might greatly increase their efficiency and effectiveness.

The greatest challenge associated with advancing DIPPR from the concept stage to reality lies in the development and testing of appropriate "smart" software systems. Some aspects of this problem are straightforward; for example, existing edge detection algorithms may be modified easily to develop software to identify and evaluate simple geometric patterns that might be indicative of stratification. However, the DIPPR system would be called upon to detect and evaluate complicated morphological patterns that might be indicative of actual fossils or indirect evidence of prebiotic chemistry. Most algorithms suitable for such analysis are still in the developmental stage in artificial intelligence laboratories. While the appropriate software may take some time and effort to engineer, there are no obvious impediments to the task and we recommend that NASA encourage such avenues of research as a next step toward the development of successful and versatile "robotic field geologists".

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