Autonomous Rock Outcrop Segmentation as a Tool for Science and Exploration Tasks in Surface Operations

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As planetary exploration missions become increasingly complex and capable, the motivation grows for improved autonomous science. New capabilities for onboard science data analysis may relieve radio-link data limits and provide greater throughput of scientific information. For surface missions, geology remains an essential focus, and the investigation of in-place, exposed geological materials provides the greatest scientific insight and context for the formation and history of geological environments. The present work develops techniques for autonomous segmentation of images of rock outcrops. Recognition of the relationships between different geological units is the first step in mapping and interpreting a geological setting, and is important even in the absence of compositional information. The goal is to allow a computer to process an image of a rock outcrop and produce a map of visually-distinguishable geological units. Several scenarios are described in which this tool could enable more efficient and effective science operations on planetary surfaces, by guiding instrument use, target selection, and other decisions in the exploration process.

I. Progress and Constraints in Planetary Exploration

Planetary exploration missions have seen continual progress in capability and complexity in recent decades, as programs have developed and technology has advanced. Flyby missions such as the successful Voyager 1 & 2[1] were followed by capable orbiters with landers, as in Cassini-Huygens.[2] In the last two decades, global mapping and long-timescale surveillance of Mars has progressed with orbiter missions carrying ever-better instruments at visible wavelengths and across the EM spectrum, as Mars Global Surveyor[3] was succeeded by Mars Odyssey,[4] Mars Express,[5] and Mars Reconnaissance Orbiter,[6] with more missions to follow. Current missions greatly exceed the capabilities of their predecessors. The European Space Agency's stunning success in imaging the nucleus of comet 1P/Halley with the Giotto spacecraft in 1986,[7][8] will soon be followed by the Rosetta mission to approach, map, orbit, and land on the nucleus of comet 67P/Churyumov-Gerasimenko,[9] as only one example of this progress.

This growth in the number and capability of missions has led to a wealth of new data and knowledge about our planetary neighbourhood, but also to challenges in data management.[10] This has led NASA to upgrade its Deep Space Network both to replace aging equipment and increase capacity.[11] Meanwhile the European Space Agency (ESA), seeing a growing constraint in communication capabilities[12] has expanded its network of tracking stations to include three 35-m antennas[13][14] Both agencies are increasing cooperation to better use the assets which are collectively available.[15] Promising developments in optical communication

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over planetary distances[16] may increase the available bandwith,[17] but there will still be a limit to the data budget available,[18] and individual missions will continue to experience bottlenecks.

Mars surface missions are a particular example of the growth of mission capability that has driven this expansion of the communications architecture. Over the last two decades, progressive improvements in entry, descent, and landing systems, vehicle design, and operational experience in conducting mobile missions on the surface of Mars have led to a growth in the scale of rover missions (Figure 1).

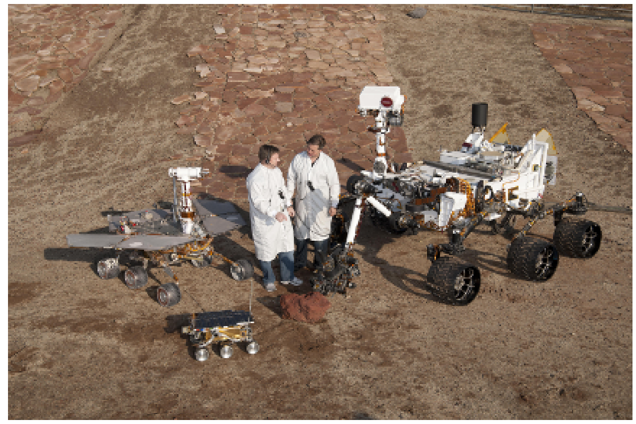


Figure 1. A progression of landed rover systems. From smallest to largest, engineering models of the Mars Pathfinder, Mars Exploration Rover, and Mars Science Laboratory rover vehicles (with humans, for scale). Image credit: NASA/JPL-Caltech

With larger vehicles came the capacity to accommodate larger and more complex payload systems – the Mars Science Laboratory (MSL) rover, launched in 2011, carries 75 kg of science payload,[19] a more than tenfold increase over the Athena payload suite carried by the Mars Exploration Rovers (MER) in 2003.[20] With more, and more complex, instruments comes the potential to generate a great deal of science data, but the communications system in place today is little changed since the start of the MER mission, giving constraints on the data that can be acquired.

Even by the time of the MER extended mission, innovative strategies to acquire more scientific information in data-efficient ways were coming into use. Uploaded in 2009, nearly 6 years after the surface mission began, the AEGIS software system allowed the MER Opportunity rover to autonomously detect science targets of specified parameters during long traverses, and target them with science instruments.[21] The system allowed greater mission science return both by reducing the amount of image data sent to Earth to be inspected for targets, and consequently, by allowing faster progress on long traverses through areas with few such targets.

AEGIS has shown that sophisticated techniques for science autonomy can help to increase mission science return and help to relieve the constrains of communication limitations. The AEGIS system is now being adapted for the MSL rover for use in instrument targeting,[22] and future missions, especially those with highly capable science payloads, could benefit from similar strategies. For surface missions to solid bodies in the solar system, the targets to be discovered and characterized by such autonomous systems will most commonly be of a geological nature, supporting investigations in geology, geochemistry, and astrobiology.[23] Such future systems must function while fitting into the scientific process of exploring and charaterizing a geological setting as executed in robotic fieldwork on planetary surfaces.

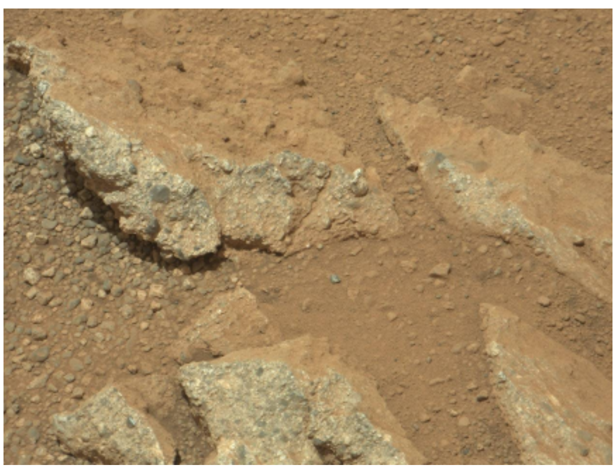
II. Exploring a Geological Setting

Regardless of the specific investigation objectives, surface exploration will generally involve delineating and characterizing a surface composed of connected masses of different rock types. The layout of these *geological units* tells the story of their formation and evolution - be it from sedimentary layers forming progressively one on top of another, igneous materials intruding between masses of older rock, violent impact processes creating shattered and mixed materials in breccias, among many other possibilites. Whatever the process of formation, evidence is encoded in the spatial relationships of the geological units - several examples of which, for different processes at different scales, are showin in Figure 2.

Finding these boundaries between units, called *contacts*, is of great importance to the task of understanding a geological setting. Their density, orientation, and position can reveal much about the type of rock present, the relative age of the materials, the mechanisms of formation, and by extension, their position within larger structures. As such, spatial relationships between different types of geological material are essential to understanding the formation and evolution of an environment. This holds true across all scales - from kilometre-sized (and larger) provinces of material, to microscopic structures. In fact, an investigation of a new environment best proceeds at a succession of decreasing scales,[24] mapping out the distribution of units at each scale before choosing targets to move in for a more detailed view at a finer scale, recursively.

(a) 100-metre cliffs cut from the central uplift of the Tunnunik impact structure in the Northwest Territories, Canada, show sedimentary layers of different materials tilted by the impact.

(b) A roughly 10 m wide face of an outcrop in the Mojave Desert, California, shows a sharp contact between volcanic units - a lahar deposit below, and a massive basalt above.



(c) In Gale Crater, Mars, the 'Link' conglomerate is visibly distinct from the surrounding material, and itself contains numerous clasts of various compositions. The field of view is about 0.25 m wide. Image credit: NASA/JPL-Caltech/MSSS.

(d) A hand sample of impact breccia from the Haughton impact structure in Nunavut, Canada shows embedded cm- and mm-sized clasts of various compositions. The field of view is about 10 cm wide.

Figure 2. Several examples of visibly expressed spatial relationships between distinct, but adjacent geological materials, at a variety of scales.

This follows the field geological practice of beginning with maps and remotely-sensed imagery, conducting field reconnaissance, and choosing first sites, then outcrops, then samples, before moving to microscopic analysis. In the case of a rover mission, this cascade of mapping geological units at finer scales ends with instrument placement on chosen targets, perhaps including sampling operations.

III. Completing the Picture with Chemistry and Composition

The application of chemical and mineralogical instruments is an important part of the investigation. Vision is often sufficient to reveal spatial relationships. But vision can only give partial information as to the composition of rocks, because of their great variety, the variability in the appearance of a given rock type, and the numerous effects,such as weathering, which can alter the appearance of a rock. In terrestrial field geology, samples from each unit are often taken for analysis in a laboratory; in the planetary setting, the analysis must generally be done at the field site. Miniaturized versions of many common laboratory tools used by geologists have been developed for planetary missions. They can be grouped, operationally, into three categories: remote-sensing instruments, contact science instruments, and sample-analysis instruments.

A. Remote-sensing instruments

Remote-sensing instruments gather data on targets at some distance from the rover, typically with a range limit of metres to kilometres. Cameras are common, and can often be targeted blindly unless detailed range is needed for focusing, or particular targets are desired and the field of view is small. Stand-off spectrometers may require detailed information for targeting, such as range to the target and fine pointing instructions. The laser-induced breakdown spectromer of MSL's ChemCam instrument, for example, analyzes spots with a diameter of 350 to 550 µm,[25] so targeting it calls for a decision about which spot(s) on an outcrop are to be analyzed.

B. Contact science instruments

Contact science instruments require placement against the surface of a target, or, sometimes, in very close proximity to it. This category includes contact chemistry instruments - all four Mars rovers to date have carried a version of an Alpha Particle X-ray Spectrometer (APXS).[26][27][28] It could also include close-range high resolution imagers which must be placed in close proximity to desired portions of an outcrop, such as MSL's Mars Hand Lens Imager (MAHLI),[29] or sampling systems such as drills or scoops (which MSL also carries[30]). Deploying such instruments requires identifying high-value science targets within an outcrop. These must also suit relevant engineering limitations such as reachability, flatness, and orientation. Such detailed information often takes time to acquire, and may require several cycles of passing information through operators on Earth. This means that contact science observations are currently costly in time and other resources.

C. Sample-analysis instruments

Sample-analysis instruments conduct their observations on a portion of sample material, which must first be acquired by a contact tool. They might include various chemistry experiments and spectrometers, such as on the Viking[31] and Phoenix[32][33] landers and the MSL rover[34][35] . This implies prerequisite contact science work, at least for the sample acquisition system, but likely also for instruments to chracterize and select the sampling sites. Significant mission resources may be expended for such sample analyses, in fact, the instrument is often capable of excuting only a limited number of them, so careful selection of sampling sites and of samples is generally needed. This implies significant work by other science instruments first, and generally many steps of ground-in-the-loop decision-making and interpretation ahead of the analysis, making sample-analysis observations a significant events which depend on approriate identification and selection of science targets for sampling.

D. A progressive investigation sequence and the place for autonomy

This division of instruments implies an hierarchy of investigation tools, in increasing scale of resources expended, with the more resource-intensive instruments generally dependent on preceding work by those which are less demanding, though providing more detail about the targets being investigated. This hierarchy mirrors, and parallels, the cascading levels of details and scale inherent in the mapping and imaging aspect of the work. The two streams of tasks are, in fact, mutually complementary, with chemical and compositional data aiding the interpretation of the imagery, and vice versa. They thus fit into a single, iterative investigation process whereby an environment is explored and analyzed at finer scales and increasing detail.

A notional description of the portion of this investigation which occurs during a rover traverse on a planetary surface is set out in Table 1. In practice, the tactical steps described here fit into the mission-scale strategy of the investigation, and will be repeated at each site of interest explored. Moreover, individual steps here described may be iterated several times to gather the data or prepare the conditions needed to proceed to later steps, and the process can be interrupted at any point if the present investigation site is judged unsuitable for expending the resources needed at those later steps.

Table 1. Simplified investigation sequence for exploring a geological environment

Step	Task
1	Acquire imagery of the region surrounding the rover
2	Identify outcrops in acquired images
3	Rank and select outcrops
4	Map the selected outcrop by regonizing geological units and their boundaries
5	Use map to identify remote-sensing targets in the outcrop
6	Take remote-sensing measurements to confirm or refine the outcrop map
7	If desired, identify targets in the outcrop for contact science observations
8	Conduct contact science to improve the charcterization of the units
9	If desired, identify targets in the outcrop for sampling
10	Conduct sampling operation
11	Conduct sample-analysis science operations

The process in Table 1 is very generalized; the details will depend on the instrument suite available, the science questions being addressed, and the overall mission strategy. But such an approach of cascading scales and detail is very generally applicable, and mirrors the approach used in terrestrial field geology.[24] As presently implemented in planetary surface missions, this sequence, from start to finish, requires multiple ground-in-the-loop steps, each of which imply data transmission to Earth for analysis and assessment, and time delays for that assessment to occur. If any of these steps can be achieved even semi-autonomously, the number of command cycles needed to complete this process could be reduced (saving time on a limited-duration mission) as could the amount of data sent to Earth (relieving constrained data budgets).

There are many points in this investigation sequence where autonomy could make a useful difference. The present work focuses on step #4 – visual mapping of geological units at the outcrop scale, and the potential utility of such a computer vision capability which is currently in development.

IV. The visual segmentation algorithm

Recent work has devloped a computer vision algorithm able to segment images of rock outcrops along geological units. The work was presented in Ref. 36, with the technical underpinnings developed in detail in Ref. 37. While at least one other project has attempted to address a similar problem using information from visual texture in the image,[23] the present work represents, to our knowledge, the first attempt to identify geological contacts in a single image using wholly unsupervised machine learning. The technique is based on the premise that in a scene containing a visible geological contact, the geological units on each side of the contact will visibly differ from each other simultaneously in several distinguishing characteristics - perhaps colour, albedo, or texture, for example.

In order to take advantage of this property, the system extracts several types of visual information which can be obtained at low computational cost – colour, brightness, texture, and others as desired – and, for n such characteristics, creates a set of n-dimensional vectors each representing a pixel of the image. An example scene is prepared showing the types of materials to be recognized, and the system uses Multiclass Linear Discriminant Analysis[38] to determine the linear matrix transformation for these vectors which maximally separates pixels belonging to different geological units. A vector clustering technique (k-means in the current implementation) then groups the pixel vectors together and assigns them to units.

The learned transformation matrix can be trained on exemplar images, retained, and applied to the pixel vectors when analyzing new images of scenes not previously shown to the system. In this way, the system can be trained to find the distinctions between a set of rock types, and segment images of new scenes containing these lithogies. The system has been successfully tested on a variety of scenes, in several geological settings, shown in Figures 3-6. Each represents a separate instance of training the system for a new geological locality. Some pixelization in the segmentation maps is apparent, due to 4-by-4 pixel decimation of the photograph, employed to reduce computational costs.

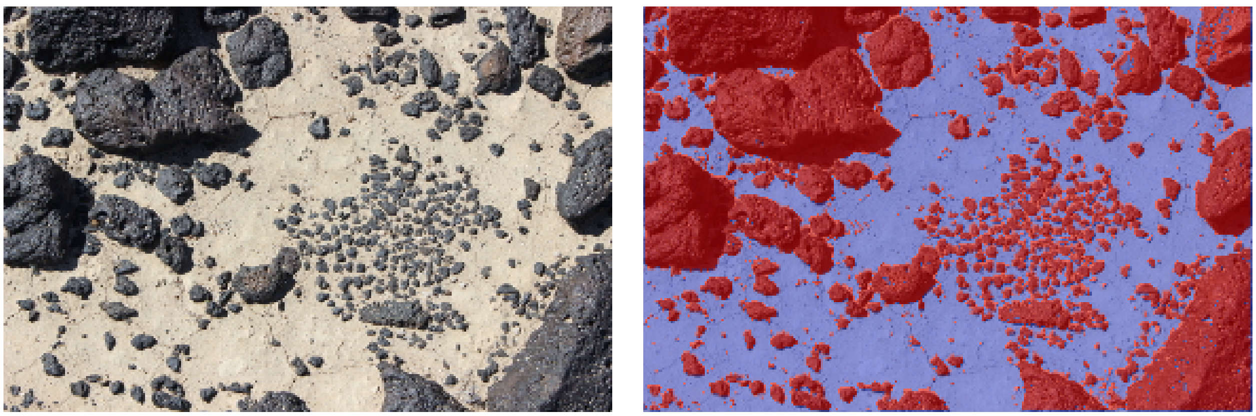


Figure 3. A scene showing basalt blocks and pebbles embedded in fine sand, in the Mojave desert, California (left), and the 2-class segmentation result (right).

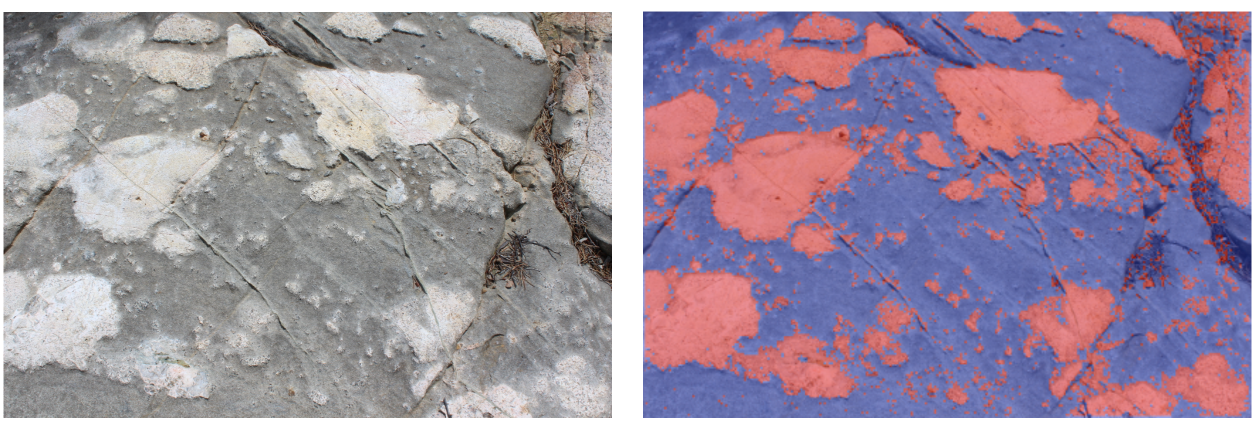


Figure 4. An outcrop of impact breccia in the Sudbury impact structure shows light-coloured clasts embedded in a darker matrix (left). The 2-class segmentation successfully divides the clasts from the matrix, unimpeded by the variations in shape, size, or texture of the clasts (right).

Figure 3 shows a scene where loose and embedded blocks and pebbles of basalt are readily distinguished from the fine sand between them. The segmentation algorithm readily separates the two components of the scene; even with the pixel binning, small pebbles and deposits of sand in hollows in the cobbles are often identified.

In Figure 4, an outcrop of impact breccia gives a complex visual scene. The clasts are irregular in shape,

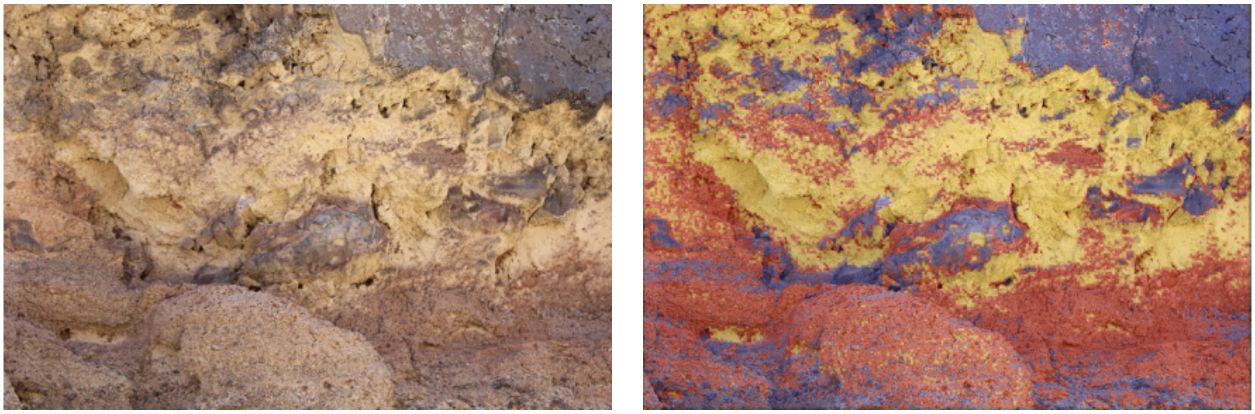


Figure 5. A volcanic deposit in the Mojave desert, California, shows layered materials with complex spatial relationships and boundaries (left). Treating it as a 3-class scene, the system produces a very successful segmentation (right).

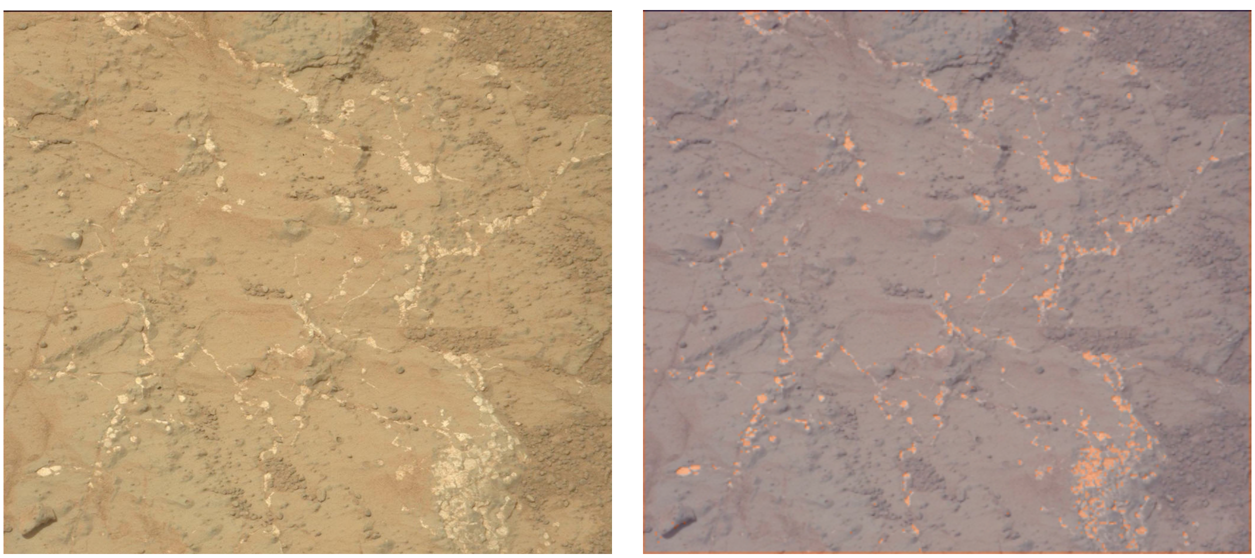


Figure 6. An image of the 'Knorr' science target acquired by the MSL right-side MastCam on sol 133 shows light-toned veins of calcium-rich material in a host rock of clay-bearing mudstone (left, image credit: NASA/JPL-Caltech/MSSS). The 2-class segmentation readily identifies the veins (right).

of varying texture, and show a great range of sizes. The system nonetheless distinguishes them from the surrounding matrix in this highly glacially-eroded outcrop.

Figure 5 shows a scene with still greater visual complexity. This outcrop is formed of a variety of volcanic deposits, with enclaves of each embedded in the others and complex, irregular boundaries. The segmentation map appears to adequately divide the scene into three constituents in a way that produces a useful map of the outcrop.

Figure 6 is a particularly challenging scene. This outcrop of mudstone in Gale Crater, Mars, is covered with a thin layer of reddish dust, and soil, obscuring some of its details. This is the 'Knorr' science target investigated by the MSL science team, which shows veins of calcium-rich materials inferred to be precipitated calcium sulfates;[39] these reveal a past habitable environment and aqueous alteration of the mudstone host rock.[40] This high-value science target was the site of the first two drilled samples obtained by MSL, after initial visual interpretation of this scene by scientists, and subsequent use of remote and contact contact science tools which extended the interpretation. The algorithm shows great success in segmenting this difficult and and important scene, separating the veins from the host rock despite their small width in relation to the pixel binning applied.

The ability of this algorithm to be trained on a diversity of scenes, and to thereafter map new outcrops with novel appearance or composition, makes it a potentially valuable tool for a robotic mission exploring a planetary surface. Rovers traveling long distances could use a similar approach to draft maps of outcrops and respond appropriately before these features are seen by operators on Earth. The following section describes several operational scenarios in which this kind of visual mapping system could improve the time and/or data efficiency of a robotic surface investigation.

V. Autonomy scenarios enabled by visual outcrop mapping

Autonomous segmentation of geological scenes in a scientifically meaningful way provides several ways to enhance mission science yield.

A. The map as data product

On its own, the generated map of geological units is a useful data product. The arrangement of the units and the nature of their boundaries provide relevant diagnostic information, and for a sufficiently uniform surface or environment, some operations scenarios could allow the map, or some reduced description of it, to be transmitted to Earth, rather than transmitting a full suite of photographs for each outcrop.

Even if implemented as ground software, the system could be used to analyze returned images, as a tool for scientists tasked with analyzing large data sets and inspecting images for interesting features.

B. Regional mapping

What applies for a single outcrop also applies at the regional scale when considering the outcrops in an area. Detection of the regional distribution of certain geological units, or of the presence of veins or contacts in certain areas, for example, can inform larger-scale mapping of a region, as inferred from the windows into the subsurface that the outcrops provide. This could be done on Earth using the software system as a tool, or potentially with a degree of autonomy by a rover itself. For example, if one type material consistently occurs as clasts or veins in outcrops, but after some distance on a traverse begins to appear in large, continguous units, this may indicate that a significant boundary in the regional geology has been crossed, which may warrant certain action by the rover or the mission science team.

C. Data triage

While every new part of an unexplored environment is potentially interesting, exhaustive imaging is not often the central goal, nor permitted by data constraints. Outcrop maps, and in general, maps of the terrain in the working environment, could inform decisions about which data to send to Earth. For example, in a sedimentary environment, the same sequence of materials will generally repeat itself at many distinct outcrops over a large area. New images of the same sequence may not be of great scientific interest if it has already been well-studied. But an outcrop where this pattern is changed may indicate any of several disruptive events that affected the sedimentary beds, or a previously unrecognized complication in the sedimentary history, such as an unconformity.

D. Discovery-driven activities

Criteria from the map morphology might be used to drive rover decisions - veins or clasts might be important, or the detection of sharp linear contacts might indicate a fault or other feature making for a valuable investigation site. Operators could use science goals to define criteria for novelty in the constituent units of the map or spatial relationships. For a rover on a long traverse to a distant destination, or tasked with surveying a wide area, such morphological cues might be used to interrupt the traverse, collect additional imagery, and wait. Such an interruption might even allow the rover itself to decide whether and how to react to such discoveries, and perform instrument operations in line with defined criteria and conditions.

E. Targeting instruments

Instrument operations, whether autonomously triggered or initiated by operators on Earth, could be guided by the outcrop-scale map of geological materials. A stand-off spectrometer might be targeted to several points in each identified unit, to ascertain its composition and confirm its homogeneity. The results of those observations, if processed on-board, might even be fed back into the algorithm for mapping the units, if they show a need to reconsider the number of units present.

A stand-off instrument could also be used to take a raster series of observations across detected geological contacts, or across veins, clasts, or other small-scale features, characterising them and directly comparing immediately adjacent materials, while simultaneously confirming the position of the detected boundary.

F. Enabling contact science

Having mapped an outcrop (and perhaps also studied it with remote-sensing instruments), the outcrop segmentation could be used to identify areas of suitably homogeneous material which are sufficiently large to accommodate a contact instrument. Together with 3D shape and range information from onboard sensors, these candidate targets could also be assessed for safety and suitabily for the instrument placement. Where it is not practical to target the same part of the outcrop with multiple contact or remote instruments, the segmentation could be used to identify separate regions of the same material in the outcrop, suitable to each instrument.

The further step of using these identified targets autonomously by placing contact instruments on the outcrop in response to autonomous identification of scientific value, safety, and suitability, is a very ambitious propostion with significant risks, and would require an extremely robust system worthy of great confidence in its reliability. Such a step may not even be necessary or desired, since by the final stages in fine-scale science investigation, the science team employing the robotic system will be very interested in understanding the environment for themselves in great detail, and in guiding the investigation now that the autonomous sytem has found targets worth their interest. As well, contact science operations entail both greater risks to the robotic systems and instruments, and greater consumption of time and resources, so will merit a manual approval step for the foreseeable future.

G. Strategic use to improve mission throughput

Even the most conservative autonomy scenarios could make valuable use of visual geological segmentation. Their best role in the process of Table 1 will depend on the mission architecture, instrument suite, scientific goals, and exploration strategy. They might best be implemented where they can reduce data volumes, improve the value of the data returned, or save time by reducing the number of ground-in-the-loop cycles needed to achieve a particular task, or more broadly, to achieve the mission goals. This could also imply a division in time - the system might be used in certain environments, during certain phases of the mission, or during certain kinds of traverses - for example long traverses over mostly familiar terrain, or survey operations aiming to map out the extent and position of materials of interest. Regardless of the specfic application, a reliable strategy for autonomous geologic segmentations in images is a powerful and flexible tool for autonomous rover geology.

VI. Conclusion

Computer vision techniques are progressing with respect to interpretation of natural scenes, and a tool has recently been developed which is capable of segmenting images of geological scenes such as rock outcrops. The system is able to be trained to recognize a variety of types of geological materials, and could be adapted to a variety of tasks. It could also be repeated at finer scales as a rover approaches a target, fitting into the exploration process at many stages. Such visual mapping is a prerequisite to many tasks in geology and surface exploration, and a variety of scenarios exist where a flight implementation of such a tool could improve the efficiency in data and time, as well as the quality of scientific data returned, of robotic exploration missions. These techniques can be implemented strategically to best make use of the capabilities of the robotic system and its operators on Earth, and to mirror in their execution the practice of terrestrial field geology, adapted to the planetary setting.

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