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Field testing of robotic technologies to support ground ice prospecting in martian polygonal terrain

Timothy D. Barfoot [a],*, Paul T. Furgale [a], Gordon R. Osinski [b], Nadeem Ghafoor [c], Kevin K. Williams [d]

[a] University of Toronto Institute for Aerospace Studies, 4925 Dufferin Street, Toronto, Ontario, Canada M3H 5T6
[b] University of Western Ontario, Depts. of Earth Science, Physics and Astronomy Canada
[c] MDA Space Missions, Toronto Canada
[d] Buffalo State College (SUNY), Department of Earth Sciences USA

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ABSTRACT

Polygonal terrain, a landform commonly associated with the presence of ground ice, is widespread throughout the high latitudes on Mars. In this paper, we present the results of field testing a potential mission concept for the robotic prospecting of ground ice in polygonal terrain. The focus of the paper is on the key robotic technologies that could be used to implement the concept and the engineering lessons we learned (as opposed to the specific scientific findings of our field tests). In particular, we have found that a lander- or rover-mounted lidar and a rover-borne stereo camera/ground-penetrating radar suite are two important scientific tools that may be used to help pin-point ground ice prior to subsurface sampling. We field tested some aspects of this mission concept on a previously - unstudied polygonal terrain site on Devon Island in the Canadian High Arctic (a common Mars/Moon analogue site) during the summer of 2008. This unique collaboration between technological and scientific communities has led to a deeper understanding of how such a science-driven mission could actually be implemented robotically.

1. Introduction

Mars represents one of the most important targets for the international space exploration communities in the near- to mid-term (i.e., 10–30 years) and is of particular scientific importance and interest because of the widespread evidence for the presence of water in the geological past (Carr, 1996; Masson et al., 2001). Environmental conditions on Mars today are such that any water reserves will be in the form of ice, either in the polar caps or as ground ice at lower latitudes (Carr, 1996).

In addition to spectroscopic (Boynton and GRS Team, 2002) and numerically - simulated (Mellon et al., 1997) evidence for present-day ice presence, the Martian surface displays a variety of landforms similar to those indicative of ground ice in terrestrial polar regions. For example, polygonal terrain (a network of interconnected trough-like depressions in the ground) is a landform commonly found throughout the polar regions of both Earth (Lachenbruch, 1962; Mackay and Burn, 2002; Fortier and Allard, 2004a) and Mars (Mangold, 2005; Levy et al., 2009). In terrestrial environments, these features are formed by the response of an ice-bonded substrate to thermal forcing mechanisms induced by winter freezing and subsequent warming later in the season and are often indicative of subsurface ice bodies (Lachenbruch, 1962); on Mars, it is believed that such thermal forcing mechanisms may also be responsible for the observed formations (Levy et al., 2009; Mellon et al., 2008).

On Mars, the recent Phoenix mission (Smith et al., 2008) appears to have confirmed the presence of an ice-bonded substrate in polygonal terrain, but the nature of underlying massive ice bodies has not yet been determined. While earlier research has suggested that Martian polygonal terrain could potentially be representative of subsurface ice wedges (Seibert and Kargel, 2001; Mangold, 2005), more recent work has suggested that the landforms observed on the present-day Martian surface are more likely similar to 'sublimation-type' polygons (e.g., Levy et al., 2008, 2009), a type of modified sand wedge polygon reminiscent of those in the Antarctic Dry Valleys (Marchant et al., 2002; Levy et al., 2006; Marchant and Head, 2007) more so than to the ice wedge polygons typically found in the Canadian Arctic. However, until such determiniation is conclusively made it remains important to collect and interpret data indicative of the presence of all known terrestrial ground ice forms in preparation for any future robotic exploration of Mars, as deposits of ground ice may be key sites for future human exploration missions due to the possibility for in - situ resource utilization.

It is therefore very important to develop techniques for prospecting and detecting subsurface ground ice. Consequently, this paper presents a mission concept to carry out such prospecting using robotics, perhaps as a followon to the Phoenix mission.

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* Corresponding author. Tel.: +1 416 667 7719.
E-mail address: tim.barfoot@utoronto.ca (T.D. Barfoot).

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A sensor suite consisting of a lidar, stereo camera, and ground-penetrating radar is proposed to pinpoint ice deposits for subsequent sampling. It is important to note that our main objective in this paper is to provide a proof of concept of this mission architecture in the field, not to advance the current scientific understanding of polygonal terrain. The remainder of the paper is organized as follows. First, background and related work are provided. Next, our mission architecture is detailed, followed by experimental results. Conclusions and future work complete the paper.

2. Background and related work

One possibility for the detection of ground ice on both Mars and the Moon is ground-penetrating radar (GPR), which is widely used to determine subsurface structures and the distribution of ground ice based on differences in the dielectric properties of subsurface materials (Arcone et al., 2002). The GPR transmitter emits a high-energy electromagnetic pulse into the ground at frequencies generally in the range of 10–1000 MHz. When the signal encounters an interface between layers of differing permittivity, part of the energy is reflected back towards the surface while the remainder is refracted into the subjacent medium. The reflection/refraction process continues until the signal has attenuated completely or the user-defined time window—the amount of time that the GPR receiver is programmed to search for a return signal—has elapsed (Moorman et al., 2003). Based on the two-way travel time of each reflected pulse, a trace is produced illustrating a series of reflector intensities located beneath the unit, whereby the amplitude of the reflection is proportional to the relative difference in permittivity between adjacent materials (Arcone et al., 1995). When the GPR survey is conducted along a surface transect, individual traces can be combined to produce a radargram, a two-dimensional profile showing continuous subsurface reflective layers, which allows for enhanced stratigraphic interpretation.

The application of GPR to frozen terrain was pioneered by Annan and Davis (1976) (cf. Ross et al., 2005) and is becoming increasingly widespread. Given its established utility in some of Earth's most extreme environments such as Antarctica (Arcone et al., 2002) and the Canadian Arctic (dePascale et al., 2008), rover-based GPR has thus been proposed for development on a variety of planetary missions and will be included on ESA's upcoming ExoMars mission (Vago et al., 2006). While previous studies have focused primarily on hardware development and testing (Grant et al., 2003; Kim et al., 2006; Leuschen et al., 2002), understanding the physics of dielectric signal loss in Mars-type substrates (Pettinelli et al., 2007), and possible applications to Mars analogue environments (Arcone et al., 2002; Degenhardt and Giardino, 2003; Williams et al., 2005), relatively little effort has been directed towards the deployment of a GPR using a robotic platform (Barfoot et al., 2003). Fong et al. (2008) deployed a GPR using a rover, but did not specifically study ice prospecting. Furgale et al. (2009) detail a technique to build a coupled surface/subsurface model using a stereo camera and GPR, which was used in the current work to carry out ice prospecting.

Measuring surface properties and morphologies are also of critical importance to understanding geological processes. This information can help to predict the presence of ground ice in, for example, ice-wedge polygons. Surface properties can also help in interpreting coupled subsurface geophysical data. Properties such as elevation differences and grain size (e.g., sand versus boulders) are particularly important attributes that are always recorded and studied in detail during any field campaign on Earth, typically by a geologist taking measurements using tape measures and Global Positioning Systems (GPS). In addition to being time-consuming and relatively crude in terms of accuracy, this will not be possible on future rover missions.

One potential tool for measuring surface properties on planetary exploration missions is lidar (light detection and ranging), which offers the benefit of autonomy, mm- to cm-scale accuracy over km ranges, and the ability to generate highly precise three-dimensional (3D) topographic maps and images (Berinstain et al., 2003) from a stand-off distance. Lidar technology uses light to measure ranges to objects within its field of view, which allows 3D surface relief information about a spacecraft or rover's environment to be measured in detail. Time-of-flight lidars typically emit a short pulse of laser light and measure the time required for the pulse to reflect off the target and return to a detector in the unit. Range to the target is inferred using the speed of light and half the travel time of the pulse. Typically a mirror is used to steer the laser source in azimuth and elevation, thereby creating a raster image of ranges within a specified field of view. By transforming this range image from spherical coordinates to Euclidean coordinates, one obtains a three-dimensional model of the target as a survey 'point cloud'.

Lidar has been used extensively during the past few years for in-orbit space shuttle inspection (Gregoris et al., 2004) and, more recently, for autonomous satellite rendezvous (Allen et al., 2008). The use of lidar as a vision system for long-range rover navigation has also received considerable attention (Dupuis et al., 2008). Space-based and airborne lidar has many terrestrial applications, including mapping of geological structures, such as faults (Engelkemeir and Khan, 2008), forest canopies (Hudak et al., 2002; Andersen et al., 2006), and various geomorphological landforms, such as landslides and gullies (Jones et al., 2007; Engelkemeir and Khan, 2008). In terms of rover- and lander-based surface operations, ground-based lidar has been used extensively for atmospheric studies on Earth (Ishii et al., 1999) and, now, with the Phoenix mission, for Mars (Whiteway et al., 2008). Lidar has been previously shown to be successful for geological applications at the Haughton impact structure (Berinstain et al., 2003). Osinski et al. (2008) further showed the benefit of using lidar as a scientific tool to build detailed 3D models of various geological features including polygonal terrain, terraced crater walls, impact breccias, and gullies in the Haughton impact structure.

In addition to lidar, stereo vision has proven to be an invaluable tool for rover localization and three-dimensional modelling (Barfoot et al., 2006). A calibrated stereo camera is comprised of two monocular cameras that are a known and fixed separation apart (with aligned focal axes). By identifying common tie points on a target observed in the left and right images, one may use the known camera separation to triangulate for the range between the cameras and the target. Computer vision techniques allow this process to be automated. Stereo vision complements lidar imagery by working on a shorter scale but providing photorealistic texture, not just geometry. Moreover, stereo vision enables visual odometry, a key localization tool to help estimate rover motion in the presence of loose terrain (Furgale et al., 2009). Further discussion of the relative strengths of lidar and stereo vision to our mission concept are provided below.

The current work brings together the individual strengths of GPR, lidar, and stereo vision in a single mission architecture to prospect for ground ice.

3. Mission architecture

Fig. 1 depicts the top-level steps in our concept. The processes below the dashed line would take place on Earth, while those above would take place on Mars (in the case of prospecting for ice in polygonal terrain). The labels on the arrows indicate the data products that would be sent back and forth via Earth- Mars