Devon Island as a Proving Ground for Planetary Rovers

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Abstract. The future of space exploration will be increasingly surface-based and extended-duration. Planetary rovers, both manned and autonomous, will play vital roles in transporting instruments, astronauts, and equipment across rugged and unfamiliar surfaces. To enable this vision, it is advisable to deploy prototype rover vehicles in analog environments on Earth, in order to learn how best to use these tools. Devon Island, in the Canadian High Arctic, has been used as a proving ground for planetary rovers, due to its vast scale, variety of topography/geology, challenging lighting, lack of vegetation, existing infrastructure at the well-established Haughton-Mars Project Research Station, and wealth of interesting scientific mission objectives. In this paper we review the suitability of using Devon Island for the continued testing of planetary rovers; several examples of previously conducted tests are provided. We conclude that despite the typical logistical challenges associated with remote field work, Devon Island should be considered a strong candidate for ongoing rover field deployments.

1 Introduction

Several past space exploration achievements have demonstrated the benefit of surface mobility: the Russian Lunakhod Rovers (1970-71), the NASA Apollo Lunar

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Roving Vehicles (1971-1972), the NASA Mars Pathfinder Sojourner Rover (1997), and the NASA Mars Exploration Rovers (2004-present). All but Sojourner saw traverses on the order of tens of kilometers in length. Future missions, including the NASA Mars Science Lab (2011) and the ESA ExoMars Mission ($\sim$2016), will also enjoy the freedom of surface roving, with similar large-scale traverses planned. Indeed, it is the very nature of exploration that will ensure rovers, both manned and autonomous, continue to play enabling roles on future surface missions.

Mars and the Moon represent two of the most important surface exploration targets in the near- to mid-term (i.e., 10-30 years), as indicated by the Global Exploration Strategy (2007). Future missions will almost certainly be focussed on more challenging regions of the lunar and Martian surfaces than in the past. On the Moon, we will seek the permanently shadowed regions in the rugged South Pole Aitken Basin in search of water ice; traverses of several hundred kilometers have been considered. On Mars, we will search for signs of past and present life at sites exhibiting signs of potential hydrothermal activity, and eventually attempt to return a sample to Earth [11]. These and other new challenges will require rovers that can travel further, faster, and through more difficult terrain than their predecessors. Increased autonomy will play a major role in achieving this aim. As part of the path to spaceflight, field testing will need to be conducted in relevant operational environments. One site that has seen a number of robotic field deployments is the Haughton impact crater and surrounding area on Devon Island in the Canadian High Arctic.

Devon Island presents unique qualities for planetary analogue studies because it offers an unusually wide variety of geological features and microbiological attributes of strong planetary analogue value or potential [9]. It has been used for rover testing in the past [2, 3, 5, 6, 7, 12] because it presents real challenges to field exploration that are analogous in fundamental ways to those expected in planetary exploration. Being an impact basin in a polar desert environment, the lack of vegetation and variety of terrain make it well suited for rover field tests. Moreover, the long-term presence of the Haughton-Mars Project Research Station has drastically offset the logistical burden associated with carrying out field tests at this remote venue.

The rest of this paper makes an attempt to review the suitability of this Devon Island site for planetary rover testing. The key issues discussed are scale, terrain variety, lighting, lack of vegetation, infrastructure/logistics, and potential for scientific discovery. Our aim is not to contrast Devon with other potential analog sites, but rather to evaluate it on its own merits. We approach the review from a mobility perspective, for this is the main function of the rover (both manned and autonomous). The two main facets of mobility are (i) guidance, navigation, and control (GN&C), which includes aspects of autonomous operations, and (ii) locomotion; our focus will be placed primarily on testing the former, but we will also discuss the latter. We begin with a summary of the Haughton impact crater/surroundings and past rover deployments, followed by our review, and finally a conclusion.

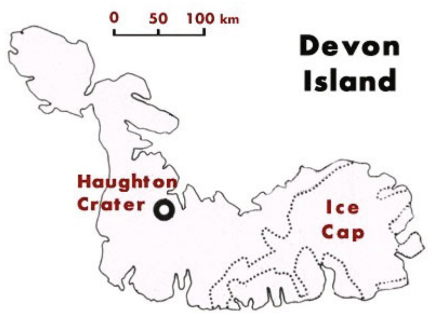
2 Site Description

In this section we provide a brief description of the Haughton impact crater and surroundings on Devon Island, followed by a summary of past rover deployments.

2.1 Haughton Impact Crater and Surroundings

The Haughton impact crater is located at latitude 75° North on Devon Island[1], within the Arctic Archipelago, as shown in Figure 1(a). The crater itself is 20 kilometers in diameter, resulting from a massive impact 23 million years ago. Haughton crater has been well preserved owing to the fact that it exists in a polar desert, with relatively slow erosional processes. Craters are considered prime sites for planetary exploration because the impact churns up deep geological layers, exposing them on the surface; basement material from 1700 meters has been found in the Haughton crater. Within the crater, a large variety of features may be found including rock outcrops,

(a) Devon Island in Canadian High Arctic.



(b) Haughton Crater on Devon Island.

(c) View from inside Haughton Crater.

(d) Haughton-Mars Project Research Station.

Fig. 1. Haughton Impact Crater on Devon Island, Nunavut.

[1] Notably, Devon Island borders the fabled Northwest Passage; explorer Sir John Franklin and his crew wintered on Beechey Island, just off the southwest shore of Devon in 1845-46.

(a) CMU's Hyperion (2001). *Photo credit: Carnegie Mellon University*

(b) NASA Ames' K10s (2007). *Photo credit: M. Deans*

(c) UofT's Pushcart Rover (2008).

(d) UofT's ROC6 (2009).

(e) HMP's Mars-1 (2003-present).

(f) HMP's Moon-1 (2010-present).

Fig. 2. Recent rover deployments on Devon Island including actual visit dates.

impact melt breccias, gullies, and rivers (see Figure 1(c)). Outside the crater, a number of other interesting features exist including ejecta blocks, canyons, lakes, mesas, plains, and polygonal terrain. The Haughton-Mars Project (HMP) Research Station is positioned near the northwest rim of the crater at $75°26'00''$ N, $89°51'47''$ W. HMP is comprised of several permanent buildings and weather havens, and boasts a fleet of all-terrain vehicles (ATVs), generators, and advanced communication systems [8]. Site access is via Twin Otter aircraft.

2.2 Past Rover Deployments

There have been several research-level rover vehicles tested on Devon Island. Figure 2 shows Carnegie Mellon University's (CMU) autonomous Hyperion sun-synchronous rover [12, 13], NASA Ames' dual autonomous K10 rovers [6, 7], the University of Toronto's (UofT) Pushcart Rover [2], UofT's autonomous ROC6 [5], and HMP's manned Mars-1. HMP's manned Moon-1 rover will join the fleet in the summer of 2010 and the NASA Ames K10 rovers will also return for a second campaign[2]. To date, no flight-design rovers have been deployed on Devon

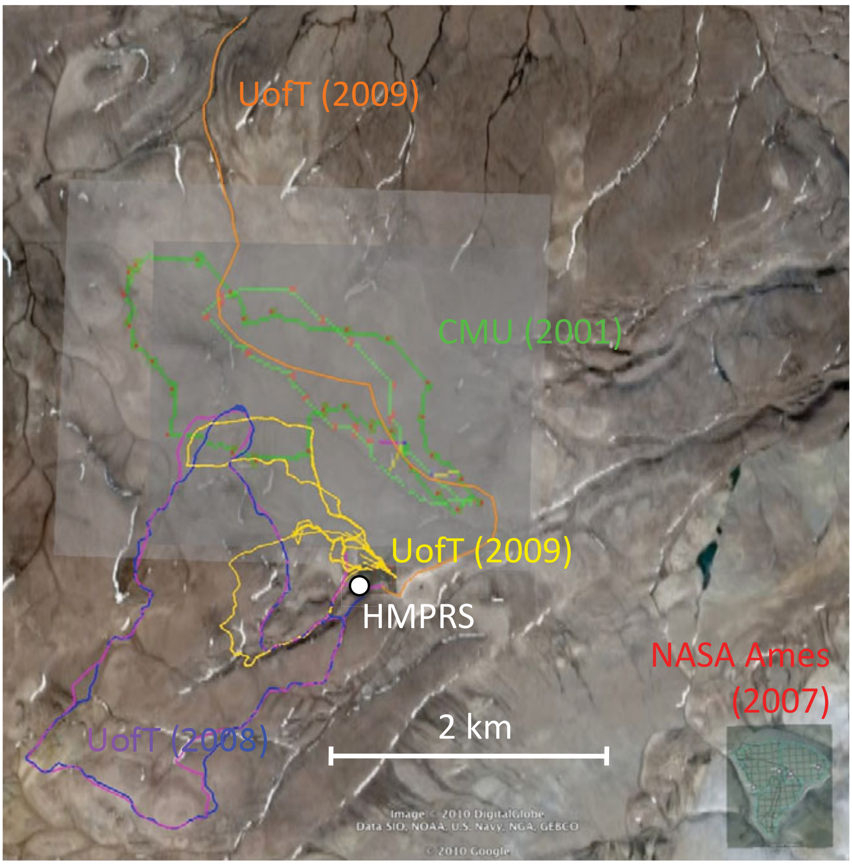


Fig. 3. Recent long-distance rover traverses on Devon Island. Note that NASA Ames traverse was a compact systematic grid in bottom right. *Photo credit: Google Earth*

[2] Personal communication with Dr. Terry Fong.

Island; testing has focussed on the operational and GN&C aspects of rover missions. Matthews [10] provides a photo montage of earlier prototypes by additional organizations.

3 Review

In this section we discuss a number of issues that affect the quality of a rover field deployment: scale, terrain variety, lighting, lack of vegetation, infrastructure/logistics, and scientific merit. The discussion is primarily focussed on guidance, navigation, and control testing, including autonomous operations.

3.1 Scale

Scale is a major issue. Past rover flight missions saw traverses on the order of tens of kilometers. Field deployments used to validate rover technologies should ideally see traverses of this scale. Past Devon rover deployments were able to accomplish mission-scale traverses: CMU Hyperion (∼15 km in 2001), NASA Ames K10s (∼42 km in 2007), UofT Pushcart (∼20 km in 2008), and the UofT ROC6 (∼44 km in 2009). Figure 3 shows a compilation of these traverses. The length of traverse is essentially only limited by testing time.

A second major issue related to scale is sensor range. Most rover guidance, navigation, and control architectures employ vision sensors such as panoramic cameras, stereo cameras, and lidar (light distance and ranging). The images captured by these sensors are typically used in appearance-based vision algorithms for localization, motion estimation, terrain assessment, and path-planning. Figure 4 shows the scale of what is visible for both camera and lidar sensors at a typical site on Devon. A panoramic camera's range is limited only by topographic occlusions; the figure shows that terrain out to 5 km may be viewed in this case. A lidar typically has a shorter range (∼1 km in practice) and we see from the figure that the Devon terrain allows the sensor to exercise its maximum range in this case.

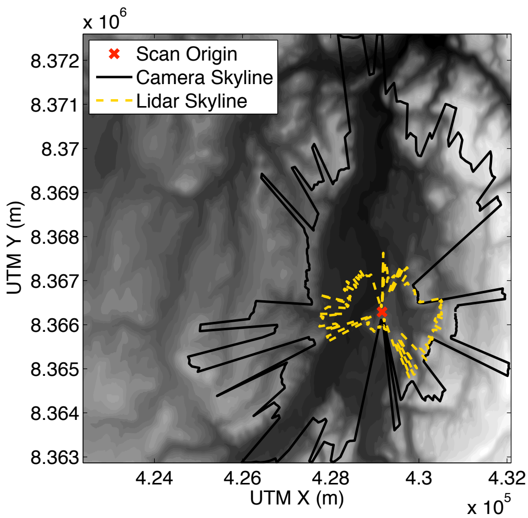


Fig. 4. Sensor ranges: lidar (∼1 km), camera (∼5 km)

(a) Polygon Trough (b) Canyon

(c) Mound/Rocks (d) Valley

(e) Vast Plain (f) Rocky Slope

Fig. 5. Variety of rover testing terrain; UofT ROC6 rover shown.

3.2 Terrain Variety

Throughout their long lives, NASA's Mars Exploration Rovers have encountered a wide variety of terrain types from terraced crater walls to flat plains. Even with high-resolution imagery gathered from orbit, it can be difficult to predict the nature of the rover-scale terrain on the ground.

Large-scale topography (10s to 100s of meters) is very important for testing certain rover GN&C methods as well as chassis capabilities. Long traverses need to encounter a variety of large terrain features to provide realism in terms of the three-dimensional motion of the platform and occlusions to vision sensors [5]. Topography is also important for testing the performance of long-range localization, which relies on topographic features and horizon silhouettes to determine position [3].

A variety of different rock distributions is also desirable to test rover chassis and GN&C methods such as terrain assessment and path planning. Fist-sized rocks and up can constitute hazards that need to be avoided. Varying the rock distribution can vary the difficulty of the traverse immensely.

Figure 5 shows a sample of the large variety in available testing terrain near HMP. These photos were all gathered on the yellow UofT (2009) path in Figure 3, except for Figure 5(a), which was gathered at a polygon terrain site 10 km north of HMP. The Haughton crater itself (see Figure 1(c)) is also within access distance of HMP and offers a wide variety of features including rock outcrops, steep impact melt breccias, and gullies.

3.3 Lighting

For rover testing, the Devon Island field season is typically early July to mid August, as this is when the ground is mostly free of snow. At latitude 75° north, the sun remains above the horizon 24 hours a day in this period. We see in Figure 6[3], that the sun's elevation hovers between zero and 30 degrees throughout the day, meaning the shadows are typically very long. From the azimuth we see that the sun moves continuously around the horizon, meaning the shadows move rapidly.

One of the main challenges for rover GN&C is the effect of lighting on visual navigation. Shadows can be a major source of error in appearance-based methods. It is therefore important to perform tests under a variety of different lighting situations. High-latitude venues tend to work well in this respect, exactly because the sun is low on the horizon and the shadows are long and moving quickly. Figure 7 shows an example of a vision algorithm failure from a UofT field test on Devon Island in 2009 [5]. A stereo image was gathered at midday; a second image from four hours later could not be matched to the original (i.e., in order to re-localize the rover) due to the dramatic changes in shadowing. A third image was taken the next morning and was successfully matched.

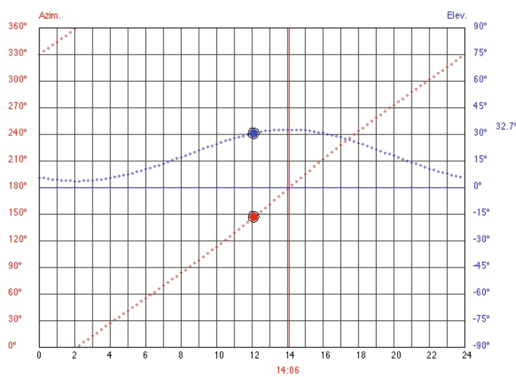


Fig. 6. Sun Azimuth and Elevation on July 31 at HMP.

Figure 8 shows a quantitative test of matching distinctive image keypoints (i.e., SURF features) from a stationary stereo camera over a nine hour test . We see that the algorithm is able to match many features well for over six hours in this case, but

[3] Created using web applet at `http://www.jgiesen.de/azimuth/`.

(a) Sunny initial image, mid-day.

(b) 4 hours later, match to (a) fails due shadows shifting in bright sunlight.

(c) Overcast next morning, match to (a) succeeds due to similar shadowing.

Fig. 7. Example of a vision algorithm failing to recognize a location due to shadows changing.

eventually fails to produce an adequate number of matches. The early 'dip' at 02:30 is likely due to the presence of temporary cloud cover, underscoring the importance of lighting on these algorithms.

It should also be pointed out that these difficult lighting conditions are representative of several mission scenarios for both Mars and the Moon. Polar missions for both targets have been considered and present major challenges not just for vision algorithms but also solar power generation. Carnegie Mellon University's Hyperion experiment conducted on Devon Island in 2001 [13] was aimed specifically at testing a mission planner that could ensure a rover would traverse a well-lit path despite dynamic shadowing. They showed that it was possible to remain synchronous with the sun over a 24 hour period. Devon has also been used for celestial navigation experiments [4], wherein a sun sensor was used to determine a rover's absolute heading; the near-polar environment makes this test relevant to high-latitude missions.

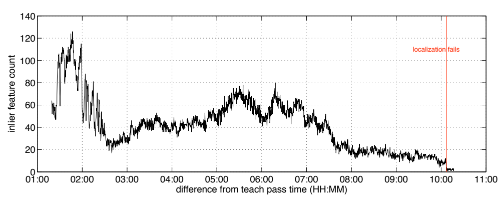


Fig. 8. Vision algorithm matching over a nine hour period. Distinct keypoints taken from a stationary stereo camera are matched to an initial image. Matched feature count remains high for over six hours, but eventually fails due to dramatic changes in appearance due to shadows shifting.

3.4 Lack of Vegetation

Perhaps the most appealing aspect of the Devon site, from a planetary rover testing perspective, is the almost complete lack of vegetation. There is some low-lying vegetation in localized areas, but most areas are completely clear of noticeable specimens. Figure 9 depicts the 'Lake Sediments' area, which is one of the most heavily vegetated areas near HMP (and not appropriate to rover testing due to environmental sensitivity). Figure 5 shows the more typical vegetation-free terrain. To understand why vegetation is problematic for rover testing we must again discuss the GN&C architecture, which has a number of sub-components. We will discuss a few of these sub-components, each impacted by vegetation in different ways.

Fig. 9. Worst-case vegetation from a rover-testing point of view near HMP. These areas are few and can/should be avoided.

3.4.1 Short-Range Terrain Assessment and Obstacle Avoidance

This GN&C component uses sensors onboard a rover (e.g., stereo camera and/or lidar) to (i) build up a local model of the terrain (i.e., within 10 m), (ii) classifies patches of the terrains as driveable or not, then (iii) plans a collision-free path to a short-range goal. The presence of vegetation makes the classification step more difficult than it needs to be. Due to the limited processing available on planetary rovers, a simple geometry-based terrain classification is typically employed (e.g., simple plane fitting). With this type of system, tall grasses, for example, can cause an area of terrain to look undriveable even though it is. A more sophisticated terrain classification method could be used (to handle vegetation), but then it would not be planetary-relevant and would likely need to be tailored to the specific vegetation encountered. Devon does not require vegetation-specific terrain assessment.

3.4.2 Long-Range Terrain Assessment and Path Planning

This GN&C method is similar to the previous one but operates on a much longer scale (i.e., hundreds of meters). A sensor such as a long-range lidar is used to build a very detailed model of the terrain in a wide region around the rover (see Figure 4). This model has scientific value, but also engineering value as it may be used to plan paths for a rover. The presence of trees and tall bushes introduce far more undriveable areas than would be encountered in a planetary situation. Moreover, they severely limit the size of area that can be scanned (e.g., using a camera or long-range lidar). This is very problematic when vegetation is taller than the rover being tested. Thus, the ability to scan several hundred meters to assess terrain on a large scale is limited when vegetation is present. Devon does not suffer from this problem.

3.4.3 Localization

There are a few different types of localization techniques. Short-range techniques such as visual odometry are employed to estimate the relative motion of a rover platform using onboard sensors (e.g., stereo cameras) [5]. Long-range techniques such as horizon matching are used to estimate global position by matching camera views to orbital digital elevation maps [3]. There are three negative aspects imposed by vegetation for localization. First, although it is possible to use localization methods in the presence of vegetation, there is an underlying assumption in many of these techniques that the terrain is not changing over time. Vegetation can change over time (e.g., wind, growth). Second, certain types of vegetation (e.g., grass, leaves) are very self-similar and thus make it difficult to find distinct visual features for tracking. In other words, the texture of the appearance is too fine. Third, other types of vegetation (e.g., far away trees silhouetted against the sky) provide features that are too easy to track (for relative localization) or too difficult to match (for global localization, due to occlusions). In summary, the presence of vegetation severely limits the quality of the test results for localization methods. Devon does not suffer from any of these problems and has proven to be a very good test venue for vision-based localization techniques.

3.5 Infrastructure and Logistics

Fig. 10. ROC6 loaded onto a Twin Otter.

Although Devon Island is extremely remote, access is not difficult in the summer months. Commercial flights may be taken from Ottawa, Canada, to Resolute Bay on Cornwalis Island and then a chartered Twin Otter to Devon Island (see Figure 10). Once on Devon Island, the Haughton-Mars Project Research Station [8] is well-equipped to serve the needs of a rover testing team. Food, water, electricity, fuel, office space, internet access, all-terrain vehicles, and guides are all available, allowing maximum time to be spent conducting experiments. Moreover, because experiments can be conducted right out of HMP basecamp, the work day is effectively 24 hours long. These attributes make it possible to conduct a very large number of experiments in a 2-3 week stay. An issue worth noting is that government and Inuit permits are required to access Devon Island and that equipment typically needs to be shipped well in advance of arrival. Also, bugs are minimal on Devon and weather is variable in July to August.

3.6 Scientific Merit

The main reason that HMP Research Station exists is the ongoing geology, geomorphology, and biology this unique site hosts. Each field season an international group of scientists visits to collect samples and take measurements. There are countless opportunities for rover researchers to team up with scientists in order to conduct [2]. missions that do real science using robotic tools. Figure 11 shows one example of an ice-prospecting mission conducted on polygonal terrain on Devon It also worth noting that Devon is a fragile environment containing valuable scientific information and wildlife. Keeping the environmental footprint to a minimum is essential; before any rover mission is planned, the impact on Devon must be weighed against the scientific merit of the experiment.

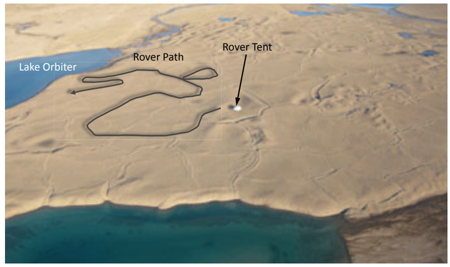


Fig. 11. A simulated rover mission to prospect for ground-ice was conducted at this polygonal terrain near Lake Orbiter on Devon Island in 2009. The UofT ROC6 used ground-penetrating radar along this 734 m path to look for ice deposits (2009).

4 Conclusion

We have reviewed the merits of using Devon Island, and specifically the Haughton crater and surroundings, as a proving ground for planetary rovers. Based on the scale, variety of terrain, lighting conditions, lack of vegetation, existing infrastructure, and wealth of interesting scientific objectives, we believe Devon Island is a strong candidate for continued rover field deployments, despite its remote locale.

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