Towards Autonomous Mobile Robots for the Exploration of Steep Terrain

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Abstract. Steep, natural terrain offers excellent opportunities for scientific investigations into the composition and history of Mars and other planetary bodies. In this paper, we present a prototype tethered robot, *vScout* (vertical scout), capable of operating in steep, rugged terrain. The primary purpose of this vehicle is to support field geologists conducting research on cliffs, in canyons, and on crater walls. However, the long-term vision is to develop a system suitable for planetary exploration (and more diverse terrestrial applications). Unlike other systems for exploration in steep terrain, vScout has demonstrated autonomous operation on steep surfaces by making use of a network of reusable paths and visual teach & repeat. Here we describe the first vScout prototype and our experiences with it. We also outline some challenges and the directions we intend to take with this research.

1 Introduction

In this paper, we present *vScout*[1] (vertical scout), a prototype tethered mobile robot with autonomous capabilities. It can operate in terrain ranging from flat to a sheer vertical drop. Figure 1 shows a photo of the vScout prototype operating in steep, rough terrain at the Canadian Space Agency's Mars Emulation Terrain.

Long-range observations of steep, natural terrain (see Figure 2) have yielded fascinating clues to the composition, history, and the current geological processes that are active on Mars. The exposed strata are a glimpse at the subsurface without the

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[1] For videos of vScout visit: http://youtu.be/fAQiyHssJYM

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Fig. 1 The vScout prototype operating in steep, rough terrain in the Mars Emulation Terrain at the Canadian Space Agency in St. Hubert, Quebec, Canada, June 2013. Video from this test is available at: `http://youtu.be/z5ud7k9ozvQ`

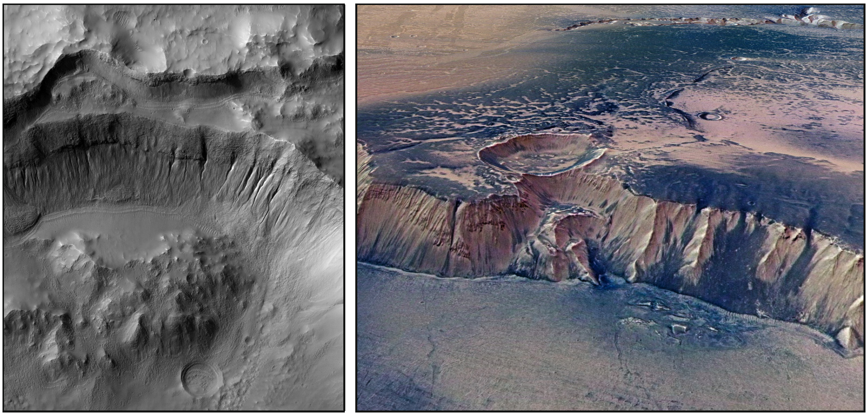

Fig. 2 Steep terrain on Mars. Left: gullies on the wall of Mariner Crater, image: NASA/JPL/University of Arizona. Right: perspective view of Echus Chasma, credits: ESA/DLR/ FU Berlin (G. Neukum)

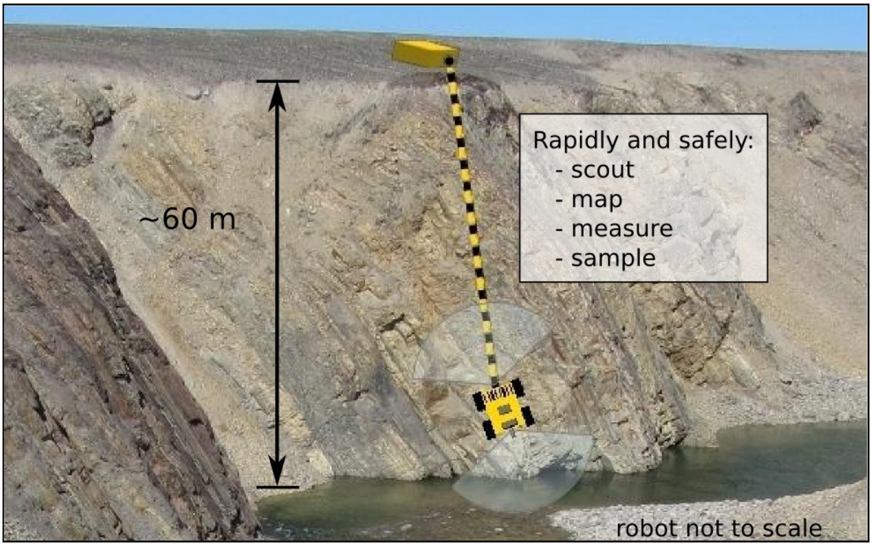

Fig. 3 Steep terrain at the newly discovered site of one of the world's largest meteorite impact craters (Victoria Island, Northwest Territories, Canada). Development of the vScout is aimed at allowing access to terrain that is scientifically important, but currently not practically accessible

need for difficult excavation or deep drilling. Yet while we have learned much from a distance, many important questions will remain unanswered while planetary scientists are without detailed local terrain models, in situ measurements, and samples returned from these steep surfaces. To obtain these we must physically access these areas. Unfortunately, steep, natural terrain is inaccessible to current planetary rovers. It is for this very reason that the Mars Science Laboratory rover Curiosity was landed *inside* Gale crater on Mars. There are only a small number of fielded research systems capable of operating in steep terrain, and fewer capable of exploring rugged, vertical cliffs [2, 6, 11]. To our knowledge, even though there has been some development of theoretical approaches to autonomy, none of these capabilities have been demonstrated in steep terrain. Autonomy is very desirable in space exploration where communications delays can make continuous, direct teleoperation far too slow or even impossible.

The Axel rover [11], in particular, is a robot for steep terrain that has been developed for space exploration. With vScout we are taking a different approach. Instead of directly targeting space exploration, we are looking to support field geologists doing work in remote areas on Earth. For an example site, see Figure 3. Even on Earth, access to steep terrain is at best difficult and time-consuming to do safely, and often it is simply not feasible because of safety, logistics, or the available time. We believe that by using existing guidance, navigation, and control (GN&C) techniques that leverage the expertise of a human operator, we can create a tool useful to scientific investigations on Earth, and that the terrestrial benefits of such a system will make it natural and reasonable to demand and expect similar capabilities in planetary exploration. This is certainly an ambitious proposal. In this paper we present the first steps toward this goal and we show preliminary results. We also outline some challenges we are working on and the directions of future research.

The remainder of this paper is as follows: Section 2 provides background information, Section 3 describes the vScout, Section 4 details the testing, the paper finishes with challenges and future work (Section 5), and conclusions (Section 6).

2 Background

The background is divided into two parts: i) an overview of robots for use in steep terrain, and ii) an overview of visual teach & repeat and a network of reusable paths, a technology that is used for the autonomous operation of vScout.

2.1 Robots for Steep, Natural Terrain

Robots have excelled at operating in some environments too dangerous for humans. This includes some types of steep areas. Although the discipline is small, the research into vertical robots has developed several promising approaches to access steep, natural terrain. Currently, none of these systems are available for regular use either because their capabilities are too limited, their cost is too high, or the deployment and operations logistics are too burdensome.

Some research has been done on developing robots that climb like humans or other more capable primates (e.g., Capuchin [16]). Similarly, other biologically inspired designs (e.g., RiSE [14]) can climb up from below with no rope (except perhaps as a safety line); however, the prototypes are still quite slow, require specific types of surfaces, or significant advances are necessary before they can reliably operate in natural environments. There are also systems that are designed for use in specialized (usually human-made) environments. For example, there are systems that have made use of magnets [5], suction [3], microspines [7], or adhesives [10]. However, the assumptions made about the surfaces and structures make general as-is use of these systems unlikely in natural terrain.

One of the most studied techniques is to have the robot descend from above using a tether. Notable examples are Dante II [2], TRESSA [6], and Axel [11]. These systems have been field tested and they can all operate on vertical slopes.

The Dante II rover [2] was an 8-legged frame walking robot used to explore Mt. Spurr, a remote Alaskan volcano, in 1994. This large robot (nearly 800 kg) was teleoperated from a remote location using onboard television cameras and laser rangefinders. The power and communications links were through the tether. Over the course of more than five days, Dante II was used to successfully complete the primary objectives of the mission. However, while it was returning to the lip of the crater, it ended up tipping over. It was eventually recovered using a helicopter and two people who hiked down to attached a sling. This experience highlights two of the many significant challenges to operating in steep terrain: i) the need for situational awareness (Dante II's laser rangefinder was inoperable at the time of tip-over), and ii) the fact that recovery in the event of mishap may be dangerous, expensive, or even impossible. If these robotic tools are to be used regularly they should, on average, be much safer and less expensive that the alternatives.

As demonstrated in Dante II and the other systems, the tether can allow operation on steep terrain, but it also makes significant lateral movement challenging. The TRESSA [6] system attempts to improve the lateral mobility by having two mobile robots at the top that are tethered to a single four-wheel Cliffbot on the steep surface. This will work well in fairly smooth steep areas but in rougher terrain it may even further complicate and limit the mobility.

The TRESSA system stores the tether at the top of the steep terrain. While this approach does reduce the weight of the vehicle on the cliff, it will also increase the wear on the tether and eventually limit the range of the tethered vehicle (once the tether drag along the ground reaches the limit of what the vehicle can pull). An alternative is the have the tether stowed on and deployed from the descent vehicle (as done by Dante II [2] and Axel [11]).

The Axel rover [11] is a two-wheeled minimalist chassis that has undergone several iterations. Unlike the other systems that have been mentioned, Axel can operate even if it is flipped over. Its two wheels are on either end of the cylindrical body and an arm extends from mid-width keeping the tether away from the main body. The tether arm can be actively controlled for improved rover mobility and to keep the tether off the ground. There has been some theoretical work done on path planning for Axel [1], but our understanding is that it has yet to move beyond simulation.

Like Dante II, Axel's power and communication links are through the tether. There are strong reasons for using the tether for more than simply mechanical support. Onboard power is a significant challenge in mobile robotics. It can be heavy and/or expensive, and the inclusion of heavy systems (such as onboard batteries or gas generators) can lead to increased structure and actuator costs. Additionally, these self-contained power systems have limited capacity and this limits the maximum mission duration (thus the vehicle cannot loiter for extended periods of time).

Similarly, a communications link integrated into the tether avoids the challenge of reliable, high-speed wireless communications. Wireless communications become difficult or impossible when there is no line-of-sight (over-the-edge). Long range antennas can be bulky and will have pointing issues. Finally, wireless communications can use a lot of power, thus exacerbating the challenges of onboard power.

2.2 Visual Teach & Repeat and a Network of Reusable Paths

We have some background experience with visual navigation and we believe it will be appropriate for use on vScout. *Visual teach & repeat* (VT&R) [4, 9] allows a robot to drive arbitrarily long distances, without the use of GPS, along previously established routes. In these systems, a chain of small maps is attached along the robot's path (estimated using visual odometry [8]) during a teaching phase; to repeat the path, the robot localizes against each small map in sequence as it drives. This

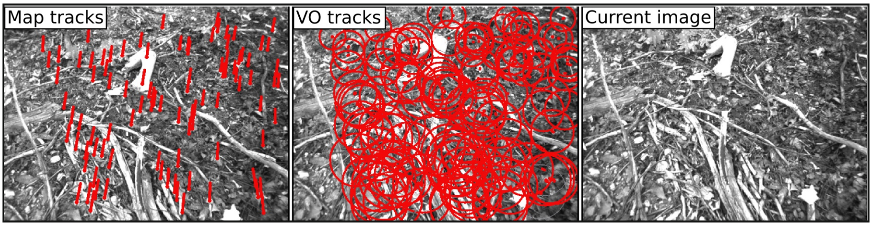

Fig. 4 Stereo-camera-based visual teach & repeat onboard the vScout. When repeating a taught route, localization against the map is interleaved with visual odometry (VO). The map tracks show the keypoints that have been matched between the taught route and the current stereo image pair. The VO tracks show the keypoint matches between the current stereo pair and the previous pair.

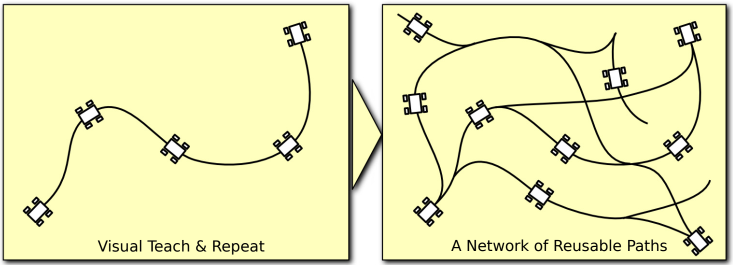

Fig. 5 A network of reusable paths (NRP) makes use of visual teach & repeat (VT&R). VT&R is a single chain of poses that the robot can repeat in either direction. NRP uses VT&R and extends it to an arbitrary network, allowing the robot to return to any previously visited pose. We use both VT&R and NRP on vScout.

local map approach works well regardless of the nature of the surface on which the robot is driving. Figure 4 shows images from stereo-camera-based VT&R onboard the vScout while repeating a path. The keypoints from the current image (right) are matched against the keypoints from the taught image (left). Visual odometry (center) is used to estimate the motion before attempting to match against the map.

The *network of reusable paths* (NRP) concept extends VT&R systems from using a simple chain of local maps, to an arbitrary network of local maps [15] (see Figure 5). The robot can return to any point on the network at any time, and by driving into new areas, the network can be extended.

On vScout, we currently use both VT&R and NRP to leverage human expertise in terrain assessment and path planning. Once a path has been taught, vScout can be entrusted to repeat it, in either direction, and the operator no longer needs to directly control the vehicle, a tedious and difficult task. Eventually we would like to have vScout autonomously teach new paths as well as repeat them. This means incorporating suitable terrain assessment and path planning capabilities. We have done this for other rovers [15] but not yet for systems in steep terrain.

3 The vScout

This section describes the current vScout proof-of-concept prototype. Our philosophy with this research has been that field experience will guide the design. Therefore, our priority has been to develop an end-to-end system rapidly, even though it is not always consistent with the long-term vision at a component level. At some points in this text we note where the long-term vision differs from the prototype and a more complete discussion of the differences is in Section 5. This section is divided into four parts: i) a description of the use scenario (Section 3.1), ii) a description of the hardware configuration (Section 3.2), iii) detail on the powered ascender mechanism (Section 3.3), and iv) an overview of the onboard GN&C (Section 3.4).

3.1 High-level Scenario

The vScout was developed with the goal of aiding field geologists. The ultimate goal is simply to have a user press a button and have the robot autonomously descend, map and document everything it can, and come back up, while carrying standard geological instruments. This preliminary system is working toward that goal. The following high-level scenario outlines how this first prototype is intended to be used.

1. Outfit the vScout with the desired measurement package.
2. Position the vScout near the top of the steep terrain and create a secure anchor.
3. As necessary:
   - Move to get a better view to remote control the vScout.
     This may be above, below, to the side, or even across from the cliff. Direct observation is used to augment data from the onboard cameras and sensors.
   - Manually drive the robot into new areas and add to the NRP.
   - Automatically generate/update a 3D model of the terrain.
   - Autonomously return to any previously visited point on the network.
4. When done at a site, command the vehicle to autonomously return to the start.

3.2 Hardware Overview

The vScout is a tethered robot designed to descend from an anchor near the top of steep terrain. For this first version we retrofitted a Husky A200 from Clearpath Robotics (see a schematic of the prototype system at the top of Figure 6). On the back of the Husky is an ascender (described in detail in Section 3.3). The ascender allows the robot to hang suspended by a 8 mm climbing rope (see Figure 7).

A Point Grey Bumblebee XB3 stereo camera is mounted on a mast facing the front of the vehicle (away from the tether). We also tried mounting the camera near the front and rear of the vehicle, as seen in photos of the vScout. There is an onboard laptop computer used for navigation and data logging. There is also a wireless connection used to connect the operator station to the vehicle. The system has a mass of approximately 70 kg, and dimensions of approximately 130 cm long and 70 cm wide. The highest point is approximately 95 cm off the ground.

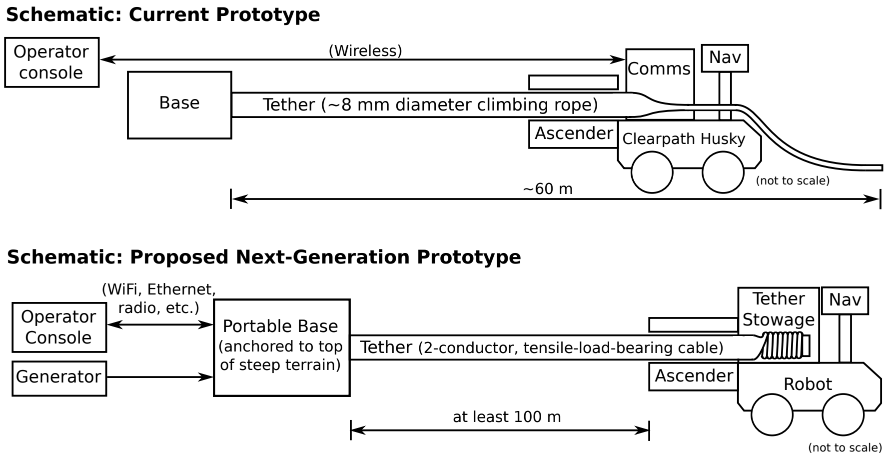

Fig. 6 Schematics of the current prototype (top) and the proposed next-generation vScout (bottom). The current prototype uses VT&R/NRP with manually taught paths. The goal eventual system is to have the vScout, with the push of a button, autonomously descend, map, and return to the top of the cliff. More details on the proposed system are available in Section 5.

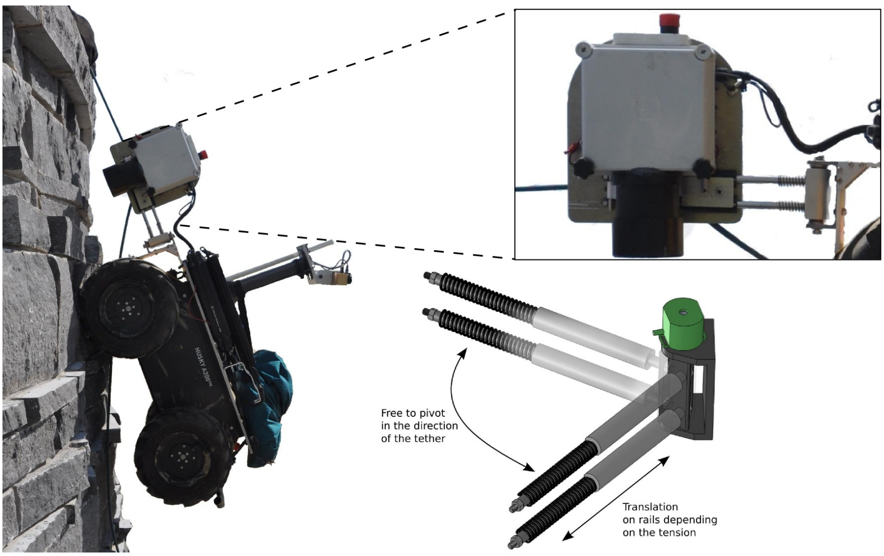

Fig. 7 The vScout on vertical terrain (left). The ascender, on spring-loaded rails that pivot, was attached to the back of a Clearpath Robotics Husky A200. The pivot angle could be measured and the tension in the tether could be estimated based on the displacement of the spring-loaded rails.

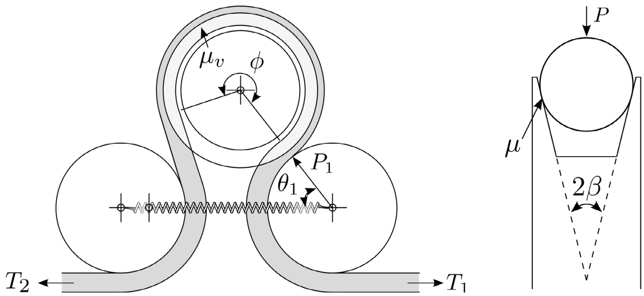

Fig. 8 A model of the ascender mechanism (left) and a profile of the grooved top pulley (right)

3.3 The Ascender Mechanism

The ascender assembly was mounted on the back of the Husky, as seen in Figure 7. It was free to passively pivot from side to side, and it could also slide on spring-loaded rails. The rails had the dual use of providing suspension to the system and, by measuring the displacement, we could estimate the tension in the tether.

The main part of the ascender consists of three wheels (see Figure 8). The middle wheel is grooved and attached to an electric motor. The other two wheels are idlers that are connected to each other through a spring-loaded mechanical linkage. The idlers slide in the x-direction and pinch the rope against the grooved pulley. The following analysis shows that the tether will not slip if the coefficient of friction between the aluminum and the tether is sufficiently high.

Assume that the tether cross-section is not deformable. Then the equivalent coefficient of friction for the groove, μ_v, as a function of the coefficient of friction between the materials of the tether and the pulley, μ, is

$$\mu_v = \mu / \sin\beta, \tag{1}$$

where β is the groove angle as shown in the right of Figure 8.

The *capstan equation* is a way to model the load that a tether wrapped around a smooth cylinder can hold without slipping. The high-tension end of the tether has a load of T_{high} and the low-tension end of the tether has a load of T_{low}. The angle swept by the tether is ϕ. The capstan equation is

$$T_{\text{high}} \leq T_{\text{low}} e^{\mu\phi}. \tag{2}$$

Considering the model of the ascender shown in the left of Figure 8, and using the relations from (1) and (2), we can write the no-slip holding load of the ascender as,

$$T_2 \leq (\mu_v P_1 + T_1)\, e^{\mu_v \phi}, \tag{3}$$

where T_2 and T_1 are the high-tension and low-tension loads on the tether, and P_1 is the pinching force between the grooved pulley and the right idler wheel. In this analysis we conservatively assume $T_1 = 0$. Due to the geometry of the pulleys and nature of the spring-loaded bar connecting the idlers, when T_2 is high, $P_1 = T_2 / \cos\theta_1$, where θ_1 is the angle of the pinching force, P_1, as shown in Figure 8. This means the equation (3), which governs the holding force of the ascender, simplifies to

$$\mu \frac{1}{\sin\beta\cos\theta_1} e^{\mu \frac{1}{\sin\beta}\phi} \geq 1. \tag{4}$$

If the inequality in (4) is satisfied, the tether will not slip. □

The threshold coefficient of friction, μ_{thresh}, beyond which slip will occur, can be found by solving

$$\mu_{\text{thresh}} \frac{1}{\sin\beta\cos\theta_1} e^{\mu_{\text{thresh}} \frac{1}{\sin\beta}\phi} = 1. \tag{5}$$

The geometry of the mechanism is such that: $\beta = 21°$, $\theta_1 = 55°$, and $\phi = 245°$, and therefore, $\mu_{\text{thresh}} = 0.08$. We have measured μ to be between 0.3 and 0.35 using an inclined plane test. Since $\mu \geq \mu_{\text{thresh}}$, the ascender on the vScout should not allow the tether to slip. In practice, we have not had the rope slip while it is under tension.

3.4 The Onboard Guidance, Navigation & Control System

VT&R and NRP use the stereo camera in order to allow vScout to return to any previous point. The paths are taught by an operator remote controlling the robot. The path tracker is that same as in previous VT&R/NRP systems [9, 15]. It does not consider the slope of the terrain. The tether controller was designed to keep the tether tight while keeping the tether speed near the speed of the vehicle. The control law governing the speed of the tether, v_t, is

$$v_t = \begin{cases} k_1 v_r & T_t \geq T_{thresh} \text{ and } v_v \leq 0 \\ k_2 v_r & T_t \geq T_{thresh} \text{ and } v_v > 0 \\ k_1 v_r + k_3 & T_t < T_{thresh} \text{ and } v_v \leq 0 \\ k_4 & T_t < T_{thresh} \text{ and } v_v > 0 \end{cases}, \tag{6}$$

where, v_v is the speed of the vehicle in the x-direction (i.e., $v_v > 0$ is moving forward, and $v_v < 0$ is moving in reverse). The measured tether tension is T_t, and the threshold tension defines the point below which the tether is considered slack. The gains, k_1 and k_2, are set close to 1, with $k_1 \geq 1$ and $k_2 \leq 1$. The gains k_3 and k_4 are used when the tether is slack, in order to take up slack, they are set so that $k_3 \leq 0$ and $k_4 \leq 0$. This approach worked well enough in these tests, but there is much room for improvement. For instance, this approach leads to higher-than-necessary tether loads, and therefore power usage. We anticipate that the path-tracking and tether controllers (especially in the context of repeating a previous path) will be active areas of future research.

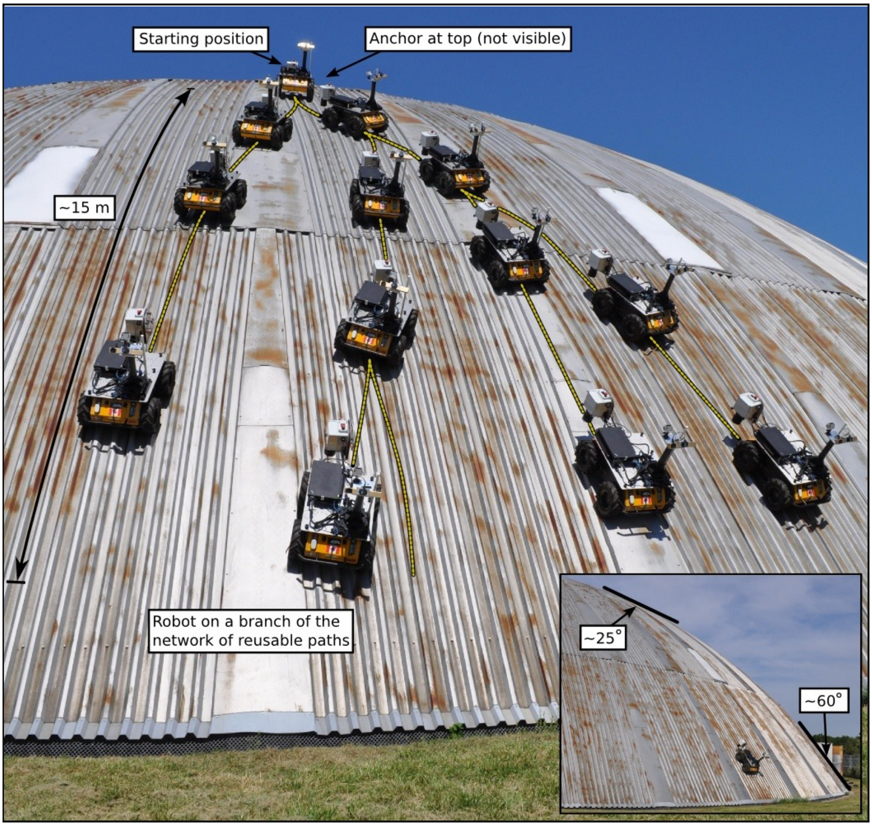

Fig. 9 A time-lapse view of the vScout operating on the Dome at UTIAS. The vScout used a network of reusable paths. It was manually taught a path and then it was able to autonomously repeat that path to return to any previously visited point.

4 Testing

The first two sets of testing we did were on a steep building (the Dome) near our lab[2], and at the Mars Emulation Terrain at the Canadian Space Agency[3] (see Figure 1). Those first two sets of testing were entirely manually controlled. In later tests on the Dome and the steep walls of a ravine, vScout demonstrated autonomous behavior that made use of visual teach & repeat and a network of reusable paths. The operator manually taught the paths, using their skill and judgment to establish safe routes, and the robot would autonomously repeat the paths.

In total, we conducted five tests that made use of VT&R on the ravine wall, four tests of VT&R on the Dome, and five tests of NRP on the Dome. Figure 9 shows

[2] A video of the first ascent of the Dome at UTIAS: `http://youtu.be/o2hrGYYP9b8`

[3] A video of vScout at the CSA's Mars Emulation Terrain: `http://youtu.be/z5ud7k9ozvQ`

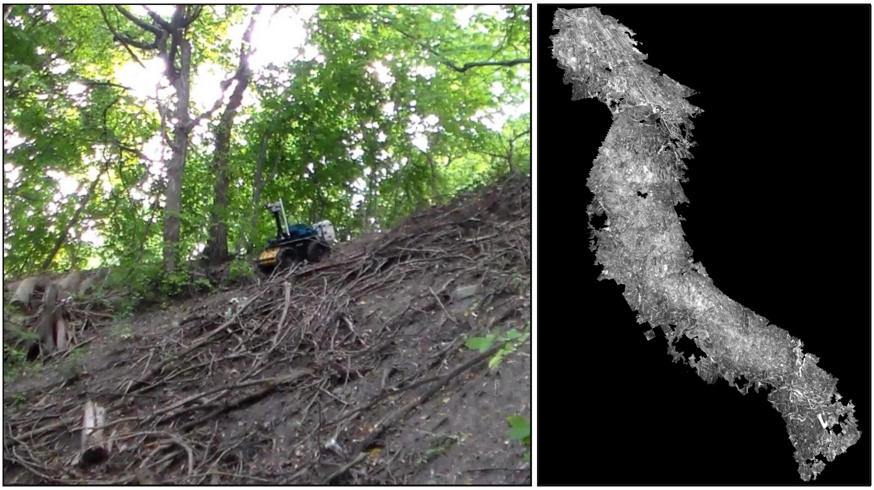

Fig. 10 The vScout in the ravine (left). A 3D model of the terrain from the first test using VT&R on the ravine wall (right). The model was made using Mobile Scene Modeler (mSM) from MDA.

the fourth test of NRP on the Dome[4]. In that test the vScout was first taught the path on the far right of Figure 9. It then autonomously reversed the path until the human operator took control and taught another branch in the network. This same process was repeated for all five branches in this network.

The vScout repeated all paths and networks on the Dome, and it was able to localize relative to the taught path. The repetitive texture of the corrugated steel was challenging for the localization system, but the discolorations created a unique, if relatively sparse, constellation of distinctive features. Additionally, the localization framerate ($\tilde{1}0\,\mathrm{Hz}$) was fast relative to the speed of the vehicle ($\leq 0.25\,\mathrm{m/s}$). However, the loose terrain of the ravine, combined with the orientation of the stereo camera (pointing down in front of the vScout in order to collect imagery for map building), meant that the appearance of the scene would change dramatically between teach and repeat phases (because the vScout would disturb the soil as it drove over). This made it difficult for VT&R to localize against the map, and instead the system had to use solely visual odometry to estimate its pose. A possible solution is to use a stereo camera that is pointed to the side in order to minimize the chance of driving over the visual features used for localization. However, this would mean that another camera would be needed in order to see in front of the vScout.

After each test, we used the stereo camera imagery to construct a 3D model of the terrain. This was done by MDA's Mobile Scene Modeler (mSM) [13]. Figure 10 shows the model generated during the first test of VT&R on the ravine wall. Only the outbound images (i.e., the images from teaching the path) were used to build the

[4] A video of the fourth NRP test on the Dome is at: `http://youtu.be/fAQiyHssJYM`

models in order to avoid the previously noted problem where the vehicle changes the visual appearance of the scene.

5 Challenges and Future Works

Using this first prototype has led to many valuable lessons, these are listed below.

1. The configuration of the terrain directly under the vehicle was critical knowledge for the operator when the vScout was in rough terrain.
   - *Later vScout designs will use more sensors and algorithms to give the remote operator better awareness of the terrain under the vehicle. These will also likely act as the foundation for terrain assessment and path planning capabilities necessary for one-button autonomous descent, mapping, and return.*
2. The ability to attach to or detach from the tether at mid length was particularly useful (as opposed to having to thread the tether through the ascender). This gave us the opportunity to quickly start the vScout from the bottom rather than the top.
3. The vehicle was more maneuverable in steep terrain with only two wheels on the ground (like Axel). However, the four wheels helped when overcoming obstacles.
4. The vehicle spent a great deal of the time with its underside in contact with the terrain. This reinforces the need for a good skid plate and adequate protection for any cameras underneath the vehicle.
   - *We embraced the fact that this prototype would often scrape, bang, or high-center during operation. In later prototypes we will modify the design to reduce the chance of the vehicle getting caught (e.g., streamline the ascender).*
5. The tether was not only useful in steep areas, but also quite beneficial on flat, but rough, terrain. The tether could be used to simply pull the vehicle off if the robot got stuck, and it provided a great deal of stability that made a tip-over seem much less likely when traversing hazards.

We have also experienced other challenges which we expect to address is the next vScout. For instance, path tracking will become difficult as we begin to have the vehicle move more laterally on steep terrain. However, our lab is currently developing a learning path tracking controller [12], that, when combined with improved tether control, may offer a solution.

Additionally, we are already testing the limits of our current version of VT&R and NRP. Prior to vScout, we had only used VT&R in relatively flat terrain. This has meant that the path was able to be reversed with the vehicle in the same orientation, and consequently the rigidly mounted camera was also in the same orientation and it saw the same scene regardless of whether the vehicle is traveling forward or reverse. However, when a skid-steer vehicle is operating on steep slopes, it must turn into the slope in order to track cross-slope paths. This means the vehicle orientation depends on the direction of travel, and a rigidly mounted camera is no longer feasible. Some possible solutions are to use cameras with a 360° field of view or a camera mounted on a pan-tilt unit.

Finally, in the next vScout, as in the bottom of Figure 6, there will be a tether stowage system. The tether will also be used to transmit power and communications to the vehicle. This should help avoid the risk of fouling the tether in the wheels, improve communications, and reduce battery weight.

6 Conclusions

This paper presented a prototype tethered robot, called vScout, intended to help field geologists in the exploration of steep terrain. The long-term objective is to develop technologies to enable the exploration of vertical surfaces on other planets. The system has been used at several sites where it operated under manual control and at times autonomously, and built a three-dimensional model of the terrain. The autonomous capabilities make use of VT&R and NRP to repeat previously traveled routes. Later versions of the hardware, software, and operations scenarios will build on our experiences with this first system, leading toward a vScout that will autonomously descend, map, and return, all with the push of a button.

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