Planetary Exploration in USARsim: A Case Study Including Real World Data from Mars[*]

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Abstract. Intelligent Mobile Robots are increasingly used in unstructured domains; one particularly challenging example for this is planetary exploration. The preparation of according missions is highly non-trivial, especially as it is difficult to carry out realistic experiments without very sophisticated infrastructures. In this paper, we argue that the Unified System for Automation and Robot Simulation (USARSim) offers interesting opportunities for research on planetary exploration by mobile robots. With the example of work on terrain classification, it is shown how synthetic as well as real world data from Mars can be used to test an algorithm's performance in USARSim. Concretely, experiments with an algorithm for the detection of negotiable ground on a planetary surface are presented. It is shown that the approach performs fast and robust on planetary surfaces.

1 Introduction

Planetary exploration is a task where intelligent mobile robots can be valuable tools as impressively demonstrated by the Mars Exploration Rover (MER) mission [1][2][3][4]. Also, the control of the systems still involves a major amount of human supervision [5], i.e., there is still significant need for research to increase the robots' intelligence and autonomy. Furthermore, the preparation of according missions is highly non-trivial. It requires a significant amount of preparation and testing. Here, the use of the Unified System for Automation and Robot Simulation (USARSim) for the purpose of research, testing and planning of planetary exploration missions is evaluated. Concretely, a case study is made were USARSim is used for an approach to terrain classification in the context of planetary exploration.

The Unified System for Automation and Robot Simulation (USARSim) [6] is a high fidelity robot simulator built on top of the Unreal Tournament[7] game engine. Its feature include a commercial physics engine (Karma [8]) and a real-time,

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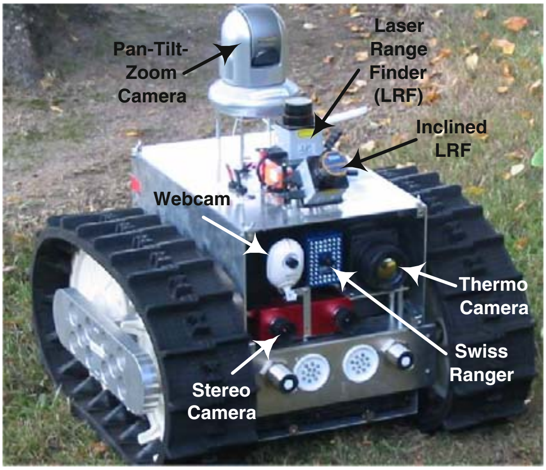

Fig. 1. The autonomous version of a *Rugbot* with some important on-board sensors pointed out. The SwissRanger SR-3000 and the stereo camera deliver the 3D data for the terrain classification.

Fig. 2. Two Rugbots at the Space Demo at RoboCup 2007 in Atlanta

three-dimensional visualization engine. It is important that these components have been tested for their physical fidelity [9,10,11,12]. The robot model used for the case study in this paper is the Rugbot - from rugged robot - (figure 1), which was first developed for work on Safety, Security, and Rescue Robotics (SSRR). But due to its capabilities to negotiate rough terrain [13][14], it is also an interesting platform for research on planetary exploration (figure 2). The software architecture on the Rugbots is designed to support intelligent functions up to full autonomy [15][16][17].

The case study conducted here deals with terrain classification, especially the detection of drivable ground. This is a very important topic in the space robotics community [18,19,20,21,22] as - despite a human in the loop component - the robots have to move some distances autonomously on their own; the long delay in radio communication simply prohibits pure tele-operation. Here we present an extension of work described in detail in [23], which deals with a very fast but nevertheless quite robust detection of drivable ground. The approach is based on range data from a 3D sensor like a time-of-flight camera like a SwissRanger, respectively a stereo camera. The main idea is to process the range data by a Hough transform with a three dimensional parameter space for representing planes. The discretized parameter space is chosen such that its bins correspond to planes that can be negotiated by the robot. A clear maximum in parameter space hence indicates safe driving. Data points that are spread in parameter space correspond to non-drivable ground. In addition to this basic distinction, a more fine grain classification of terrain types is in principle possible with the approach. An autonomous robot can use this information for example to annotate its map with way points or to compute a risk assessment of a possible path.

The approach has already proven to be useful in in- and outdoor environments in the context of SSRR. The results presented in [23] are based on experiments with datasets with about 6,800 snapshots of range data. Drivability is robustly detected with success rates ranging between 83% and 100% for the SwissRanger and between 98% and 100% for the stereo camera. The complete processing time for classifying one range snapshot is in the order of 5 to 50 msec. The detection of safe ground can hence be done in real-time on the moving robot, which allows using the approach for reactive motion control as well as mapping in unstructured environments. Here, the question of interest is whether the approach is also suited for planetary surfaces and how USARSim can be used to answer this question.

2 Detection of Negotiable Terrain

The terrain classification is based on the following idea. Range images, e.g. from simple 3D sensors in the form of an optical time-of-flight camera and a stereo camera, are processed with a Hough transform. Concretely, a discretized parameter space for planes is used. The parameter space is designed such that each drivable surface leads to a single maximum, whereas non-drivable terrain leads to data-points spread over the space. The actual classification is done by three simple criteria on the binned data arranged in a decision tree like manner (see algorithm 1). In addition to binary distinctions with respect to drivability, more fine grain classifications of the distributions are possible allowing to recognize different categories like plane floor, ramp, rubble, obstacle, and so on in SSRR domains, respectively flat ground, hills, rocks, and so on in planetary exploration scenarios. This transform can be computed very efficiently and allows a robust classification in real-time.

Classical obstacle and free space detection for mobile robots is based on two-dimensional range sensors like laser scanners. This is feasible as long as the robot operates in simple environments mainly consisting of flat floors and plain walls. The generation of complete 3D environment models is the other extreme, which requires significant processing power as well as high quality sensors. Furthermore, 3D mapping is still in its infancy and it is non-trivial to use the data for path planning. The approach presented here lies in the middle of the two extremes.

Algorithm 1. The classification algorithm: First, it checks the bin corresponding to the floor. If it has enough hits, the result "floor" is returned. Otherwise it uses two simple criteria to verify the usability of the bin with most hits bin^{max}. In this case, the class is assigned based on the parameters of bin^{max} (line 1). Otherwise, no plane dominates the Hough space, so an obstacle is reported. $\#S$ is the cardinality of S, PC is the used point cloud. Constants were $t_m = 0.667$, $t_p = 0.125$, $t_n = 6$, $t_h = 0.15$

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1. if $\#\text{bin}_{\text{floor}} > t_h \cdot \#\text{PC}$ then
2.    class $\leftarrow$ floor
3. else
4.    if $(\#\{\text{bin} \mid \#\text{bin} > t_m \cdot \#\text{bin}^{\text{max}}\} < t_n)$ and $(\#\text{bin}^{\text{max}} > t_p \cdot \#PC)$ then
5.       class $\leftarrow$ type( $\text{bin}_{\text{max}}) \in \{\text{floor}, \text{plateau}, \text{canyon}, \text{ramp}\}$
6.    else
7.       class $\leftarrow$ obstacle
8.    end if
9. end if
```

A single 3D range snapshot is processed to classify the terrain, especially with respect to drivability. This information can be used in various standard ways like reactive obstacle avoidance as well as 2D map building. The approach is very fast and it is an excellent candidate for replacing standard 2D approaches to sensor processing for obstacle avoidance and occupancy grid mapping in non-trivial environments. More details about the implementation of the approach in general can be found in [23].

3 Experiments and Results

The terrain classification algorithm is now tested with synthetic and real world data from Mars in USARSim. The real world data covers the Eagle crater on Mars, which is modeled in USARSim based on ground truth data from the Mars Exploration Rover (MER) mission data archives [24] (see also figures 3 and 4).

Three different areas are used, each with 12 samples. Example images for these terrains can be seen in figure 5. The ground truth is based on visual assessment by two experienced USARSim users. The results of the classification are in table 1. It turns out that the algorithm is nearly as successful as in the original scenario, but significantly faster. This is due to the comparably small number of points, which nevertheless hardly hinder the success.

In figure 6, you can see exemplary Hough spaces for the four terrains corresponding to the images in figure 5. For the passable Terrain A, the Hough space is relatively empty except for one maximum. In the histogram in the right column, it can be seen how one bin with many hits stands out from the others. In Terrains B and C, a number of planes receive many hits, so an obstacle is reported. Also note that the algorithm was invariant to the considerably varying magnitudes in the bins: the maxima were 571 and 527 for A and C, but 1477 for B.

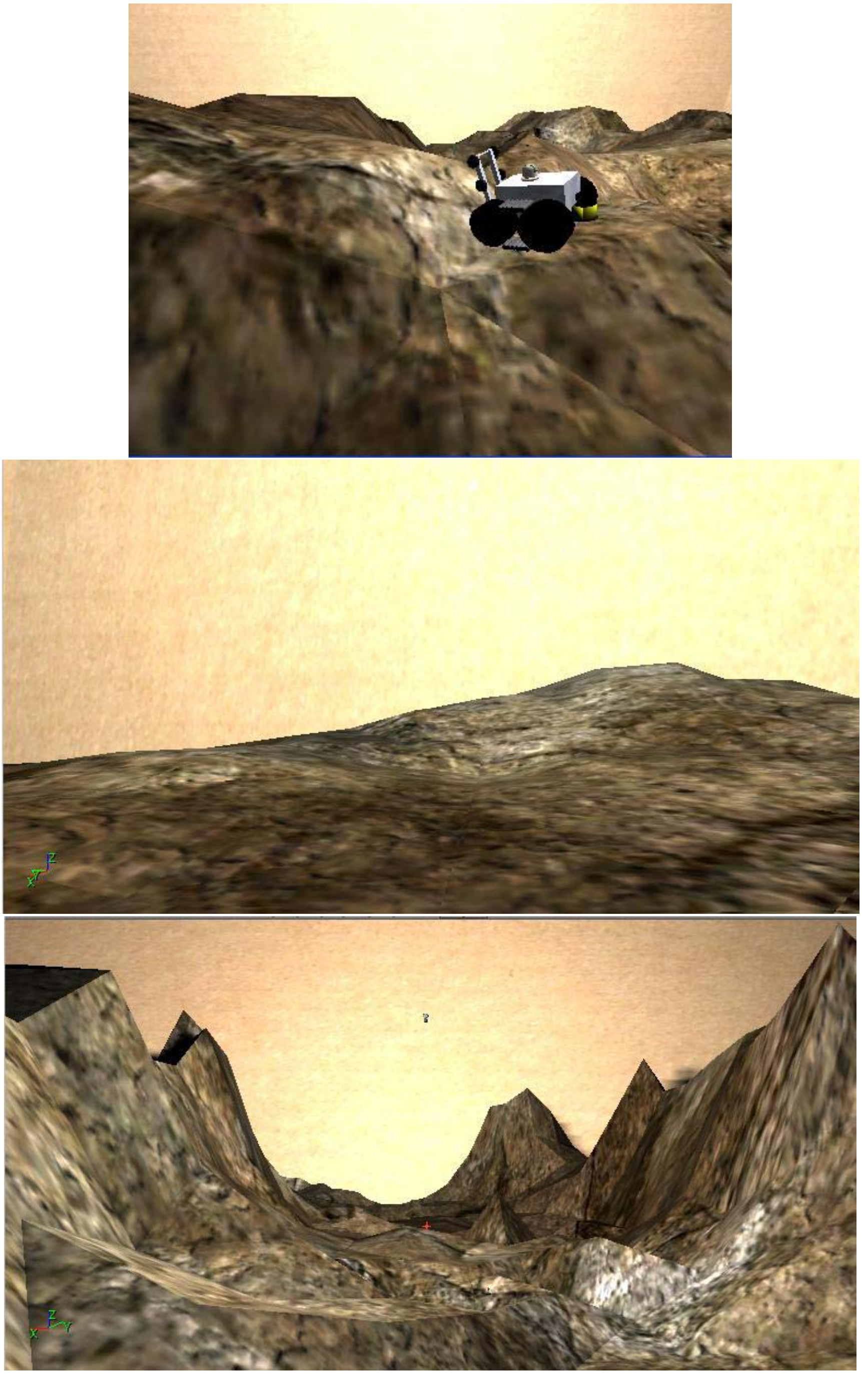


Fig. 3. A Jacobs Rugbot in the RoboCup Virtual Simulator (left), exploring its environment on different planetary surface types (center and right)

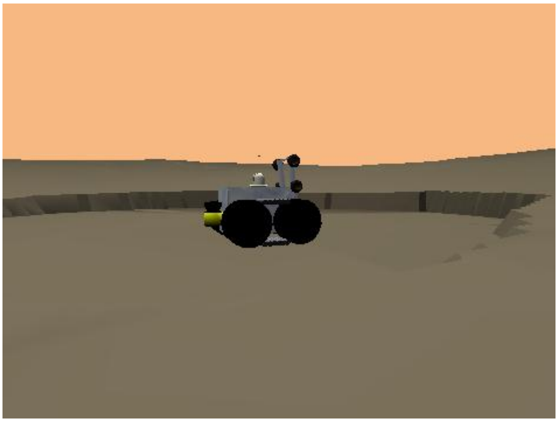
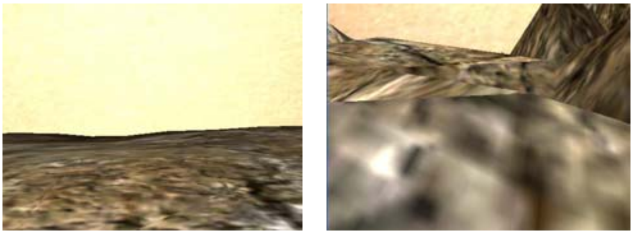
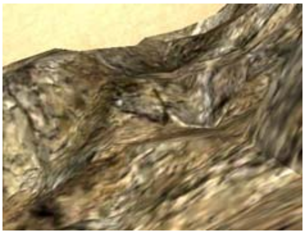


Fig. 4. A Rugbot on Mars in the vicinity of the Endurance crater; the environment is modeled based on original data from the opportunity mission



(a) Terrain A: 829 points (b) Terrain B: 1724 points

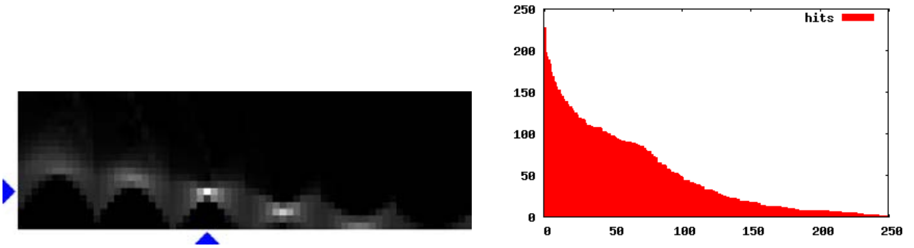


(c) Terrain C: 1567 points

Fig. 5. Example CGI for the terrains used in the classification experiments with given number of points in the corresponding point cloud

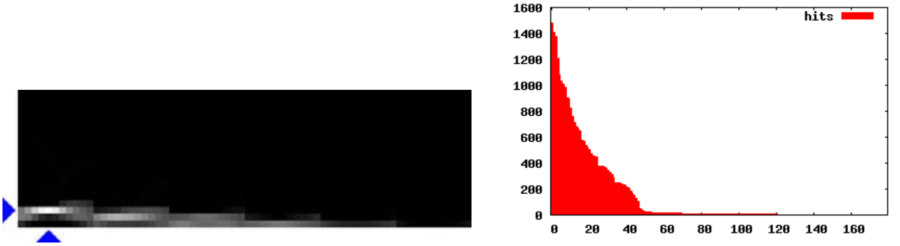
Table 1. Results of the classification experiments

Terrain	Correctness [%]	median time [msec]	median #points
Terrain A	100	5.124	814
Terrain B	83	8.048	1724
Terrain C	83	8.424	1567



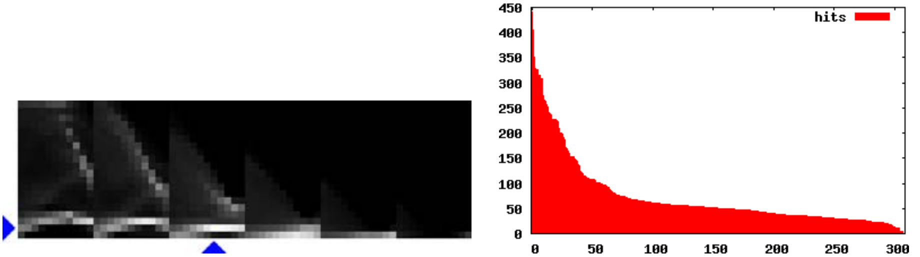
(a) Hough space for Terrain A

(b) Histogram of Hough bins for Terrain A



(c) Hough space for Terrain B

(d) Histogram of Hough bins for Terrain B



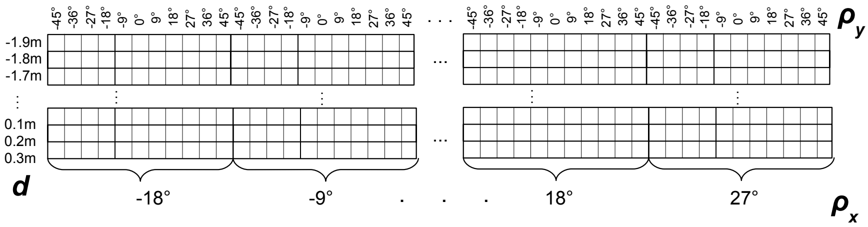
(e) Hough space for Terrain C

(f) Histogram of Hough bins for Terrain C

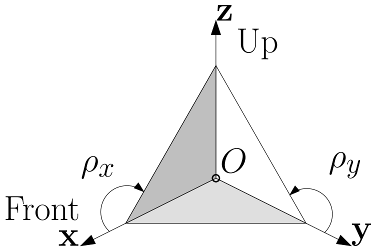
Fig. 6. Results for the scenes in figure 5. In the left column there is a 2D flattening of the 3D hough space (legend in figure 7). The two arrows point at the bin with the maximum number of hits bin^{max}. In the right column there are the bins of the hough space re-ordered by magnitude.

4 Conclusion

We demonstrated the validity of USARSim as a tool for simulation by successfully applying an algorithm that has been shown to work in the real world. This underlines USARSim's usability in the preparation of planetary exploration. A lot of emphasis is put on this phase since many resources are at stake in the actual mission. A low cost software framework like USARSim allows a wider range of companies and research groups to take part in the space effort as it reduces the need for expensive testing environments.



(a) Layout of the 2D flattening of the 3D hough space in figure 6



(b) Parameterization of planes: The angles ρ_x and ρ_y, d is the distance to the origin

Fig. 7. Properties of the Hough transform used

At the same time, we pointed out another domain for the Hough transform based terrain classification introduced in [23]. In the planetary exploration domain, the algorithm does nearly as good as it does in the original indoor and outdoor domains without special adaptations. It was also observed that it also works well with relatively few points (circa 5% of the 25K in the original application). In addition, the low number of points significantly reduced the run time.

Acknowledgments

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References

1. Erickson, J.: Living the dream - an overview of the mars exploration project. IEEE Robotics and Automation Magazine 13(2), 12–18 (2006)
2. Biesiadecki, J., Baumgartner, E., Bonitz, R., Cooper, B., Hartman, F.R., Leger, P.C., Maimone, M.W., Maxwell, S.A., Trebi-Ollennu, A., Tunstel, E.W., Wright, J.R.: Mars exploration rover surface operations: driving opportunity at meridiani planum. IEEE Robotics and Automation Magazine 13(2), 63–71 (2006)
3. Lindemann, R., Bickler, D., Harrington, B., Ortiz, G.M., Voothees, C.J.: Mars exploration rover mobility development. IEEE Robotics and Automation Magazine 13(2), 19–26 (2006)
4. Ai-Chang, M., Bresina, J., Charest, L., Chase, A., Hsu, J.C.-J., Jonsson, A., Kanefsky, B., Morris, P., Rajan, K.R.A.K., Yglesias, J., Chafin, B.G., Dias, W.C., Maldague, P.F.: Mapgen: mixed-initiative planning and scheduling for the mars exploration rover mission. IEEE Intelligent Systems 19(1), 8–12 (2004)
5. Backes, P.G., Norris, J.S., Powell, M.W., Vona, M.A., Steinke, R., Wick, J.: The science activity planner for the mars exploration rover mission: Fido field test results. In: Proceedings of the IEEE Aerospace Conference, Big Sky, MT, USA (2003)
6. USARsim: Urban search and rescue simulator (2006), `http://usarsim.sourceforge.net/`
7. games, E.: Unreal engine (2003)
8. Karma: Mathengine karma user guide (2003)
9. Carpin, S., Lewis, M., Wang, J., Balakirsky, S., Scrapper, C.: Bridging the gap between simulation and reality in urban search and rescue. In: Lakemeyer, G., Sklar, E., Sorrenti, D.G., Takahashi, T. (eds.) RoboCup 2006: Robot Soccer World Cup X. LNCS (LNAI), vol. 4434, pp. 1–12. Springer, Heidelberg (2007)
10. Carpin, S., Lewis, M., Wang, J., Balarkirsky, S., Scrapper, C.: USARSim: a robot simulator for research and education. Proc. of the 2007 IEEE Intl. Conf. on Robotics and Automation (ICRA) (2007)
11. Carpin, S., Stoyanov, T., Nevatia, Y., Lewis, M., Wang, J.: Quantitative assessments of usarsim accuracy. In: Proceedings of PerMIS (2006)
12. Carpin, S., Birk, A., Lewis, M., Jacoff, A.: High fidelity tools for rescue robotics: results and perspectives. In: Bredenfeld, A., Jacoff, A., Noda, I., Takahashi, Y. (eds.) RoboCup 2005. LNCS (LNAI), vol. 4020, pp. 301–311. Springer, Heidelberg (2006)
13. Birk, A., Pathak, K., Schwertfeger, S., Chonnaparamutt, W.: The IUB Rugbot: an intelligent, rugged mobile robot for search and rescue operations. In: IEEE International Workshop on Safety, Security, and Rescue Robotics (SSRR). IEEE Press, Los Alamitos (2006)
14. Chonnaparamutt, W., Birk, A.: A new mechatronic component for adjusting the footprint of tracked rescue robots. In: Lakemeyer, G., Sklar, E., Sorrenti, D.G., Takahashi, T. (eds.) RoboCup 2006: Robot Soccer World Cup X. LNCS (LNAI), vol. 4434, pp. 450–457. Springer, Heidelberg (2007)
15. Birk, A., Carpin, S.: Rescue robotics - a crucial milestone on the road to autonomous systems. Advanced Robotics Journal 20(5), 595–695 (2006)
16. Birk, A., Markov, S., Delchev, I., Pathak, K.: Autonomous rescue operations on the IUB Rugbot. In: IEEE International Workshop on Safety, Security, and Rescue Robotics (SSRR). IEEE Press, Los Alamitos (2006)

17. Birk, A., Kenn, H.: A control architecture for a rescue robot ensuring safe semi-autonomous operation. In: Kaminka, G.A., Lima, P.U., Rojas, R. (eds.) RoboCup 2002. LNCS (LNAI), vol. 2752, pp. 254–262. Springer, Heidelberg (2003)
18. Iagnemma, K., Brooks, C., Dubowsky, S.: Visual, tactile, and vibration-based terrain analysis for planetary rovers. In: IEEE Aerospace Conference, vol. 2, pp. 841–848 (2004)
19. Iagnemma, K., Shibly, H., Dubowsky, S.: On-line terrain parameter estimation for planetary rovers. In: IEEE International Conference on Robotics and Automation (ICRA), vol. 3, pp. 3142–3147 (2002)
20. Lacroix, S., Mallet, A., Bonnafous, D., Bauzil, G., Fleury, S., Herrb, M., Chatila, R.: Autonomous rover navigation on unknown terrains: Functions and integration. International Journal of Robotics Research 21(10-11), 917–942 (2002)
21. Lacroix, S., Mallet, A., Bonnafous, D., Bauzil, G., Fleury, S., Herrb, M., Chatila, R.: Autonomous rover navigation on unknown terrains functions and integration. In: Experimental Robotics Vii. Lecture Notes in Control and Information Sciences, vol. 271, pp. 501–510 (2001)
22. Gennery, D.B.: Traversability analysis and path planning for a planetary rover. Autonomous Robots 6(2), 131–146 (1999)
23. Poppinga, J., Birk, A., Pathak, K.: Hough based terrain classification for realtime detection of drivable ground. Journal of Field Robotics 25(1-2), 67–88 (2008)
24. MER-Science-Team: Mars exploration rover (MER) mission data archives (2007), `http://anserver1.eprsl.wustl.edu/anteam/merb/merb_main2.htm`