Towards legged robots for planetary exploration

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***Abstract*— Robotic exploration of celestial bodies has been performed solely with wheeled systems until today, making access to highly unstructured, compressible, and sloped areas very challenging. On the other hand, walking robots have advanced rapidly over the last decade and have reached a maturity level where commercial applications have become viable. Thus, it is only a matter of time until walking robots will be used to explore so far unreachable regions of our solar system. In this work, we showcase the recent advancements of our dynamically walking legged systems for future planetary exploration missions. In detail, we summarize our work performed on walking on steep, granular slopes, low-gravity locomotion, robot-payload integration and mission scenario execution. Finally, we showcase several real-world deployments and our lessons learned from the experiments.**

***Paper Type* – Recent work [1] [2] [3]**

I. INTRODUCTION

Future robotic exploration missions into our solar system are characterized by increasingly challenging terrain. Scientists are interested in investigating diverse geological areas, which are extremely difficult or even impossible to reach with traditional, wheel-based robots due to the highly scattered surface, steepness, or uncertainty of the terrain properties [4].

The visible layers within the Victoria crater (Figure 1b) on Mars, for example, gave hints about the groundwater processes [5]. A closer observation or sampling of the cliff's material was not possible, as a full descent into the crater with the Opportunity rover was considered too dangerous. Similar terrains are also found on other celestial bodies. On the moon, for example, steep crater walls, cliffs, and collapsed lava tubes are of high interest to the scientific community. Figure 1a shows the central peak of the Aristarchus crater, which potentially exposes some of the deepest crustal materials of the Moon [6]. In-situ investigations via sampling would offer insights into the composition, formation, and evolution of our closest neighbor's volcanic deposits. Future missions are also interested in providing faster mobility, traversing larger distances, or operating under time constraints [7]. Beyond the Moon or Mars, there are many more exciting worlds in our solar system waiting to be explored but are characterized by an extremely complex surface geometry. Examples include icy worlds like Enceladus and Europa or places that are partially covered by liquids such as Titan. All in all, those examples highlight the need for highly versatile surface exploration robots.

Meanwhile, dynamically walking legged robots, such as the ones developed by Boston Dynamics [8], Unitree [9], [10], ANYbotics [11] and others have made tremendous advancements in the last decade for terrestrial application [12]. However, the technology is still at an early stage with regard to planetary deployments, although recent commercialization of dynamically walking quadrupeds of becoming a strong driver to robustify the technology in a terrestrial setting.

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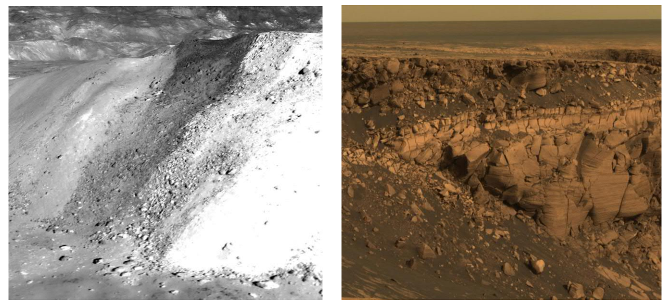


(a) (b)

Fig. 1: Geologically interesting terrains, such as the central peak of the lunar Aristarchus crater or the Victoria crater on Mars highlight the need for versatile exploration robots.

In this work, we highlight our contributions over the last two years, focusing on legged robots for planetary exploration. We developed and validated walking systems to cope with sandy slopes, low-gravity and performed analog mission deployments.

II. LOCOMOTION VALIDATION

We performed experimental work on traversing steep, granular Martian analog slopes with the dynamically walking quadrupedal robots SpaceBok [13], and ANYmal [14] (Figure 2) [2]. SpaceBok was hereby using a classical, virtual model-based locomotion controller with a predefined gait pattern [15], while ANYmal was using a reinforcement learning-based locomotion controller [16]. SpaceBok has, compared to ANYmal, legs with two Degrees of Freedom (DOF) and without the commonly used Hip adduction/abduction DOF. SpaceBok was further tested with point feet and specially designed passive adaptive planar feet to test leg-ground interaction on soil (Figure 3). The passive-adaptive feet reduced sinkage and provided traction on planar and inclined granular soil. Single-foot experiments revealed that a large surface area of $110\,\mathrm{cm}^2$ per foot reduces sinkage to an acceptable level even on highly collapsible soil (ES-1). Implementing several $12\,\mathrm{mm}$ grouser blades increases traction by 22% to 66% on granular media compared to grouser-less designs. With both robots, we validated - for the first time - static and dynamic locomotion on Martian analog slopes of up to 25°(the maximum of the testbed) [2].

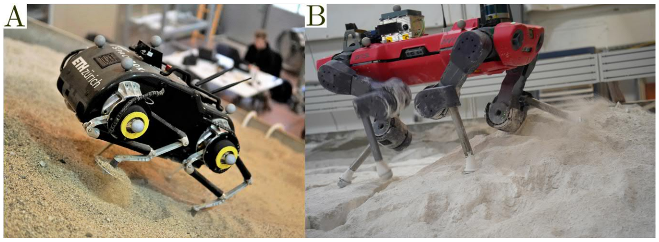


Fig. 2: SpaceBok (A) and ANYmal (B) on the robot testing facility at RUAG Space

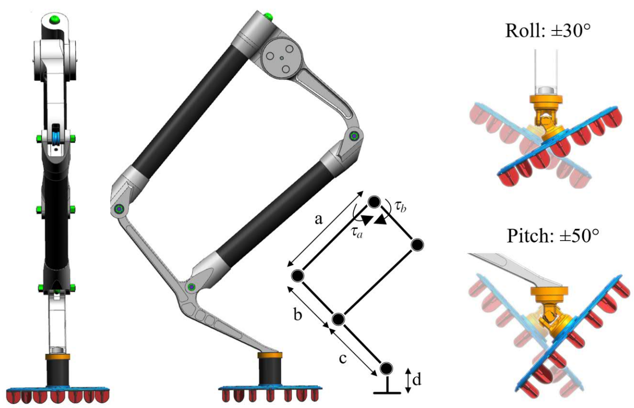
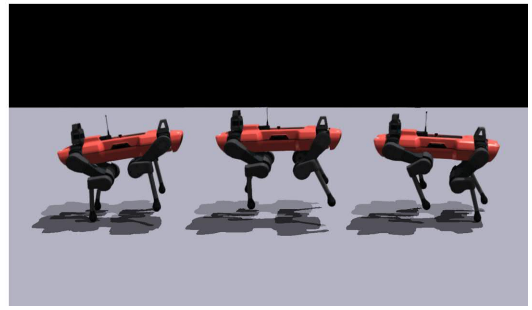


Fig. 3: The passive-adaptive foot developed for SpaceBok

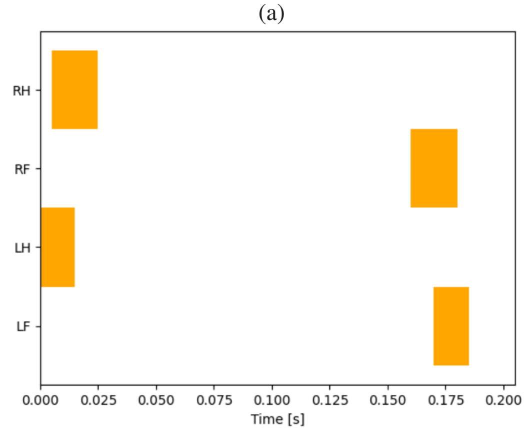
We evaluated the performance of the two robots, point- and planar feet, and static and dynamic gaits regarding stability (safety). We showed that dynamic gaits are energetically more efficient than static gaits but are riskier on steep slopes. The reinforcement learning controller on ANYmal has proven to be highly robust on the slope. However, even the basic locomotion controller of SpaceBok could overcome the maximum slope of the terrain. Further work would concentrate on tackling steeper slopes and varying soil types, as current tests have only been performed on a single martian simulant.

III. Low-gravity locomotion

Understanding the system's requirements regarding power budget, traversal risk, and actuator specification is essential to scale legged robots for planetary exploration. To tackle this, we developed locomotion policies following a reinforcement learning approach in simulation [1]. As a physics simulator, we used Isaac Gym [17], using the method presented in [18]. We simulated thousands of robots in parallel in lunar gravity, on a lunar terrain curriculum, consisting of slopes and boulder fields of varying difficulty. To do so, we assumed that the controller has data from both proprioceptive and exteroceptive sensors and directly sends joint position references to the actuators. Besides velocity reference commands and proprioceptive measurements, we assume that the robot has a detailed elevation map of its surroundings, thus providing elevation points around the robot as observations. Following an end-to-end learning approach, we define the actions as joint position references, giving the agent the freedom to adopt any gait. The resulting gait is a dynamic bounding gait with a long



(a)



(b)

Fig. 4: A bounding gait with extended flight phases emerges from a reinforcement learning policy, as the system is trained in lunar gravity conditions.

flight phase depicted in Figure 4. Similar gaits, that increase efficiency via long flight-phases in low-gravity have been found also in the past with model-based control techniques [19]. This gait has shown good robustness in simulation and can overcome slopes of up to about 40° and obstacles as high as 0.5 m. While the resulting gaits are promising, they lack the real interaction with granular material which should be incorporated with higher fidelity simulators in the future.

IV. Analog mission

The European Space Agency and the European Space Resources Innovation Centre initiated the Space Resources Challenge to assess current European and Canadian off-world resource prospection technologies and accelerate the development of critical technologies. We participated as team GLIMPSE (Geological Lunar In-Situ Mapper and Prospector) in the first round of the challenge, which took place in November 2021 [3]. The field trial took place in a lunar analog environment simulating the adverse conditions at the lunar south pole. Challenges include unknown terrain with granular soil and steep slopes, high solar incidence illumination, and network communications with high latency (2.5 s delay)a and intermittent signal loss. Robot operators where physically separated from the challenge area and had no line-of-sight to the system. The expected outputs of the trial, which had to be performed within two hours, were a map and a report on the mineralogical composition of several rock samples scattered over a region of interest.

TABLE I: Qualitative evaluation of the slope walking experiment. The pie indicates the stability of the gait for walking. Assessment was made based on observation and number of successful trials.

			Inclination						
			0°	5°	10°	15°	20°	22.5°	25°
SpaceBok, VMC, Static walk	planar foot	ascent	●	●	●	●	●	◕	◓
		descent	●	●	●	●	●	●	◕
	point foot	ascent	●	●	●	●	●	◕	◓
		descent	●	●	●	●	◓	◔	○
SpaceBok, VMC, Dynamic walk	planar foot	ascent	●	●	●	●	●	◓	◔
		descent	●	●	●	●	●	◓	◔
	point foot	ascent	●	●	●	●	●	◕	◕
		descent	●	●	●	●	◕	◓	◓
ANYmal, RL policy, Dynamic walk	planar foot	ascent	n/a	●	n/a	●	●	n/a	◕
		descent	n/a	●	n/a	●	●	n/a	◕

● = High safety, ○ = Non-traversable, n/a = not tested

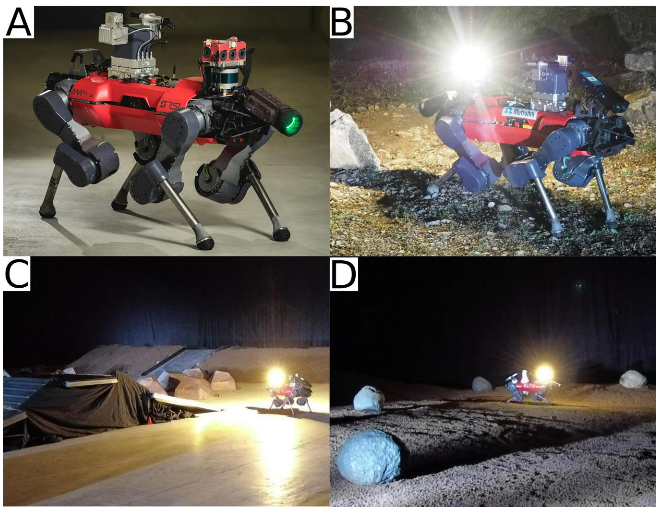


Fig. 5: Team GLIMPSE payload-equipped robot during the ESA-ESRIC Space Resource Challenge

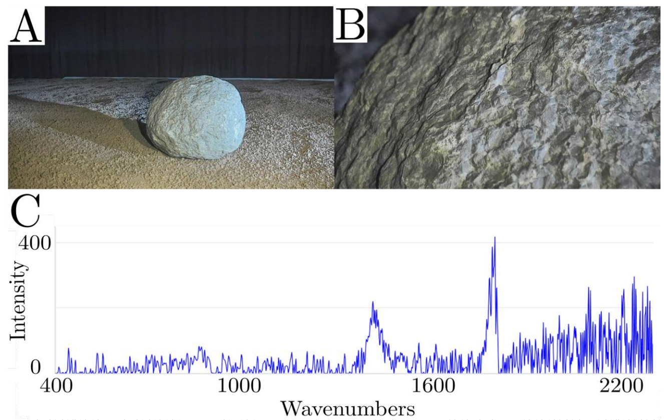


Fig. 6: (A) Example of a context image taken of a high-interest rock (B) close-up image (C) Acquired Raman spectrum of the same rock.

For this challenge, we integrated three scientific payloads on ANYmal, mimicking a real exploration mission. The robot was equipped with a Raman spectrometer, an imager on a pan-tilt head that provided context and zoom images, and a microscope to provide microscopic information on the rock surface (Figure 5). Our team competed against twelve European and Canadian teams and qualified, together with four other teams, for the second round of the challenge, which will take place in September 2022. The machine did not encounter any issues when traversing the obstacles or the granular material, again highlighting the applicability of such robots for future missions. An example of the outputs can be seen in Figure 6. While the system performed well in the challenge, further work is required, among other aspects, to increase the system's autonomy to reduce unnecessary downtime during loss-of-signal episodes and increase the scientific return in the given timeframe.

V. Discussion

We researched several aspects of legged locomotion to increase visibility and Technological Readiness for future exploration. While the robots are becoming more mature and the technology better understood, the following next steps are required for future development.

- Planetary bodies such as the Moon or Mars are largely covered by fine-grained, dry, granular media. To generate more accurate locomotion policies that can properly account for slippage and sinkage effects, modeling those environments in a high-fidelity simulation would drastically improve the performance prediction. Predicting the robot's performance is useful to size actuators more accurately and validate the estimated locomotion performance in high-sloped and unstructured terrain. Furthermore, the simulation results need to be validated through locomotion validation campaigns once obtained.
- As legged robots venture into unstructured environments, an elevated level of autonomy and situational awareness is required to take frequent actions without direct oversight from an earth-based operator. While such capabilities are an ongoing research effort, the applicability and realization for planetary robots have yet to be developed.
- The systems shown in this contribution are not space-graded. In order to account for the hostility of space, hardware adaptations have to be performed. More specifically, the highly articulated robots have to be

ingress protected and energy-independent, for example, by placing solar arrays without impeding the locomotion capability. Furthermore, thermal aspects of the design have to be considered.

We believe that considering legged robots for a defined mission scenario would drastically help the scalability of a current legged system for planetary exploration, as more targeted developments could be performed.

VI. CONCLUSION

This work summarized our developments on scaling legged robots toward future planetary exploration. We identified several application scenarios where those robots provide value over traditional wheeled systems. Furthermore, we have developed locomotion policies that can locomote efficiently in simulated lunar environments. Locomotion validation tests performed on martian soil simulant have proven that dynamically walking robots can perform well on high slopes of granular media with terrestrial gravity. Equipping the robots with a payload suite representative for a lunar prospecting mission further highlights the potential of the technology. Finally, we identify potential future improvements, which aim at increasing the simulation capability of robot-soil interaction, increase in robot autonomy, and specific hardware needs required for the space environment.

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REFERENCES

[1] S. C. Wells, P. Zhang, H. Kolvenbach, L. Wellhausen, N. Rudin, and M. Hutter, "Optimal global path planning for multimodel locomotion on lunar terrain," in *16th Symposium on Advanced Space Technologies in Robotics and Automation (ASTRA 2022)*, 2022.

[2] H. Kolvenbach, *et al.*, "Traversing Steep and Granular Martian Analog Slopes With a Dynamic Quadrupedal Robot," *arXiv:2106.01974 [cs]*, June 2021.

[3] P. Arm, *et al.*, "Results and lessons learned from the first field trial of the esa-esric space resources challenge of team glimpse," in *16th Symposium on Advanced Space Technologies in Robotics and Automation (ASTRA 2022)*, 2022.

[4] T. D. Glotch, *et al.*, "The scientific value of a sustained exploration program at the aristarchus plateau," *The Planetary Science Journal*, vol. 2, no. 4, p. 136, 2021.

[5] S. W. Squyres, *et al.*, "Exploration of victoria crater by the mars rover opportunity," *Science*, vol. 324, no. 5930, pp. 1058–1061, 2009. [Online]. Available: https://science.sciencemag.org/content/324/5930/1058

[6] J. F. Mustard, *et al.*, "Compositional diversity and geologic insights of the aristarchus crater from moon mineralogy mapper data," *Journal of Geophysical Research: Planets*, vol. 116, no. E6, 2011. [Online]. Available: https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2010JE003726

[7] D. Rodriguez-Martinez, M. Van Winnendael, and K. Yoshida, "High-speed mobility on planetary surfaces: A technical review," *Journal of Field Robotics*, vol. 36, no. 8, pp. 1436–1455, 2019. [Online]. Available: https://onlinelibrary.wiley.com/doi/abs/10.1002/rob.21912

[8] Boston Dynamics. (2022) Spot Mini. [Online]. Available: https://www.bostondynamics.com/spot

[9] Unitree Robotics. (2022) Aliengo. [Online]. Available: https://www.unitree.com/products/aliengo/

[10] ——. (2022) Laikago. [Online]. Available: https://www.unitree.com/products/laikago/

[11] Anybotics. (2022) ANYmal. [Online]. Available: https://www.anybotics.com/anymal-autonomous-legged-robot/

[12] C. D. Bellicoso, *et al.*, "Advances in real-world applications for legged robots," *Journal of Field Robotics*, vol. 35, no. 8, pp. 1311–1326, 2018.

[13] P. Arm, *et al.*, "Spacebok: A dynamic legged robot for space exploration," in *2019 International Conference on Robotics and Automation (ICRA)*. IEEE, 2019, pp. 6288–6294.

[14] M. Hutter, *et al.*, "ANYmal - toward legged robots for harsh environments," *Advanced Robotics*, vol. 31, no. 17, pp. 918–931, 2017.

[15] J. Pratt, C.-M. Chew, A. Torres, P. Dilworth, and G. Pratt, "Virtual Model Control: An Intuitive Approach for Bipedal Locomotion," *The International Journal of Robotics Research*, vol. 20, no. 2, pp. 129–143, Feb. 2001.

[16] T. Miki, J. Lee, J. Hwangbo, L. Wellhausen, V. Koltun, and M. Hutter, "Learning robust perceptive locomotion for quadrupedal robots in the wild," *Science Robotics*, vol. 7, no. 62, p. eabk2822, 2022.

[17] V. Makoviychuk, *et al.*, "Isaac gym: High performance GPU-based physics simulation for robot learning," *arXiv*, 2021. [Online]. Available: https://arxiv.org/abs/2108.10470

[18] N. Rudin, D. Hoeller, P. Reist, and M. Hutter, "Learning to walk in minutes using massively parallel deep reinforcement learning," in *Proceedings of the 5th Conference on Robot Learning*, ser. Proceedings of Machine Learning Research, A. Faust, D. Hsu, and G. Neumann, Eds., vol. 164. PMLR, 08–11 Nov 2022, pp. 91–100.

[19] H. Kolvenbach, D. Bellicoso, F. Jenelten, L. Wellhausen, and M. Hutter, "Efficient Gait Selection for Quadrupedal Robots on the Moon and Mars," in *International Symposium on Artificial Intelligence, Robotics and Automation in Space (I-SAIRAS)*, June 2018.