RHex Slips on Granular Media

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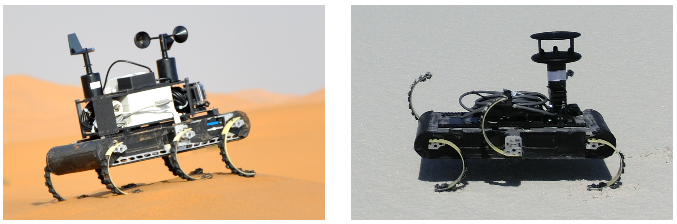

(a) RHex in the Tengger (b) RHex at White Sands

Fig. 1: RHex with two example sensor suites for current collaborations with desert researchers interested in desertification processes and dune movement at the Tengger desert in China and at White Sands National Monument, respectively. Photos taken from [3] and [4].

I. Introduction

RHex is one of very few legged robots being used for real-world rough-terrain locomotion applications. From its early days, RHex has been shown to locomote successfully over obstacles higher than its own hip height [1], and more recently, on sand [2] and sand dunes [3], [4] (see Figure 1). The commercial version of RHex made by Boston Dynamics[1] has been demonstrated in a variety of difficult, natural terrains such as branches, culverts, and rocks, and has been shipped to Afghanistan, ostensibly for use in mine clearing in sandy environments [5]. Here, we discuss recent qualitative observations of an updated research version of RHex [6] slipping at the toes on two main types of difficult terrain: sand dunes and rubble piles. No lumped parameter (finite dimensional) formal model nor even a satisfactory computational model of RHexs locomotion on sand dunes or rubble piles currently exists. We briefly review the extent to which available physical theories describe legged locomotion on flat granular media and possible extensions to locomotion on sand dunes.

II. Slipping on sand

We took RHex to two natural dunefields, at the Tengger desert in northern China [3] and at White Sands National Monument in New Mexico [4], as part of ongoing collaborations with scientists interested in dune movement and desertification processes. The Tengger sand is fine and dry, and the angles of the lee sides of dunes we ascended ranged up to almost 30 degrees of inclination[2]. White Sands is a gypsum desert formed by windswept gypsum from a nearby lake, with relatively large sand grains and a water table only a few inches below the surface of the sand, making the sand more cohesive than at the Tengger. Slopes tested on at White Sands ranged up to 28°[3].

(a) Tengger desert (slope: $29 - 30^\circ$) (b) White Sands (slope: 27°)

Fig. 2: RHex exhibiting slip during steep ascents at the Tengger and in White Sands. Photos taken from [3] and [4].

At each of these sites, we attempted ascents on the steep lee sides of multiple dunes (Figure 2). RHex was reliably able to ascend slopes at the Tengger of up to 27° using a quadrupedal gait recirculating the front and back pairs of legs together and inserting the middle pair of legs into the sand to prevent belly slip between steps ("hill-climbing"), and at White Sands of up to 26° using a hexapedal gait recirculating all six legs together ("pronk"). RHex exhibited visually obvious slip at the toe while locomoting on dunes in both locations, with the slip becoming more visually obvious as the angle of inclination increased.

III. Slipping on rubble

We took RHex to Revolution Recovery,[4] a recycling center in Philadelphia, to observe its behavior on roughly sorted (still heterogeneous in particle size) piles of "rubble" (recyclables) near their angles of repose. Angles of inclination varied widely within a pile due to the size of the individual rubble pieces and were difficult to measure directly. Here, we describe the robot's

[1] Boston Dynamics, now part of Google's Alphabet

[2] Angle of inclination was measured with an iPhone level application. The phone was laid on virgin slope next to the robot for measurement.

[3] Angle of inclination was measured with iGaging eLevel digital level. As with the iPhone, the digital level was laid on virgin slope next to the robot.

[4] Revolution Recovery

(a) Drywall pile (b) Concrete pile

Fig. 3: RHex exhibiting slip while ascending piles of drywall and concrete pieces at Revolution Recovery, a recycling center in Philadelphia.

behavior on the two piles we anticipate will be most relevant to search-and-rescue applications [7]: pieces of drywall and chunks of concrete (Figure 3).

On the drywall pile, RHex slipped most in areas where the drywall pieces were small (in the range of 2-10cm), and appeared visually to slip more in areas of higher inclination. When RHex reached an area in which it exhibited a large amount of slip, it would fling pieces of drywall behind it at each step and dig into the material, reducing the angle of inclination in its immediate vicinity and increasing the angle of inclination of the material in front of it. Given that drywall is comprised of gypsum and we have already seen that RHex exhibits slip on small gypsum particles in the White Sands environment, it is not necessarily surprising that RHex exhibited slip on small drywall pieces.

The more surprising observation from Revolution Recovery was that RHex also slipped on chunks of dry concrete, which has a rough surface that should be gripped easily by the rubber treads on its legs. The slipping behavior on concrete did not visually appear to be directly related to the robot's inclination angle, but rather to the stability of the piece of concrete it stepped on. A small or particularly unstable piece of concrete might move in response to interaction with a RHex leg, or might be angled in such a way that the corner (or even side) of the leg slips against it without gaining a firm foothold.

IV. Missing: A theoretical framework

Although we have observed that RHex slips frequently in these real-world relevant environments, theoretical treatments do not take slip into account. The best analytic account of RHex walking in sand is currently the rotary walking model [2], which predicts the locomotion speed of a robot with c-legs from its leg penetration depth as the robot walks on flat preparations of homogeneous, idealized sand, with simplifying assumptions that the sand is homogeneous and spherical, the leg is rigid, and there are no relevant hydrodynamic forces. More recently, the development of terradynamics [8] enables the prediction of reactive forces on an intruder of arbitrary size, shape, and orientation into granular media by combining resistive forces on infinitesimal intruder segments, the forces on which are estimated using the results of a series of experiments in which aluminum plates were intruded into idealized granular media at a variety of angles and orientations. A scale-invariant empirical pattern described in [9] relates leg penetration ratio (the ratio of the length of leg penetrating the media to the effective leg length) to a scale-invariant forward speed metric, whose domain of applicability we have recently attempted [10] to extend to more natural, field relevant settings. Research has been initiated on RHex-like leg interactions with individual boulders on sand [11], but not on multiple simultaneous boulders, as would be expected on a rubble pile.

V. Conclusion

RHex locomotes successfully over a variety of difficult terrains, including sand dunes and rubble piles. Current theory can explain some aspects of RHex's locomotion behavior, but neither mathematical nor computational models, nor even physically well-reasoned empirical principles yet exist to describe RHex's behavior during either sand dune ascents or rubble pile navigation. We have observed qualitatively that RHex exhibits slip during these locomotion behaviors, which may account for some of the unexplained variance in RHex's performance.

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References

[1] U. Saranli, M. Buehler, and D. E. Koditschek, "Rhex: A simple and highly mobile hexapod robot," *The International Journal of Robotics Research*, vol. 20, no. 7, pp. 616–631, 2001.

[2] C. Li, P. B. Umbanhowar, H. Komsuoglu, D. E. Koditschek, and D. I. Goldman, "Sensitive dependence of the motion of a legged robot on granular media," *Proceedings of the National Academy of Sciences*, vol. 106, no. 9, pp. 3029–3034, 2009.

[3] S. F. Roberts, J. Duperret, X. Li, H. Wang, and D. Koditschek, "Desert RHex technical report: Tengger desert trip," 2014. Available online.

[4] S. F. Roberts, J. Duperret, A. M. Johnson, S. van Pelt, T. Zobeck, N. Lancaster, and D. E. Koditschek, "Desert RHex technical report: Jornada and White Sands trip," 2014. Available online.

[5] L. Greenemeier, "Boston Dynamics' crawling army soldiers to join fight in Afghanistan?," *The Huffington Post*, 2012. Available online.

[6] G. C. Haynes, J. Pusey, R. Knopf, A. M. Johnson, and D. E. Koditschek, "Laboratory on legs: An architecture for adjustable morphology with legged robots," in *Unmanned Systems Technology XIV* (R. E. Karlsen, D. W. Gage, C. M. Shoemaker, and G. R. Gerhart, eds.), vol. 8387, p. 83870W, SPIE, 2012.

[7] R. R. Murphy, "Human-robot interaction in rescue robotics," *Systems, Man, and Cybernetics, Part C: Applications and Reviews, IEEE Transactions on*, vol. 34, no. 2, pp. 138–153, 2004. Available online.

[8] C. Li, T. Zhang, and D. I. Goldman, "A terradynamics of legged locomotion on granular media," *science*, vol. 339, no. 6126, pp. 1408–1412, 2013.

[9] F. Qian, T. Zhang, W. L. Korff, P. B. Umbanhowar, R. J. Full, and D. I. Goldman, "Principles of foot design in robots and animals determining terradynamic performance on flowable ground," *Bioinspiration and Biomimetics (in press)*, 2015.

[10] S. F. Roberts and D. E. Koditschek, "Leg compliance and foot pressure for sand dune ascent in RHex-like robots," *ICRA*, 2015 (submitted).

[11] F. Qian and D. I. Goldman, "The dynamics of legged locomotion in heterogeneous terrain: universality in scattering and sensitivity to initial conditions," *RSS*, 2015.