Desert RHex Technical Report:
Tengger Desert Trip

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Abstract

Desertification is a long-standing issue in China, but research on the processes of desertification is limited by availability of personnel and technical equipment. This suggests a perfect application and further testing ground for the mobile desert sensing technology described in a previous technical report [1]. We describe here the first of two trips to the Tengger Desert as part of a collaborative effort to bring Desert RHexes to China, with the goal of this trip being to discover and address potential locomotor challenges. Our robots were able to ascend 20° slopes with an 8.5kg payload, indicating that they could indeed be used for this novel mobile desert sensor application. We achieved locomotion on up to 30° slopes unreliably and on up to 27° slopes using morphological and behavioral adaptations inspired by our last desert trip [1].

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1 Introduction

Desertification is a long-standing issue in China and has garnered substantial research for a number of years (see [2] and [3] for reviews). However, research on desertification processes, particularly in the northern regions of China (including in our desert of study, the Tengger), has been stymied by a shortage of technical equipment and personnel [2].

To address current issues in desertification research, Shanghai Jiaotong University and Ningxia University organized the First[1] and Second[2] IEEE Workshops on Future Intelligent Desert. This led Workshop Organizer Prof. Xinwan Li to organize a major collaborative effort between SJTU, Ningxia University, and the Shapotou Cold and Arid Regions Research Institute funded by the Chinese Ministry of Science and Technology. The University of Pennsylvania received a small travel grant from this collaborative effort to begin the present project, which is to comprise of two trips to the Shapotou research station in Ningxia.

The goal of this first trip was to demonstrate the capability for ascents of dunes with slopes of 20° with an 8kg payload under normal Tengger desert conditions. The University of Pennsylvania researchers were interested in testing this capability in particular, already demonstrated in Jornada and White Sands [1] in new sand conditions, and more generally, the limits of the sensorimotor capabilities of our most recently developed X-RHex generation robot, Desert RHex 2.0 (hereafter D-RHex) in a variety of dune environments [1].

1.1 D-RHex and the RHex platform

D-RHex represents the latest expansion of the X-RHex model in the RHex family of robots, specifically oriented towards desert research and mobility [1].

Figure 1: D-RHex in the Tengger desert with sensor package.

After our previous desert trip to Jornada and White Sands [1], we hypothesized that (1) wider legs would decrease substrate failures; (2) an under-belly “rib” or intrusion of the middle legs into the substrate could prevent the robot

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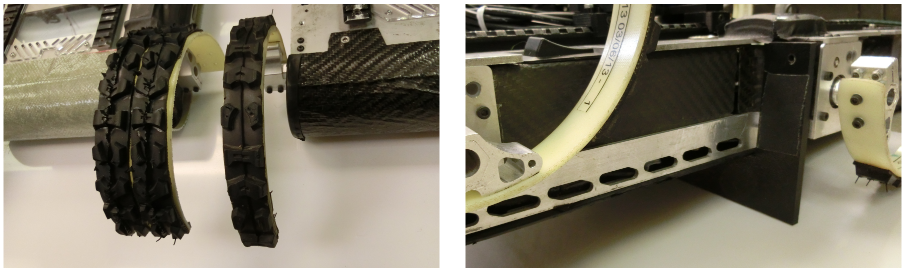
[1] `http://www.ieee.org/conferences_events/conferences/conferencedetails/index.html?Conf_ID=19515`

[2] `http://www.ofs2.sjtu.edu.cn/FIT2012.html`

from sliding down during a difficult slope ascent; and (3) a more carefully-designed turning maneuver that is more robust to poor ground contact could aid in control affordance on inclined sand dune ascents. We anticipated that these adjustments should increase the maximum climbable dune slope angle.

For this trip, we implemented (1) by manufacturing new fiberglass legs of twice the width of our current legs. We ran one robot in the Tengger desert with these fat legs and one robot with the standard thin legs for comparison. The two leg sizes are compared in Figure 2a. We implemented the rib in (2) with a single sheet of ABS which we attached to the robot in the middle of the belly. This rib can be seen in Figure 2b. We also developed a leg-intrusion climbing gait, which is explained in Figure 3. To test (3), we developed a turning maneuver which stands the robot up on all six legs, rotates the three legs on the left and right sides of the robot in opposite directions until the robot is lying flat on the sand, and then stands the robot back up again. This sand turn is described in Figure 4.



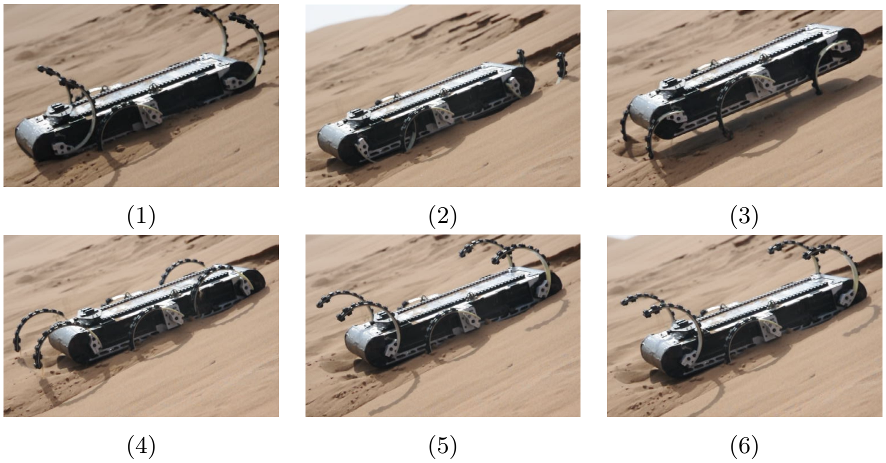
(a) Two robots with two different sizes of legs, side-by-side.

(b) The rib used to prevent downward sliding on steep inclines.

Figure 2: Potential morphological adaptations for desert conditions include wider legs and an under-belly rib.

1.2 Sensor payload

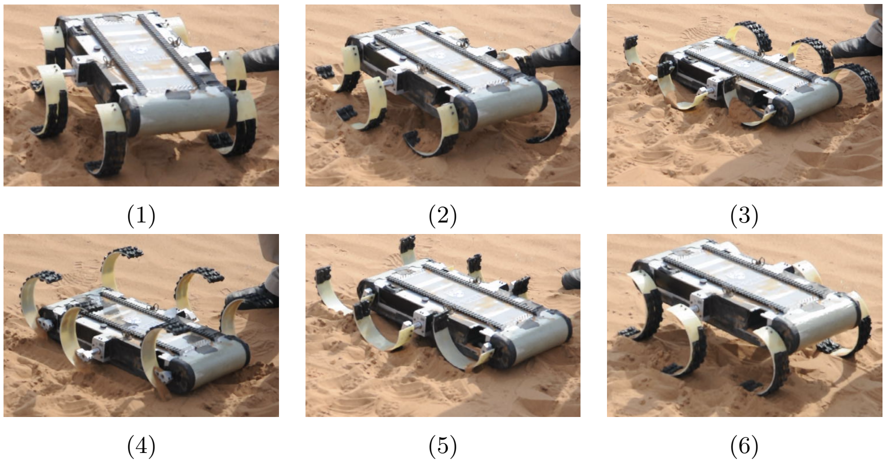
For this trip, we outfitted the robot with an anemometer, wind vane, barometric pressure sensor, temperature sensor, and electronic compass. These sensors were developed for desert research purposes in-house at Ningxia University. We verified that the robot could read data from each of these sensors in the desert environment, as we did in our previous trip to Jornada [1]. We also mounted a forward-facing GoPro Hero3 camera. However, sensor integration was not the focus of this first trip, and we do not present this data here. A picture of the robot with all sensors mounted can be seen in Figure 5.



(1) (2) (3)

(4) (5) (6)

Figure 3: The quadrupedal leg-intrusion hill-climbing gait developed for this trip.



(1) (2) (3)

(4) (5) (6)

Figure 4: The sand turn maneuver developed for this trip.

2 Observations from and experiments performed in the Tengger Desert

2.1 Observations from the Tengger

2.1.1 The study site at the Tengger

Our study site was the Chinese Academy of Sciences Shapotou Desert Research and Experiment Station, which is located in the southeastern part of the Tengger Desert, in Zhongwei, Ningxia Province, People's Republic of China. According

Figure 5: D-RHex with wide legs and Chinese sensor package.

to local meteorological records (as cited in [4]), the annual rainfall is 180.2mm with an annual potential evaporation of 2900mm. The area is characterized as between a steppified and a sandy desert, with short (< 1m) bushes scattering the study site and a range of elevations between 1300 and 1350m.

We spent two days at the Shapotou Research Station (pictured in Figure 6). Two days before our arrival, heavy rainfall raised the water table substantially and compacted the sand dune surface. Over the two days of experiments, we experienced a range of sand compactions and cohesiveness as the water evaporated and the sand dried. By the end of the second day, the sand was quite dry and loose again. Mobility experiments were repeated on both days to correct for this potential source of variability.

2.1.2 Sand dune substrate differs wildly within one robot body length and within short time periods

Variations in the sand were observed on the order of half a robot body length. The slope measurably varied in both the vertical and horizontal directions on the order of a half a robot body length due to the curved nature of many of the dunes; in particular the slope varied at the tops and bottoms of the dunes, with sudden or gradual transformations from gentle 20-degree slopes for the majority of the dune to steep angles up to 30 degrees immediately at the top of the slip face. A qualitative observation of sand compaction found it to differ between lee and windward sides as well.

Figure 6: The Tengger landscape at the Shapotou Desert Research and Experiment Station.

Variations in the sand were also observed between days 1 and 2 in the field. Rainfall the day before we reached the field resulted in compacted and cohesive sand on day 1. On day 2, the surface of the dunes was noticeably drier with a cohesive and compacted sand layer underneath. The cohesive and compacted sand layer receded noticeably during the day as the dune dried. There were also noticeable variations in compacted sand layer depth within a dune vertically (towards the crest vs. towards the bottom) and horizontally, in particular between the ends of the dune and the middle, and also between the windward and the lee sides, though this may have had more to do with sunlight than dune mechanics.

2.1.3 Behavioral responses to seemingly similar substrates vary wildly

We observed highly variable robot behavior on similar virgin slopes of approximately the same slope angle (within 2 degrees), on the same dune face (within 3 meters) or adjacent dune faces (within 10 meters), and within 30 minutes from first to last experiment. In one comparison experiment between the fat and thin legs, the fat-legged robot was able to travel approximately half a body length further vertically up a dune when the robots were placed half a body length away from each other. We were then unable to replicate these results either by moving the robots down the same slope by one body length or by moving the robots to an adjacent virgin slope with a similar slope angles (within 1 degree): In both of these attempted replications, both robots performed the same. We were unable to determine in the uncontrolled natural desert environment whether this variation in robot behavior was due to differences in sand compaction, cohesiveness, minor variations in slope angle, or minor differences in robot orientation or other initial conditions; however, given the observed differences between different dune portions, we hypothesize that the variation lies at least in part with the substrate differences.

2.2 Mobility experiments performed at the Tengger

2.2.1 Ascent performance on a sandy incline

We attempted to ascend sand dunes with slopes of 18-20, 25-27, and 30 degrees with both the thin-legged and fat-legged robot. Both robots were able to ascend vertically on sandy slopes of 0 to 20 degrees without trouble. Both had significant difficulty on slopes greater than 20 degrees, and although we did not observe a slope of greater than 30 degrees in the field, we expect that they would fail on a slope of greater than 30 degrees. We were, however, able to achieve locomotion at 25-27 degrees of inclination using the rib and a slow pronk or using the quadrupedal leg-intrusion gait, and we were able to achieve locomotion at up to 30 degrees with the thin-legged robot in one case. This represents a significant improvement over our last desert trip to Jornada and White Sands [1]. Both robots were able to descend slopes at all speeds at up to 30 degree slope.

We were interested to see that while the fat legs seemed to confer an advantage in some cases, on a dry 30-degree incline when the robots were performing a fast crawl gait (described in [1]) the thin-legged robot was able to ascend while the fat-legged robot was not. We hypothesize that this may have been because the thinner legs penetrated deeper, making them more able to reach the compacted sand beneath the surface. The difference in leg penetration depth is visible in Figure 7.

(a) Successful ascent of a 30-degree dry slope by the thin-legged robot performing a fast crawl.

(b) Failed ascent of the same 30-degree dry slope by the thick-legged robot performing the same gait.

Figure 7: Comparison of fat- and thin-legged robots during vertical climbs of 30-degree incline with a fast crawl gait.

There seem to be two failure conditions on slopes greater than 20 degrees, which mirror the failure conditions discovered in White Sands [1]: A stalling out of the rear legs, and a loss of friction due to substrate failure. As in Jornada and White Sands, the stalling issue could be addressed by an appropriate choice of gait: Gaits where the back two legs recirculated together performed better and did not result in stalls. The substrate failures were substantially reduced by the use of our rib and quadrupedal leg-intrusion gait, adaptations that were inspired by our last trip [1].

2.2.2 Efficiency (specific resistance)

We measured specific resistance over a 30-minute run, walking both robots together in a single-file line over 430 meters of a modestly challenging dune environment (see Figure 8). The robot with wider legs had a specific resistance [5] of 1.1, as compared with the robot with the thin legs, which had a specific resistance of 1.3. This 0.2 advantage in specific resistance that the wide-legged robot had was evident in its speed: For a given gait frequency it traveled noticeably faster than the thin-legged robot. We hypothesize that the wider legs afford better leg friction, allowing the robot to travel farther in a single gait cycle. If true, this would indicate a significant affordance provided by the wider legs as they would allow for a 20% increase in energy efficiency, expanding the robot's range during operations.

Figure 8: Specific resistance experiment in which the two robots walked together for 30 minutes over the same territory.

2.2.3 Yaw control on a sandy incline and flat ground

Without human adjustment, the RHex family of robots will tend to yaw naturally to one side or another during such an ascent; in particular, during crest ascents, which have a dangerous slip face off to one side, failure to maintain proper heading can result in an unrecoverable failure [1]. We attempted vertical ascents with both the fat- and thin-legged robots on several dunes on both days of experimentation without the human driver adjusting heading to maintain vertical orientation. Examples of the natural yaw resulting from this type of ascent can be seen in Figure 9. This comparison did not yield a qualitatively obvious difference in natural yaw. However, when the human driver was permitted to adjust heading, qualitatively the fat-legged robot seemed easier to control. In particular, when a robot had yawed sufficiently to one side such that it could not be directed back towards the vertical while walking, the fat-legged robot could be oriented back towards the top of the dune with the sand turn described in Section 1.1.

To test the hypothesis that the fat legs did confer better control affordance, we compared turning performance between the two robots using both our new sand turn maneuver and our standard alternating tripod turn. We performed 4 turns to the right and to the left in each of these modes, and repeated the experiment a second time on fresh sand. The sand turn consistently yielded a turn of 30 degrees per gait cycle with the fat legs and approximately 23 degrees per gait cycle with the thin legs, indicating that turning performance is increased with the fat legs with the sand turn. Relative turning performance in a tripod was inconclusive.

(a) Natural yaw during vertical ascent with thin legs.

(b) Natural yaw during vertical ascent with fat legs.

Figure 9: Comparison of yaw with fat and thin legs during vertical climbs.

2.2.4 Performance with 8.5kg payload on sandy inclines

We performed ascents under two weight conditions and two leg conditions, both on day 1. First, we attempted to climb the 20-degree incline with a flat 8.5kg steel plate on thin legs, uniformly distributing the load over the body of the robot (see Figure 10). The robot completed the task with the standard alternating tripod gait. We observed that the robot pitched backwards during the vertical ascent, so we then cut the steel plate in half with the intention of applying both halves to the front of the robot.

We attempted a 20-degree incline with the front-loaded fat-legged robot, now carrying 8.4kg of steel. With the cut plate and fat legs, the weight seemed qualitatively to confer an advantage: We observed less slippage on the front legs. It is unclear whether this qualitative difference will be repeatable, or whether it was a result of inconsistencies in substrate. Again, we were able to ascend with the alternating tripod gait.

Towards the crest of the dune, where the slope increased suddenly, we began to experience failures again. To improve performance, we attempted a variety of gaits including our standard alternating tripod, a slow pronk, a back-to-front crawl, and our new quadrupedal leg-intrusion gait (described in 3) which holds the middle two legs in position slightly below the surface of the sand to provide friction. The quadrupedal gait did improve performance on the steeper inclines but it is still unclear what the upper limit on traversable incline is.

Figure 10: D-RHex with an 8.5kg steel plate for a payload.

3 Conclusions drawn and hypotheses generated by Tengger Desert trip

3.1 Physical robustness in the desert environment

The robots only had a single failure during the 2 day series of experiments. An encoder cable came loose from the back left leg of the thin-legged robot during the the 30 minute endurance run. This effectively ended the run; however, a simple fix in future designs will prevent this from occurring again.

A significant amout of sand entered the robot over the course of the experiments. While this did not present a problem for any of our experiments during this trip, it is possible that over extended use sand could enter the motor housing and get into the bearings and gearing for the secondary encoder. We plan to pre-empt this concern by addressing it in future designs with an improved sealing of the motor housing.

Extreme temperatures were not seen on this trip so it remains to be seen how the robot operates in very cold or hot environments characteristic of the summer and winter of the Tengger Desert.

3.2 Differences in fat and thin leg performance lead to new hypotheses about the effects of leg properties on behavior

The potential benefits of the wider legs remain unclear, and we remain unsure of whether these benefits outweigh the cost of the increased sand disturbance. Tracks from the fat- and thin-legged robots can be compared in Figure 11. We plan to investigate several questions relevant to the potential benefits of the wider legs that remain unanswered between now and our next planned trip. First, we are curious whether the additional ground contact provided by the wider legs affords better ground contact friction, resulting in less slippage during a gait cycle.

We were curious about the effect that this difference in slippage would have on the natural yawing behavior, or on control affordance. The natural variability in the dunefield environment made this a difficult question to address directly during this trip, but we plan to construct a more carefully controlled inclined sandy environment at the University of Pennsylvania and perform more careful tests in between trips.

We were surprised to see that doubling the leg width did not prevent substrate failure. It is possible that this is simply because the nature of the rolling contact of the legs means that the area contacting the ground is always quite small, and the pressure required for penetration is still easily achieved. However, we also saw during this trip that substrate penetration is not necessarily a bad thing: The robot with the thin legs was able to climb up a steeper incline than the robot with the fat legs during a very fast crawl gait, and it is possible that this was because the thin legs were able to penetrate down to to the compacted, wetter sand underneath the dry surface layer of sand. We are curious whether drier sand would have resulted in a different outcome for this comparative experiment.

There are also several questions about the comparative performance of these legs in this desert that are relevant to leg morphoogy more generally: For example, the stiffness profiles of the wider legs are not yet characterized, and it is possible that differences in stiffness (or damping in legs with similar stiffnesses but different widths) could explain some of the differences in behavior of the two leg widths.

3.3 Vertical ascent experiments lead to new hypotheses about mobility in dune environments for RHex-family robots

We have seen previously that RHex-family robots will yaw naturally during vertical ascents [1]. During this trip, we attempted to examine this behavior more carefully. We noted that both fat- and thin-legged robots were able to walk over the crest of a dune while exhibiting a natural yaw behavior without correction. We are curious to investigate this natural behavior further, and in particular, we wonder whether the natural yaw might confer some dvantage (e.g., is transverse cresting more energy efficient or does it better spread the work across all six motors?) or whether turning mid-stride confers such a disadvantage that the natural yaw is preferred to correction. After a certain angle of ascent different from vertical, we lost control affordance of the robot, but we were not able to specify exactly what this angle was in the variable dune environment. Further experimentation in a more carefully controlled area will be necessary to address this question.

For a constant weight, that is, with the same payload we saw better performance when the payload moved the center of mass towards the front of the

Figure 11: Comparison of the tracks from fat- and thin-legged D-RHexes.

robot. We hypothesize that pitching the robot forward relieves pressure on the rear legs and delays stall. However, we saw worse descent performance from the robot when it had a forward center of mass. It is unclear whether the benefits conferred by increased ascent capability are worth the cost of hitting the nose of the robot on the ground during descent. We did not succeed in this trip in finding a failure case for robot descent, but it is possible that even a successful descent that bumps the sensors too frequently might result in misaligned sensors and therefore poor measurements.

3.4 Turning experiments lead to new hypotheses about ground reaction forces on failing substrates

The turning experiments performed on flat ground and our qualitative experiences attempting to turn the robots back towards the vertical during attempted vertical ascents indicate that the fat legs confer greater yaw control affordance; however, this claim must be tested more rigorously in a repeatable environment, as the dune environment we tested in was far too variable to be able to make these assessments with great confidence.

We wonder also what led to this difference in yaw control affordance, if it exists. Could it be simply due to differences in leg stiffness? Could it more specifically be due to differences in torsional leg-spring stiffness, which we anticipate we should see between two structures of the same shape and material if one is simply twice as wide as the other? Could it be because the decreased pressure of individual legs on the ground results in a decrease in leg penetration depth and therefore an increase in effecive leg length?

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