Stable Stair Climbing in a Simple Hexapod Robot

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SYNOPSIS

RHex is a hexapod robot with compliant legs and only six actuated degrees of freedom. Its ability to traverse highly fractured and unstable terrain has already been documented. In this paper, we describe open loop controllers for our small robot to climb and descend regular stairs. The reliability is 90% (9/10) for climbing and 100% (10/10) for descending, based on ten successive trials. Specific resistance, a measure of energy efficiency, during stair climbing is 10.9, and 4.5 during descent.

1 INTRODUCTION

RHex (Figure 1) is comfortable on off-road terrain.[1,2] The goal of the current work is to make it more adept at traversing the world of humans. Stairs are one of the most common and challenging features of human environments. Several legged robots have successfully demonstrated stair climbing – recently the Honda humanoid climbed quasi-statically.[8,10] A few robots had limited success climbing steps or stairs dynamically, given knowledge of the stairs, or an external power source.[3,4,5,6,7] However, to our knowledge, RHex is the smallest legged robot (Length: 51cm, Width: 20cm, Height: 12.7cm, Leg length: 16cm) to climb human-scale stairs (Horizontal: 28cm, Vertical: 16cm). Even though the step height is the same as the leg length, it exceeds the robot's ground clearance by 66%! Due to the high cost of failure, we focused initially on climbing stairs quasi-statically.

Figure 1. RHex hiking outdoors.

2 ROBOT MODEL

In order to improve stability, RHex has a wide body and sprawled posture. In our stair climbing algorithms, the front, middle, and back pairs of legs work in tandem, preventing significant roll or yaw. Small offsets between legs in the pairs are used for steering in experiments, but we can ignore this and reduce RHex to a collection of bodies in the sagittal plane. The model is shown in Figures 2 and 3, and the physical parameters of the real robot, as used in the simulation are given in Table 1.

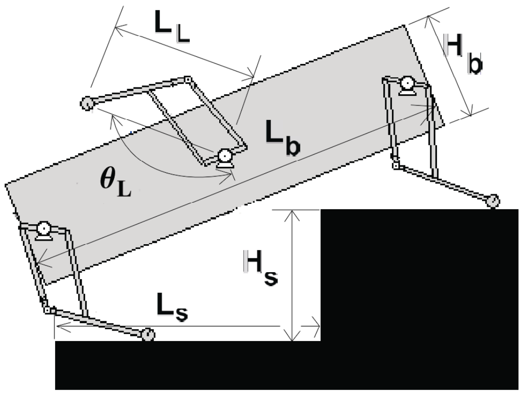

Figure 2. Physical Parameters

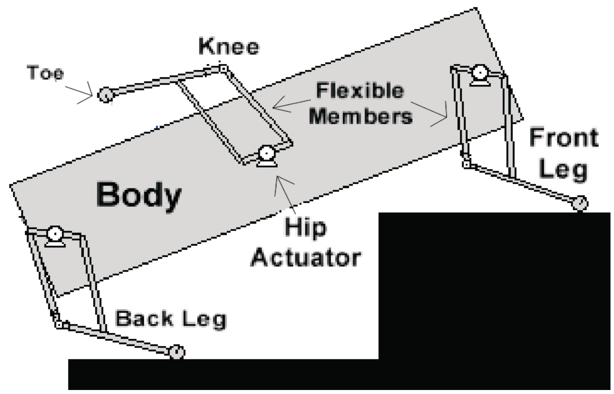

Figure 3. Main Components

Figure 4. Dynamic tripod gait on shallow stairs – legs highlighted for clarity

Body Mass	M_B	7.6	kg
Leg Mass	M_L	0.13	kg
Body Length	L_B	0.51	m
Body Height	H_B	0.127	m
Leg Length	L_L	0.16	m
Stair Height	H_S	0.16	m
Stair Length	L_S	0.28	m
Leg Spring Constant (linear approximation)	K_L	1628	N/m
Maximum Motor Torque	τ_{max}	5.34	Nm

Table 1. Physical Properties

3. ALGORITHMS

3.1 Tripod Walking on Stairs

Initially we implemented shallow stair climbing (Figure 4) based on an open loop tripod gait, as used during walking on flat terrain.[1] RHex climbed stairs measuring 40cm x 12cm. However, the success rate was less than 30%, though this increased somewhat with operator experience. Main failure modes were due to uncontrolled and unstable dynamic pitch and yaw motion.

3.2 The Open Loop Stair Climbing Algorithm

Through experimentation, we confirmed out empirical insight that it should be feasible to achieve successful and reliable stair climbing based on sequences of open loop limb motions. The cycle time for each stair is about 1.27 s. The controller is based on the following motion phases (also shown in Figure 5):

RHex starts from a standing position, all three pairs of legs are on the ground. The rear and middle legs lean the body forward, and the front legs sweep around to catch the first step.

Phase 1: The front pair and the left rear legs are holding position, the right rear leg is swinging around to the next stair, and the middle legs are finishing their rearward sweep.

Phase 2: The front and middle, and right rear legs are holding position, and the left rear leg is swinging around to the next stair. Staggering the rear leg swing ensures good support.

Phase 3: The front and rear legs raise the body over the next stair, the middle legs finish poised above the next stair.

Phase 4: The front legs finish this phase up in the air, halfway through re-circulation, the middle legs push hard on the next stair, and the rear legs continue their backward sweep.

Phase 5: The front legs are poised above the next stair, the middle legs hold position, and the rear legs finish their rearward sweep.

Phase 6: The front and rear legs hold position while the middle legs continue their rearward sweep.

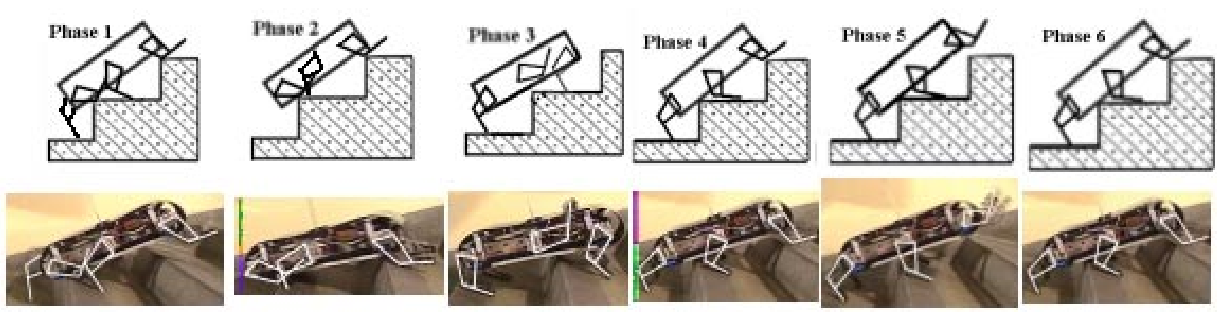

Figure 5. Phases of one complete stair climbing cycle. Top: Diagram (robot and stairs are to scale). Bottom: Corresponding video snap shots from an experiment – legs are highlighted for easier viewing. All images depict position at the end of a phase. Note that the camera was not horizontal during filming.

3.3 The Open Loop Stair Descending Algorithm

Similar to climbing upstairs, it is possible to achieve successful and reliable stair descending based on sequences of open loop limb motions. The cycle time for each stair is about 1.4 s. The robot backs down the stairs to take advantage of the leg geometry. The controller is based on the following motion phases (also shown in Figure 6):

Phase 1: Front legs rotate counter-clockwise, middle and rear legs hold position to support the body.

Phase 2: All legs sweep counter clockwise to lower body to next stair. This phase consists of 3 linear trajectories for each leg. The first is the longest, and lowers the body most of the distance to the next stair. The other 2 trajectories help to decelerate the robot at the end of this phase.

Phase 3: Front, middle and left rear legs hold to support body, right rear leg rotates counter clockwise to the next stair.

Phase 4: Front, middle and right rear legs hold to support body, left leg rotates counter clockwise to the next stair.

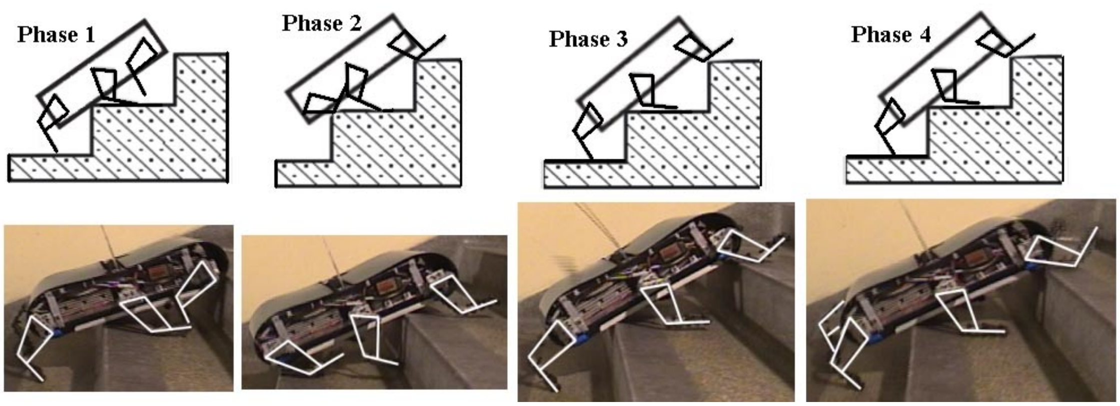

Figure 6. Phases of one complete stair descending cycle. Top: Diagram (robot and stairs are to scale). Bottom: Corresponding video snap shots from an experiment – legs are highlighted for easier viewing. All images depict position at the end of a phase.

Experimental Results

Figure 7 shows the desired and actual leg trajectories for both climbing and descending experiments. Low tracking errors are exhibited, except during temporary torque saturation, primarily in the back legs.

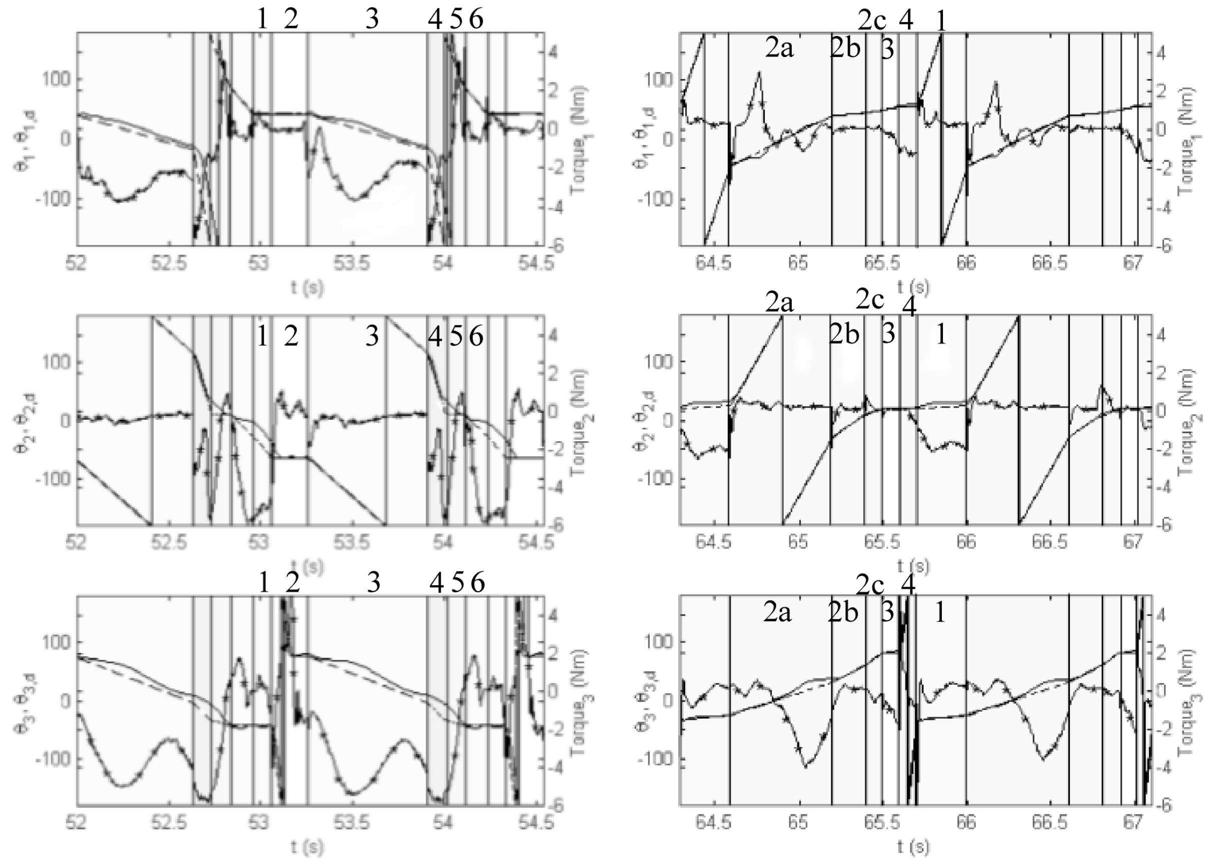

Figure 7 - Desired (dashed) and actual (solid) leg trajectories for two cycles of stair climbing (left) and stair descending (right). Hip torque data is solid with "*" marks. Numbers are shown which correspond to phases of Figures 5 and 6.

4 Results

4.1 Energetics

Energetic cost of stair climbing is substantial, based on an average power consumption of 183 W (Fig. 8). The resulting specific resistance is

$$\varepsilon = \frac{E}{m \cdot g \cdot d_X} = 10.9\,,$$

where E is the energy consumption for a horizontal displacement of d_x, m is the total robot mass, and g is the gravitational constant. This specific resistance value is about three times that for walking on even terrain. It would be interesting to compare this energetic cost to that incurred by other robots during stair climbing. Unfortunately, to our knowledge, no such data is available in the literature.

Energetic cost of descending stairs is much smaller, with an average power consumption of 68 W (Fig. 9). The resulting specific resistance is 4.5, when the calculation is as defined above. This specific resistance value is about twice that of walking on even terrain.

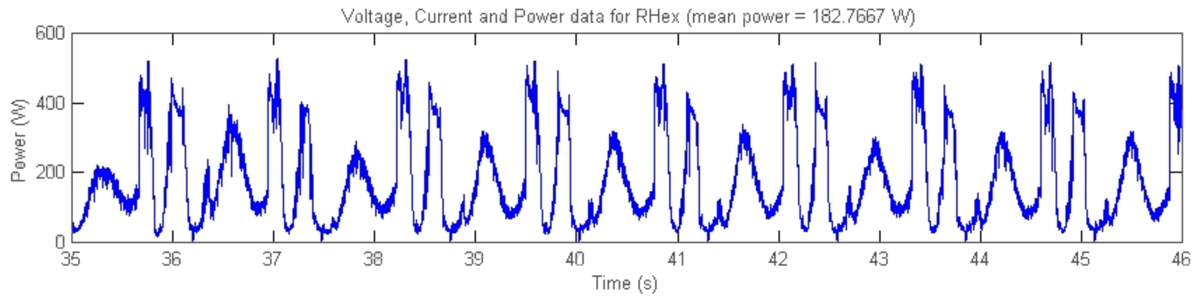

Figure 8. Total electrical power consumption while climbing nine stairs.

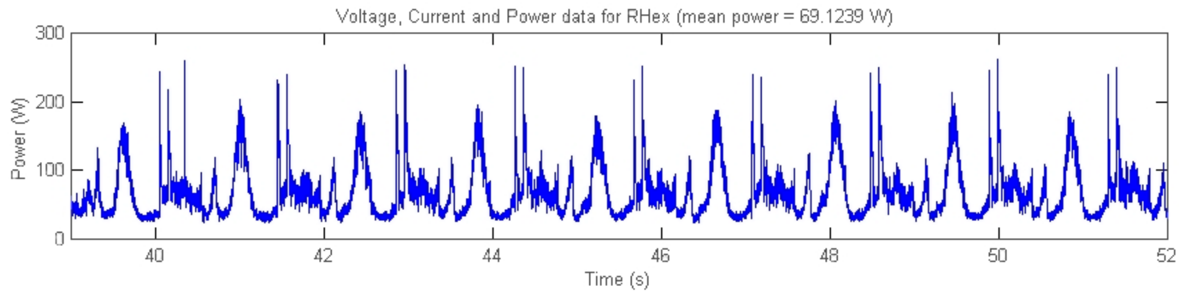

Figure 9. Total electrical power consumption while descending nine stairs.

4.2 Reliability

In order to document the reliability of the experiments, we first divided the task into pure climbing and descending tasks with the robot being placed on the stairs by the operator, and the task of climbing and descending the first step. The tasks were repeated ten times successively, logging successes and failures. Due to the high power consumption of the climbing task, the robot was given a rest after three or four successive runs to permit the rear motors to cool down.

RHex climbed a flight of stairs with ten steps successfully in 9 out of 10 attempts, with human assistance on the first step. It descended the same set of stairs 10 consecutive times, again with human assistance on the first stair.

We ran another series of tests to determine the reliability of the robot when climbing the first stair. We deemed the test successful if the robot climbed to the 3rd stair completely unassisted. The robot was started about 1m from the first stair, and a standard tripod gait was used to drive the robot closer to the stair. The human driver initialized the stair-climbing controller at an appropriate distance from the stair. When ascending the stairs, the robot successfully climbed the first stair 10 consecutive times out of 10 attempts. It was similarly able to descend the first stair successfully 10 times in a row out of 10 attempts.

4.3 Failure Modes

Before the controllers were optimized for reliability on the stair geometry described, and when we ran RHex on other stair geometries, two main failure modes could be observed. RHex avoids pitching over backwards – by far the most likely failure mode - by maintaining low speed. The second most dangerous failure mode is not as disastrous: If the rear legs fail to catch the next step during phase 5, RHex will slide backwards during phase 6. This occurs more often as the length of the step increases. RHex will generally only slide down one step before a pair of legs catches a foothold. A pattern of reaching forward, and sliding back may be repeated several times before the rear legs manage to catch the next step.

The very first step of a flight poses special challenges to the controller. The robot must go through a large pitch angle while remaining stable. The first step is the only element in the algorithm that benefits from human input. The first cycle of the controller is run very slowly to keep the pitch velocity low. No other failure modes are statistically significant.

5 Conclusion

We are inspired to build robots that can traverse any terrain a human can. We have shown that RHex is capable of ascending and descending human sized stairs in a timely and efficient manner. It is able to do this using only simple pre-programmed leg trajectories. Research into climbing a range of stairs that vary in size, inclination, and surface finish is ongoing.

Acknowledgements

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References

1. M. Buehler, U. Saranli, D. Papadopoulos, and D. E. Koditschek, Dynamic Locomotion with four and six-legged robots, Int. Symp. Adaptive Motion of Animals and Machines, Aug 2000.
2. U. Saranli, M. Buehler and D. E. Koditschek, "Design, Modeling and Preliminary Control of a Compliant Hexapod Robot," IEEE Int. Conf. Robotics and Automation, p. 2589-2596, 2000.
3. O. Matsumoto et al., Dynamic trajectory control of passing over stairs by a biped type leg-wheeled robot with nominal reference of static gait, Int. Conf. Intelligent Robots and Systems, p. 406-412, 1998.
4. S. Talebi, M. Buehler, and E. Papadopoulos, Towards Dynamic Step Climbing for a Quadruped Robot with Compliant Legs, 3rd Int. Conf. on Climbing and Walking Robots, Madrid, Spain, Oct 2000.
5. M. Buehler et al, SCOUT: A Simple Quadruped that Walks, Climbs, and Runs," IEEE Int. Conf. Robotics and Automation, p. 1701-1712, 1998.
6. K. Yamazaki, The Design and Control of SCOUT I, M. Eng. thesis, McGill University, 1997.
7. M. H. Raibert, *Legged Robots that Balance*, MIT Press, Cambridge, MA, 1986.
8. K. Hirai, M. Hirose, Y. Haikawa, and T. Takenaka, The development of Honda humanoid robot, IEEE Int. Conf. Robotics and Automation, p. 1321–1326, 1998.
9. R. Riener, M. Rabuffetti, and C. Frigo, Joint powers in stair climbing at different slopes, BMES/EMBS Conference, p. 530, 1999.
10. S. Hirose, K. Yoneda, K. Arai, and T. Ibe. Design of a quadruped walking vehicle for dynamic walking and stair climbing. *Advanced Robotics*, 9(2): 107-124, 1995.