Reliable Stair Climbing in the Simple Hexapod ‘RHex’

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Abstract

RHex is a hexapod with compliant legs and only six actuated degrees of freedom. Its ability to traverse highly fractured and unstable terrain, as well ascend and descend a particular flight of stairs has already been documented. In this paper, we describe an open loop controller that enables our small robot (Length: 51 cm, Width: 20 cm, Height: 12.7 cm. Leg length: 16 cm), to reliably climb a wide range of regular, full-size stairs with no operator input during stair climbing. Experimental data of energy efficiency in the form of specific resistance during stair climbing is given. The results presented in this paper are based on a new half circle leg design that implements a passive, effective leg length change.

Keywords: stair climbing, hexapod, RHex, legged locomotion.

1 Introduction

The design and control of RHex was inspired by recent research in biology[1,2] – in particular cockroach locomotion. Our research group (at McGill, UC Berkeley, U. Michigan, and recently Carnegie Mellon University) has successful captured some of the key biomimetic functions[3] in the simple RHex morphology. This has imbued RHex with outstanding mobility over many types of terrain.[4,5] We envision RHex in fire and rescue applications, land mine and bomb disposal, planetary exploration, and military and law enforcement activities. Many terrestrial mission scenarios take place in urban settings with stairs, making stair traversal a critical requirement for mobile robots. Yet, stairs can be challenging obstacles, especially for small robots.

Several legged robots have successfully climbed stairs – recently the Honda bipeds climbed quasi-statically.[6] Raibert built a biped that could hop over stairs dynamically given knowledge of the stairs placement and size.[7] Hirose outlined an algorithm to climb stairs in a closed loop manner using a tethered quadruped.[8] Matsumoto built a robot that could climb flights of small stairs.[9] Yamazaki et al. and Talebi et al. each worked on climbing a single step with the Scout I and Scout II quadrupeds[10,11,12] but to date, neither of these two robots was able to climb full-scale stairs. To our knowledge, RHex (Fig. 1) is the smallest and simplest legged robot capable of climbing a range of human-scale stairs in a reliable manner.

Figure 1 - RHex in rough terrain

2 Platform

The diagram in Figure 2 describes RHex’s major components, and the physical parameters are provided in Table 1. RHex’s legs have evolved over the past two years, to increase compliance, improve ruggedness, and to improve stair climbing (Figure 3). Two main factors affect a leg’s suitability for stair climbing: the horizontal distance between the hip and the ground contact point during a stance phase, and the degree to which the hip trajectory parallels the slope of the stairs.

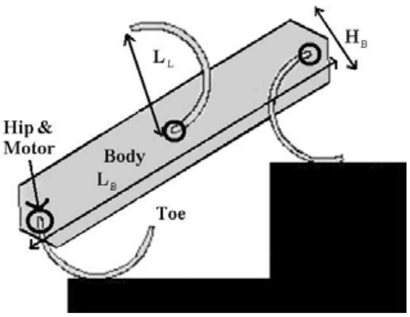

Figure 2 – Major components and parameters

Body Mass	M_B	7.5 kg
Leg Mass	M_L	0.08 kg
Body Length	L_B	0.51 m
Body Height	H_B	0.127 m
Leg Length (unloaded)	L_L	0.16 m
Leg Spring Constant (linear approximation)	K_L	1900 N/m
Maximum Hip Torque	τ_{max}	~7 Nm
Maximum Hip Speed	ω_{max}	5 rpm

Table 1- Basic RHex Characteristics

The horizontal distance between toe and hip determines the hip torque required to support the robot against gravity, and thus contributes substantially to energy cost. The compass leg is not suitable for stair climbing as the horizontal distance between the foot and the hip can be quite large, as long as the leg itself (Figure 4).

Figure 3 – "Compass", "Four-Bar" and "Half-Circle" legs.

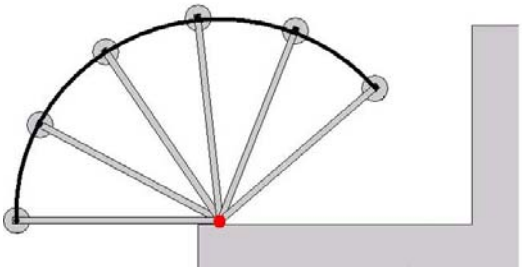

Figure 4 - A Compass leg during stair climbing. Black line is the hip trajectory, the dot is the toe contact point.

The Four-Bar leg that was used in earlier results[13] improved upon the performance of the compass leg by contacting the stair along more than one point. This reduces the horizontal distance between toe and hip initially, as illustrated in Figure 5. The Half-Circle legs take this multiple contact point action a step further by using a rolling foot contact and further reduce the toe-hip horizontal distance (Figure 6).

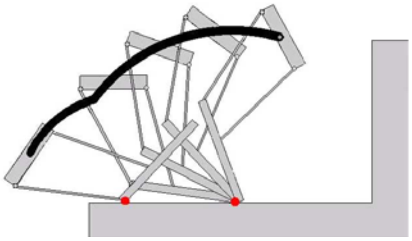

Figure 5 – A Four-Bar leg shown in stop motion. The black line is the hip trajectory. The two dots are (successive) leg contact points.

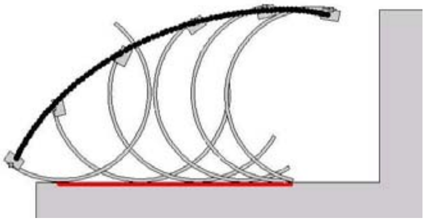

Figure 6 - A Half-Circle leg shown in stop motion. The black line is a trace of the hip motor shaft position. The straight line contains the leg contact points.

The hip would ideally follow a straight-line trajectory up the flight at stair inclination in order to minimize energy expenditure, body vertical and pitch oscillations, and the likelihood for catastrophic failure through excessive body pitching. We can see in Fig. 7 that the hip trajectory arising from the half-circle leg is closest to the ideal.

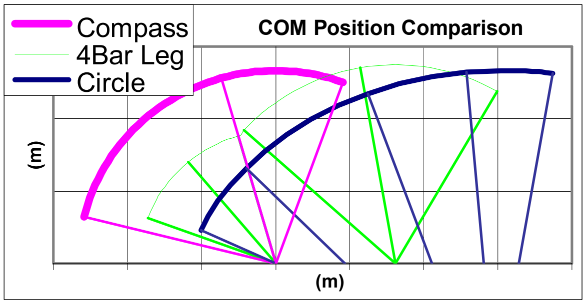

Figure 7 - Each of the three legs traces a different hip trajectory during the stance phase, shown with selected leg positions during stance. Grid lines at 6 cm increments.

To follow a linear hip trajectory and to adapt to varying stair inclinations each leg would need two actuated d.o.f. (see Fig. 8). However, this would double the number of actuators on our robot, and runs counter to our desire to find the simplest possible robot design and the smallest number of actuators to accomplish the task.

And as we will show subsequently, articulated legs are not necessary for successful stair climbing.

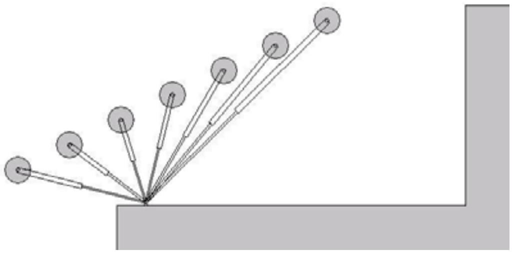

Figure 8 - A stop motion image of a two d.o.f. robot leg following a linear trajectory up a stair.

The Half-Circle legs, and to a lesser extent, the Four-Bar legs, give RHex the advantages in stair climbing of a two d.o.f. leg, without the associated disadvantages in weight, reliability, and power consumption. They change effective length by using more than one contact point on the leg. Because the Half-Circle leg rolls, it does not suffer from a discontinuity in hip trajectory, as the Four-Bar leg does when it changes contact points (Fig. 5 and 6). Finally, the rolling contact of the Half-Circle legs should allow for efficient touchdowns and liftoffs.[14]

Half-Circle legs offer improved performance in stair climbing compared to the Four-Bar legs. Using the same controller as in an earlier paper[13], which had been tuned for the Four-Bar legs, power and specific resistance decrease by 37% simply by virtue of the Half-Circle leg geometry. Finally, the Half-Circle leg design does not merely improve stair climbing performance. Early tests showed that it equals or surpasses the Four-Bar leg also in walking top speed and efficiency, slope climbing, and rough terrain mobility.

3. Stair Climbing Algorithm

RHex employs a tripod gait during slow static and fast dynamic walking over varied terrain. This gait, however, is not successful on full-size stairs, and basic stair geometry suggests that a back-to-front metachronal wave gait is more suitable. In fact, many insects, millipedes and cockroaches, use metachronal gaits, which might increase their yaw stability.[15]

The particular leg trajectories, phase times, and the sequence of leg motion used in the algorithm were dictated by the stair geometry and fine-tuned via video analysis while climbing a particular flight of stairs (Stair #4). Emphasis was placed on finding open loop leg motions, based on linear trajectory segments connecting angle set points, that maintaining a low pitch, a high constant body velocity, and a moderate ground clearance. The resulting preliminary algorithm consisted of only three phases, and succeeded consistently and reliably on one particular stair (Fig. 9) for which it was tuned, but failed on others with different geometry.

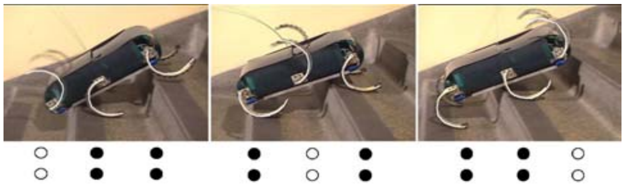

Figure 9 - RHex climbs stair #4. The three phases of the preliminary algorithm are shown. Filled dots indicate legs in stance, and open circles are legs in flight.

In general, the success of any stair climbing algorithm depends upon the robot being “in phase” with the stairs. By this we mean that when the rear legs recirculate, for instance, it is assumed that there will be a stair for it to touch down upon, at approximately a predetermined angle. Thus successful climbing requires some tuning of the controller to particular stair geometry. The geometry of other stairs may be such that the robot is not stable, i.e. at the completion a stepping cycle, it does not have the same pose as it did at the beginning of the cycle. The visible consequence of this is that the rear legs may finish their stance phase too far from the next stair to reach it at the end of their next recirculation. This will produce a failure via flipping over or by simply not progressing. This condition may not occur during every step of a flight, as the de-synchronization between robot and stair may grow over several steps.

How can we assure that the robot’s motion remains synchronized with the stairs across a variety of stair geometries? To resolve this problem, we made the following modification: at the completion of the cycle, RHex extends the final phase suitable for the longest tread (the horizontal part of the stair), which effectively moves RHex’s body forward, until the front of the body touches the next stair, and the rear legs are in the correct position (Fig. 10). This ensures that the robot ‘self-aligns’ at the end of the stair cycle by pushing against the next stair. On short stairs, the middle legs will slip backwards during this phase until reaching their target position. As an additional measure, the control will exit the extra push phase when the speed of the middle legs drops below a threshold value (10 deg/s). The leg trajectories shown in Figure 11 represent three full cycles on flight #4. This algorithm was used on all stairs reported in this paper.

This algorithm allows RHex to climb ‘human sized’ stairs, but it is implicitly assumed that RHex is already on the stairs. We use another ‘first step’ algorithm (Fig. 12) to bring the robot from standing directly in front of the first step to a pose where the stair-climbing algorithm can be safely activated. The actual and target positions and estimated motor current of the hips from an experiment are shown in Fig. 13.

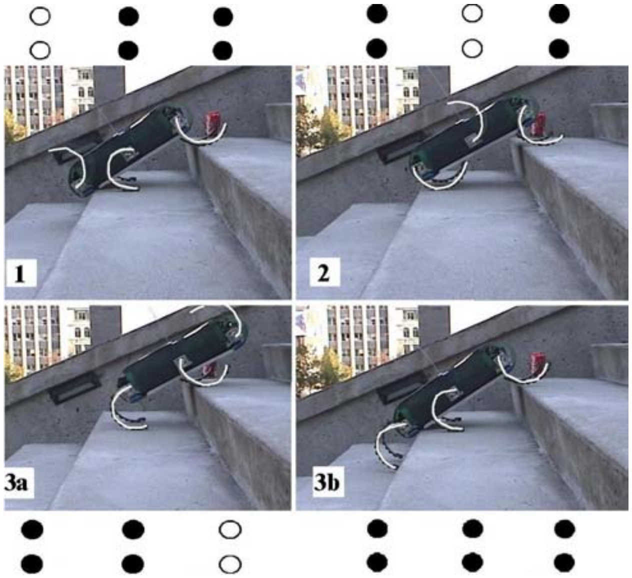

Figure 10 – Climbing stair #2. Phases 1, 2, and 3a are identical to those in preliminary algorithm. Rear legs are too far from stair in Phase 3a. Phase 3b is added to move rear legs close enough to next stair for the rear legs to reach it. Legs are highlighted for clarity. Filled dots indicate legs in stance, open circles are legs in flight.

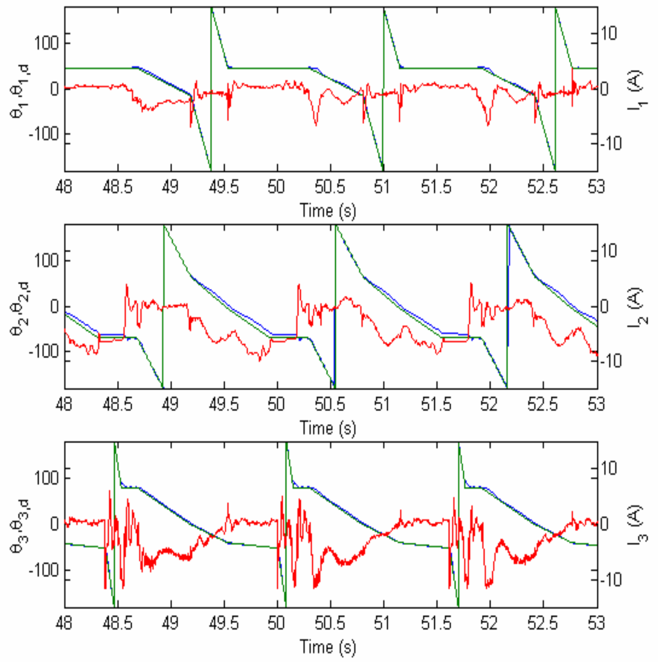

Figure 11 - Leg target and actual trajectories and estimated motor current while climbing three steps of stair #4. Right and left legs are very similar, so only left side is shown. Top figure is the front of RHex.

Figure 12 – 'First step' algorithm. Left: robot stands before flight. Center: front left leg recirculates and pulls RHex onto first stair. Right: Front right leg recirculates so that RHex is posed to enter the stair climbing algorithm.

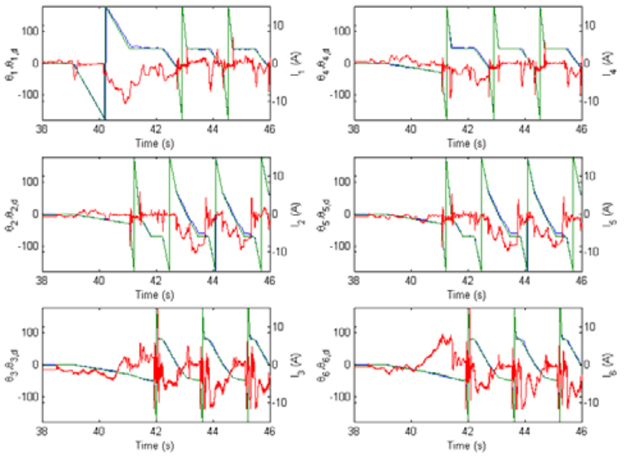

Figure 13 – 'First step' algorithm. Leg target and actual trajectories and estimated motor current while climbing the first two steps of stair #4.

4 Experimental Stair Climbing Results

We tested stair climbing on five different stair geometries (Table 2) representing the range of stairs found on the McGill University campus, all the way to a 42 deg inclination fire escape (stair #5). For each run, RHex was started at a standing position a short distance (0-6 cm) perpendicularly to the first stair and the operator simply enabled the automatic sequence of the 'first stair' controller followed by the stair climbing controller. No operator input was provided until the robot either failed or reached the end of the stair. The success rate over ten successive runs is given as well in Table 2. The single reported failure among all the 50 stair climbing runs was due to slipping on the second step on stair #1.

We found during development that the best predictor of success was the height of each step, not the length, average slope, or surface finish. There are stairs that RHex cannot yet climb, such as circular stairs and stairs with very round edges.

#	H_S (m)	L_S (m)	# of Steps	Material	Success Rate	Slope (°)
1	.13	.33	13	Smooth Concrete	90%	21.5
2	.16	.338	10	Rough Concrete	100%	25.3
3	.16	.285	13	Heavy Outdoor Carpet	100%	29.3
4	.16	.28	10	Smooth Stone	100%	29.7
5	.20	.22	19	Metal Grate	100%	42.0

Table 2 - Stair geometries and reliability over ten runs – pictures of each flight are shown below.

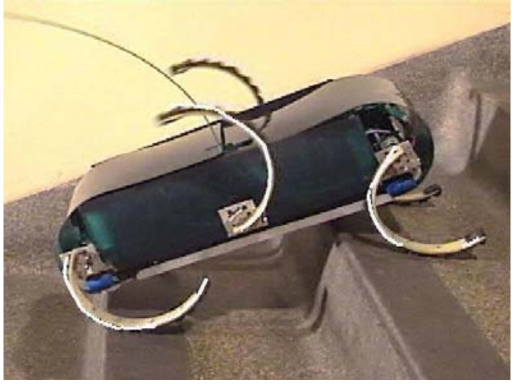

Figure 14 – Stairs Climbed, in ascending order; Stair #3 does not show carpet present when experimental data was taken.

Energetic cost of stair climbing varies with stair geometry. Average total electrical power consumptions were between 90 W and 250 W (157W on #4) on the various stairs. We calculated the specific resistance

$$\varepsilon = \frac{E}{m \cdot g \cdot d} \tag{4.1}$$

where E is the total electrical energy consumption for a linear displacement of d along the stairs (not including the start and end portions), m is the total robot mass, and g is the gravitational constant.

The average specific resistance based on ten successive experiments for a stair with average geometry was calculated to be 12.4, with a standard deviation of 0.2. 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.

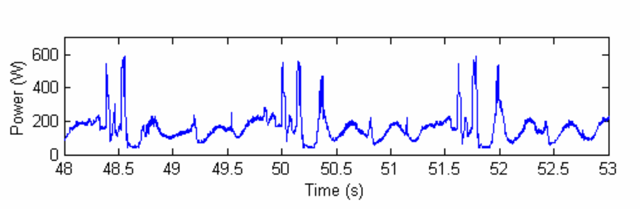

Figure 15 – Total electrical power consumption over three steps of stair #4, average value 157 W.

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 a wide range of human sized stairs in a reliable manner. It is able to do this despite its small size, simple mechanical design with only one actuator per leg, and using only simple preprogrammed leg trajectories.

In the future we plan to investigate the usefulness of the proposed algorithm on circular stairs. Touchdown detection and gyro based pitch sensing may also allow for task level feedback algorithms that further enhance reliability over even more extreme ranges of stair geometries, and perhaps most importantly, reduce energy consumption. Finally, a previously reported stair-descending algorithm[13] will be enhanced in a similar manner.

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