Stair Descent in the Simple Hexapod ‘RHex’

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Abstract

We present the first controller that allows our small hexapod robot, RHex, to descend a wide variety of regular sized, “real-world” stairs. After selecting one of two sets of trajectories, depending on the slope of the stairs, our open-loop, clock-driven controllers require no further operator input nor task level feedback. Energetics for stair descent is captured via specific resistance values and compared to stair ascent and other behaviors. Even though the algorithms developed and validated in this paper were developed for a particular robot, the basic motion strategies, and the phase relationships between the contralateral leg pairs are likely applicable to other hexapod robots of similar size as well.

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

1 Introduction

RHex is a hexapod robot inspired by research on locomotion in biological systems[1][2] – specifically cockroach locomotion. The project – with members at McGill, UC Berkeley, U. Michigan and Carnegie Mellon U. – aims to develop increasingly performant and autonomous behaviors to enhance its already large repertoire of gaits, including walking over highly broken and irregular terrain[3], pronking[4], stair climbing[5][6], swimming, flipping[7] and, most recently, bounding[8]. Many of the possible applications for RHex such as law enforcement, bomb disposal, fire fighting, or search and rescue are situated in urban areas where stairs are a frequent obstacle. The discontinuous nature of stair geometry lends itself well to legged platforms, whereas wheeled platforms can encounter great difficulty in stair traversal. Tracked vehicles must be large enough to be able to span three steps in order to overcome these obstacles in a stable fashion, and may still suffer from slipping due to low traction on the edges of the steps.

Despite the apparent suitability of legged systems to negotiate stairs, there are very few robots that successfully do so. Notable exceptions are the Honda bipeds - P2, P3 and Asimo, and Raibert’s tethered biped, yet no specific publications describing the stair climbing algorithms and performance seem to be available. To our knowledge, the Honda bipeds and RHex are the only untethered legged robots to ascend and descend full size stairs. The ability of RHex to ascend a variety of stair geometries reliably has been previously published[5][6]. In this paper, we complete this stair climbing behavior with stair descending over various stair geometries.

Figure 1 - RHex

2 Platform

RHex is a hexapod robot with a very simple mechanical design: a single actuator is located at the hip of each leg, rotating the leg in the sagittal plane. The legs are compliant, permitting dynamic gaits by embedding similar mass-spring dynamics as found in most legged animals during running. Indeed, the leg geometry and material is the result of a long design process seeking robust legs with proper compliance to enable efficient energy storage, and release, for dynamic gaits. The simplicity of the system has resulted in a robust platform for studying legged locomotion. While there are numerous sensors on board, most behaviors to date, as well as the stair ascent and descent algorithms, rely solely on leg angle sensing, used for PD position control. RHex is power and computationally autonomous, allowing for great versatility in the field. The diagram in Figure 2 describes RHex’s major components, and the physical parameters are provided in Table 1.

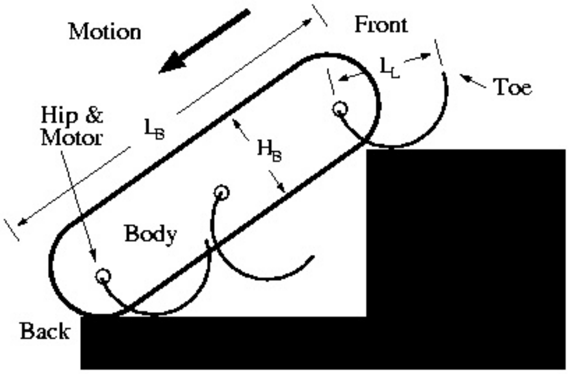


Figure 2 - Major Components and Parameters

Body Mass	M_B	8.0 kg
Leg Mass	M_L	0.08 kg
Body Length	L_B	0.51 m
Body Height	H_B	0.14 m
Leg Length (unloaded)	L_L	0.17 m
Leg Spring Constant (linear approximation)	K_L	1700 N/m
Maximum Hip Torque (intermittent only)	τ_{max}	5 Nm
Maximum Hip Speed	ω_{max}	5 rev/s

Table 1 - Basic RHex Properties

3 Stair Descent Algorithm

Some initial thoughts suggest that stair descending should be easier than ascending, after all, gravity is helping all the way down the stairs. While this is true, the difficulty comes in descending the stairs in a controlled, stable fashion, in the absence of a sensory-rich robot, and thus without complete knowledge of either the stair geometry or information about the robot state with respect to the stair geometry. The algorithm for ascending stairs works very well over a wide range of stair geometries and construction materials, due to an effective, open-loop, synchronization feature[6]. A simple time reversal of the trajectories seemed like a good starting point for a descent algorithm. This approach however was unsuccessful on steep stairs (greater than 30°). The robot quickly lost synchronization with the stair, leading to jamming or irrecoverable pitch or yaw motion.

The algorithm used for descending stairs is instead based on the idea of sliding the robot down the stairs on its belly. The robot progresses down the stairs in "reverse," with the rear legs leading the motion and the front legs higher up the flight. The legs work in contra-lateral pairs, a gait which avoids inducing a yaw moment by left-right leg contact imbalance. One of two different sets of trajectories is used depending on the slope of the staircase. Synchronization with the stair is accomplished differently depending on the parameter set used, and is described below.

Steep Stair Gait:

Through video analysis of the failures of the previous stair descent gait, a hypothesis was formed that the failures were caused by the robot gaining too much kinetic energy while the lower legs were recirculating as the robot was not fully supported by either the stair-body or the stair-leg interaction. The previous gait featured a recirculation phase for the front legs. On some stair geometries the recirculation introduced additional pitching moment when the toes collided with the stair riser. By removing this phase, there is no collision to impart the pitching moment on the robot. The legs that are now held at a fixed angle in front of the robot are also useful for assisting in a repetitive placement with respect to the stair. The repetitive placement was found to be very important in the stair ascent gaits to be able to consistently traverse flights of any number of steps using a single set of parameters. In descent mode, the same synchronization is important to avoid slipping down the stairs in an uncontrolled fashion. While for the ascent algorithm synchronization was obtainable by pushing the robot against the next stair, the direction of the motion during the descent phase prohibits a similarly active method. Instead, the front legs slide down the stair, leaving the robot at a similar distance from the edge every step.

The role of the rear legs of the robot, at the low end of the robot, is to catch and then lower the body of the robot as it slides down the stair on its belly. During this phase, as with the ascent gait, the shape of the leg plays a key role. When the toe of the leg touches the stair it is near the greatest extension of the leg and as the hip rotates the distance between the hip and the contact point of the leg decreases, effectuating a passive leg length change.

The middle set of legs is recirculated but does not touch the stair during most descents of steep staircases. Occasionally the legs touch the vertical riser of the stair, but do not affect the motion of the robot.

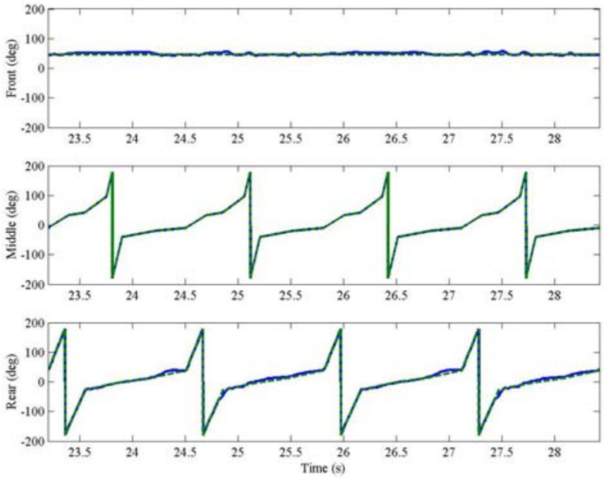


Figure 3 - Steep gait trajectories – Solid trace: actual, dashed trace: desired

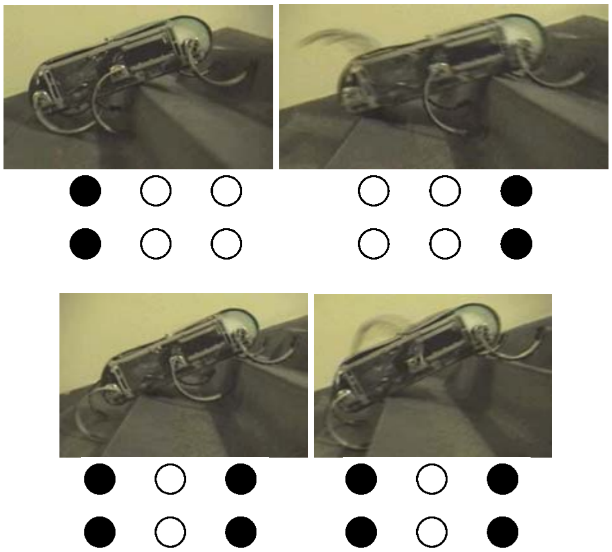


Figure 4 - Key positions for steep descent gait parameter set. A filled circle indicates a leg in contact with the horizontal surface of the stair

Shallow Stair Gait:

The shallow gait algorithm resembles closely the algorithm originally used to descend a single, fixed stair geometry[5], with all three sets of legs recirculating for every step descended. The problem with the steep stair algorithm on shallow stairs was that the front legs rubbed on the step instead of sliding to position the robot consistently. In addition, the rear and middle legs exert a great deal of force in order to drag the robot down the stairs, rather than merely catching the robot and gently lowering it (Figure 5). The recirculation phase for the front set was re-added in order to circumvent this problem.

Figure 5 - Sticking on shallow stairs

When the front legs of the robot recirculate, the toes push the body backwards through contact with the vertical riser of the stair. This causes the robot to slide farther backwards when the rear legs lower the back of the robot and recirculate themselves. The trajectories for the other pairs of legs remain unchanged (Figure 6).

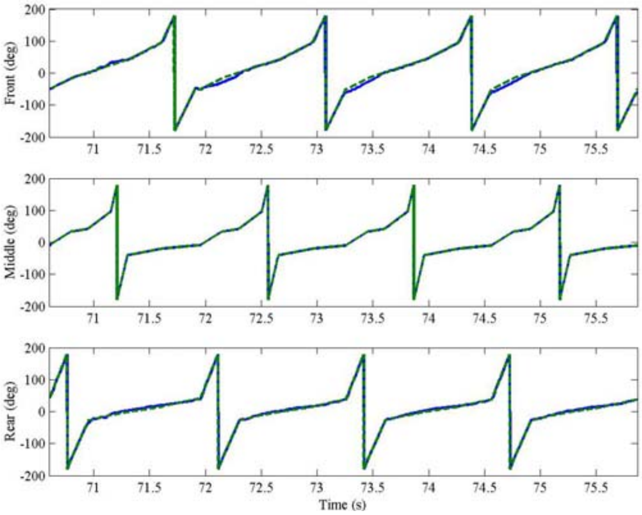
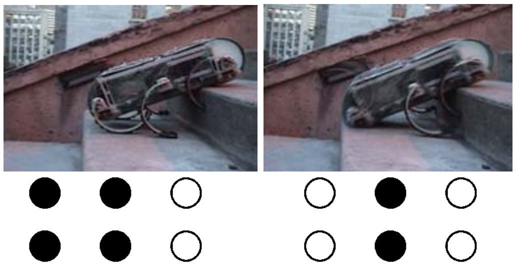


Figure 6 - Shallow gait trajectories – Solid trace: actual, dashed trace: desired



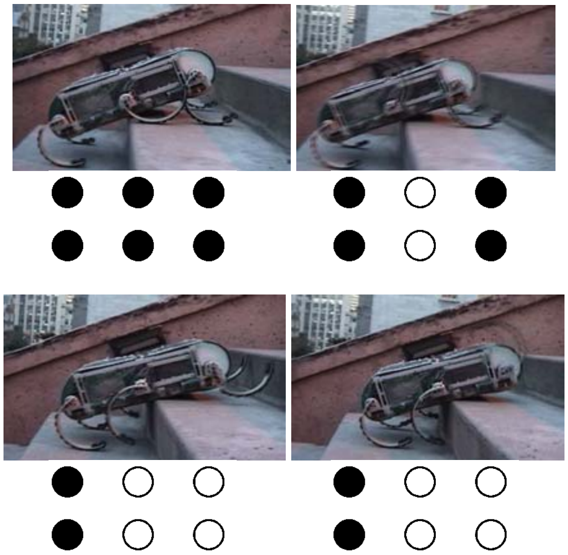


Figure 7 - Key positions for shallow descent gait parameter set. A filled circle indicates a leg in contact with the horizontal surface of the stair

The shallow and steep stair algorithms depend on two assumptions about the stairs. First, the vertical riser of the stair must be closed. For the shallow stair gait this is fairly evident since it relies on the toes pushing off the riser, but it is also a problem on some steeper stairs as the toes catch on the underside of the step. The second assumption is that there is no large "ledge" on the step. This corresponds to dimensions 'c' and 'd' in Figure 8, below. If there is a ledge (i.e. 'd' is not zero) then the toes may catch and disturb the descent of the robot, just as when there is no riser at all.

4 Experimental Stair Descent Results

We tested the descent algorithms on a variety of the stairs found around campus. All stairs selected as test sets were of the variety that have closed risers, though some also had small ledges. The stairs, described in Table 2, range in slope from 24 to 35 degrees, and are made of various textures of concrete and stone. Stairs consisting of only a few steps were avoided since there is insufficient space for synchronization errors to build up.

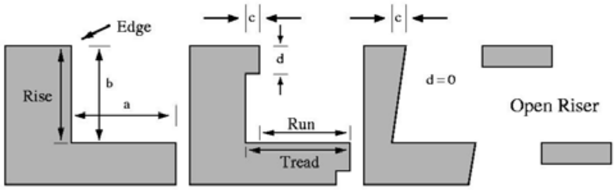


Figure 8 - Stair varieties and dimensioning

#	a (cm)	b (cm)	c (cm)	d (cm)	# of Steps	Slope (°)
1	36	15.5	0.8	0	9	24
2	30.8	15.4	0.4	0	12	27
3	28	17	0.7	0	11	32
4	29	17.8	2.5	4.3	12	34
5	29.5	18.9	2.3	4.0	17	35

Table 2 - Stairs Tested

For the purposes of these experiments the robot was manually placed on the top step in order to simplify the testing. Further research will include the development of a startup algorithm to get the robot into position, similar to the startup algorithms for stair ascending[6]. Battery voltage and current were measured to determine power consumption of the whole system, not just the actuators.

During the testing we found that the robot could recover well from occasional missteps, as long as the yaw angle was less than about 10 degrees. Shallow stairs were more difficult to negotiate because the behavior depends highly on the leg properties and toe positioning. This is due to the active nature of forcing the sliding motion on these stairs. The crossover point between the shallow and steep gaits occurs at a slope of 30°. Below this angle the steep gait had difficulty getting the robot to descend smoothly without getting stuck on a stair. On stairs steeper than this angle, the shallow gait, with the recirculating front legs, was more prone to causing skipping or pitching over backwards.

5 Energetics

The average power consumed over the different stairs ranges from 95 to 135W over a small number of full cycles. As a measure of energetic efficiency the specific resistance is used[9]. The measure of the energetic cost of locomotion is calculated as

$$\varepsilon = \frac{P}{m \cdot g \cdot v},$$

where P is the average electrical power consumed, m is the mass of the robot, g is the gravitational constant, and v is the speed of locomotion along the stair inclination. Note that this number is somewhat imprecise in our application because it does not consider the change in potential energy.

#	Average Electrical Power	Specific Resistance
1	95.9 W	4.82
2	120.5 W	5.31
3	135.2 W	7.01
4	101.8 W	5.31
5	105.9 W	7.45

Table 3 - Experimental results of energetic efficiency.

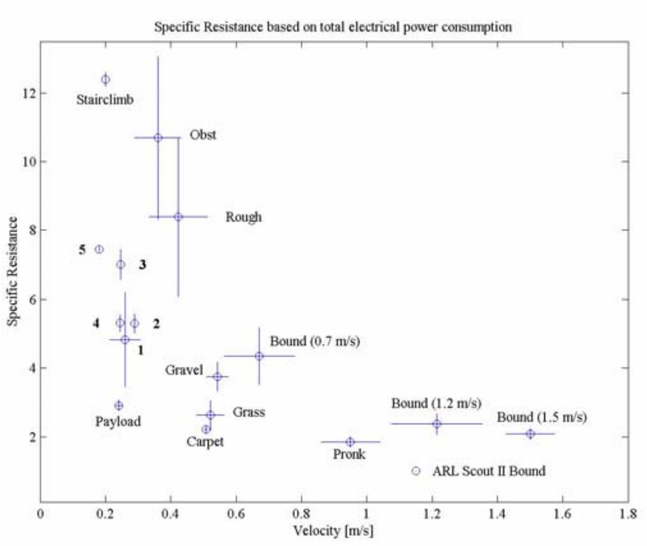


Figure 9 - Specific resistance of some legged platforms. Numbers indicate stair number

Even though stair descent has the potential for great energy efficiency, at present the robot still consumes more power descending stairs than it does walking on even terrain (Figure 9). However, when compared to ascent, descent is roughly twice as efficient. Comparison with other gaits' efficiency indicates that there is a lot of room for improvement. For example, the bulk of the power consumption takes place during the phase when the back of the robot is lowered down the step (Figure 10). If this phase were sped up, the specific resistance could be lowered.

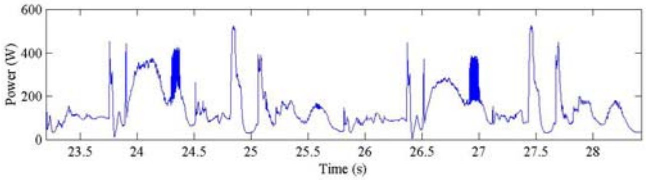


Figure 10 - Power Consumption over four steps of stair #3 with average value of 144 W

Figure 11 - Stair #1

Figure 12 - Stair #2

Figure 13 - Stair #3

Figure 14 - Stair #4

Figure 15 - Stair #5

6 Conclusion and Future Work

In the pursuit of our goal of traversing terrains in the human and urban environments we have added an important gait to complement the previously discussed stair ascent gait. Descending stairs is a challenging task that is at first taken for granted because of its apparent simplicity compared to ascending stairs. Yet, descending stairs still requires more complex shallow/steep stair algorithms, compared to the single algorithms for stair ascent. Still, in the end, despite its small size and simple design, the robot is able to accomplish the stair descent repeatedly.

In the near future, we will improve the range of stairs that can be traversed, and develop an algorithm to position the robot on the top step without operator intervention. A more complete study of the reliability of the descent algorithm also needs to be made, with more trials per stair attempted. More analytic approaches will also be pursued, developing optimal trajectories from geometric analyses. Such parameters could then be used in conjunction with stair sensing to automatically choose the best set for the specific stair encountered.

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