Towards Pronking with a Hexapod Robot

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Abstract

This paper presents a pronking controller for our six-legged robot RHex. Development of the controller begins with a passive-dynamics approach, ensuring that the robot is naturally suited to running. Running with flight phase is then achieved using only proprioceptive (joint angle sensing only) feedback for touchdown detection and for tracking fixed joint reference trajectories. Body pitch oscillation is attenuated by means of an open loop leg speed change during stance. The robot achieves speeds of about two body lengths per second with a specific resistance of 1.85.

1 INTRODUCTION

In searching to extend the mobility of robots in unstructured environments, we have developed RHex, a hexapod robot [8], and gaits for walking, climbing slopes and swimming. Recently, we have also succeeded in demonstrating stair-climbing behaviors, as described in a companion paper [5]. We now seek to improve the speed and efficiency of our robot by making it pronk. The pronk is a single-beat gait where all four (or in RHex's case, all six) feet leave the ground and land at the same time. It is an uncommon gait, but is sometimes seen in young deer, llamas and impalas during play or to ward off predators. The animal best known for pronking is the springbok, or springbuck, a small brown and white gazelle (Antidorcas marsupialis) of southern Africa, noted for its habit of repeatedly leaping high into the air when startled.

A large number of hexapedal robots have been developed in the past but to our knowledge, there exists, apart from RHex, only one other robot, Sprawlita [4], capable of dynamic locomotion. Similar to RHex, it is inspired by biology, aiming to capture essential functional aspects of animal locomotion without attempting to copy all actuation and morphological details. It achieves a top speed of 42 cm/s or 2.5 body lengths per second. Since Sprawlita is powered by external pneumatics, it appears that RHex is the first and so far only power-autonomous hexapod capable of dynamic locomotion, and the only one capable of pronking.

Pronking has been modelled in quadrupeds [3], but the few quadrupedal running robots built to date use bounding or trotting gaits [7,9].

In this paper we present a pronking controller that enables RHex, Fig. 1, to run at about two body lengths per second (approximately 1 m/s). The controller is "open loop" in that the desired leg motion is re-played as a fixed pattern, but triggered based on inferred touchdown events. The success of this strategy depends on the proper timing and shape of the stance leg trajectories, in sync with the vertical dynamics formed by the body-legspring system, the proper selection of the touchdown angles and tracking gains during the stance and flight phases. Still lacking a proper analytical framework for synthesizing stable controllers, we aim to identify some of the key ingredients for the stabilization and control of running robots, based on an empirical approach.

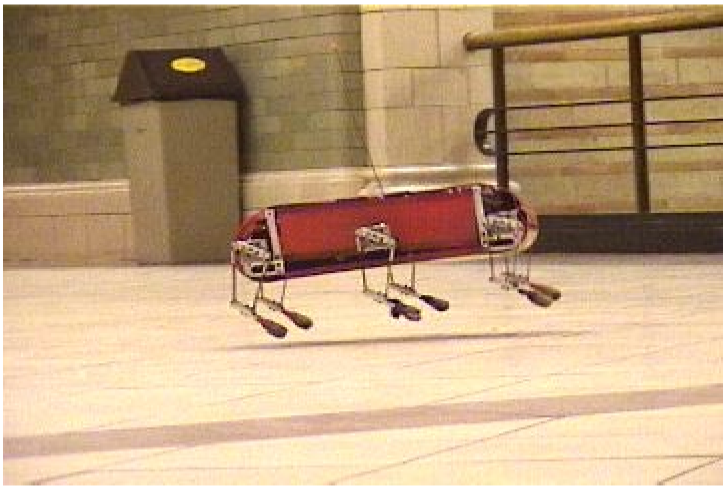


Fig. 1 Pronking RHex in flight phase

2 PASSIVE-DYNAMIC DESIGN

We begin by considering the unforced response of the robot during a hopping cycle, in order to minimize the power needed from our actuators [1,2]. If we can design a robot that hops efficiently at a low enough duty cycle, we should be able to control the motion of the robot to generate efficient forward running.

To simplify the analysis, we treat the robot as a single, parallel spring-mass system, where the spring constant of this system equals the sum of the six spring constants of our robot's legs. When the robot touches down it behaves as a spring-mass oscillator [6], subtending one half cycle before again leaving the ground, with a stance time of

$$T_{\text{stance}} = \frac{1}{2}\frac{2\pi}{\omega_{\text{stance}}} = \pi\sqrt{\frac{m}{k}},$$

where m is the mass of the robot and k is the estimated spring constant when the six legs are treated as a single spring.

From the above calculation, and based on our current robot mass of 8 kg and a leg stiffness 1628 N/m, the expected stance time is 88.5 ms. By performing a series of ten drop tests in front of a high-speed video camera, this value was indeed verified as 85.1 +/- 4 ms. While not as long as we would like, this stance time was long enough to achieve reasonable joint position tracking under load using RHex's actuators (Maxon RE 118751 20 W DC motors equipped with 33:1 planetary gearheads) and its 1 kHz control loop.

3 CONTROL

3.1 Open-loop trajectory control

The simplest controller for this spring-mass system is one that stimulates the horizontal and vertical modes with a fixed periodic leg trajectory. Even after much experimentation with this strategy, such open loop stimulation invariably led to de-synchronization of the leg sweep control and the robot's vertical motion, causing the retraction phase to propel the robot backward or resulting in a summersault.

A sensible next step was to add touchdown detection, in order to synchronize the leg swing trajectory with its vertical (hopping or pronking) body motion. In order to make our reference trajectory propel the robot forward, we required that protraction coincide with stance and retraction occur while the robot was airborne. The result of this strategy was a purposeful and promising forward hop, though often punctuated by front-leg handstands.

3.2 Touchdown detection

The current version of RHex does not include leg displacement or explicit touchdown sensors. Instead, we used two proprioceptive quantities — joint rate and motor voltage command — to estimate the joint torque (via estimating the motor current) and to apply a threshold to determine when each leg made contact with the ground.

Motor current was estimated based on a simple model of a DC servomotor,

$$i_{motor} = \frac{V_{motor} - Emf}{R_a + R_{drive}}$$

where V_{motor} is the voltage applied to the motor at the last iteration, EMF is the motor's electromotive force (back EMF), calculated as $K_s \cdot \omega$ (K_s is the motor speed constant), R_a is the motor armature resistance, and R_{drive} is the MOSFET resistance of our Apex SA60 PWM amplifiers. The motor current estimation is thus based only on joint rate measurements (which are obtained as the derivatives of joint angles measurements), together with known system parameters.

The motor voltage used in the above equation is not known directly. Instead, it is calculated as $V_{motor} = D \cdot V_{battery}$, where $V_{battery}$ is the battery voltage supplying the PWM motor drives,

and D is the duty cycle, commanded from the computer by means of an analog voltage output. For the purpose of leg touchdown detection, the battery voltage is approximated as a constant (this results in reduced accuracy at high currents).

Touchdown for each leg is based on individual, low-level leg state machines. Each such state machine begins when its corresponding leg is in the retraction phase and estimated motor currents are high. When the estimated motor current remains below a threshold of 0.7 A for 15 ms, the leg state machine switches to the waiting for touchdown state. Next, when the estimated motor current rises above 0.9 A the leg state machine switches to the stance state. When three or more leg state machines or when both of the front legs are in stance, the reference trajectory state machine switches to the protraction phase.

Flawless performance of the touchdown detection state machines was critical to avoid de-synchronization and toe stubbing. The touchdown detector was therefore tested by viewing high-speed video of the robot pronking, with LEDs on the side of the robot to indicate the controller state.

3.3 Open-loop body pitch correction

To address the body pitch stabilization problem, a scheme was devised for applying corrective torques on the robot's body during stance, as follows. The stance phase was broken into two stages: a rapid sweep phase, where the springs are being compressed by the robot's landing, and a second, slower phase, to correct the pitch error generated by the first phase. Figure 4 illustrates this effect by overlaying the robot's body pitch rate and a sample leg trajectory. Protraction phase I pitches the robot backwards, overcoming the forward pitching moment caused by the touchdown impact. Next, the decrease in leg sweep rate and subsequent toe dragging cause a corrective forward pitching moment, reducing the robot's body pitch rate.

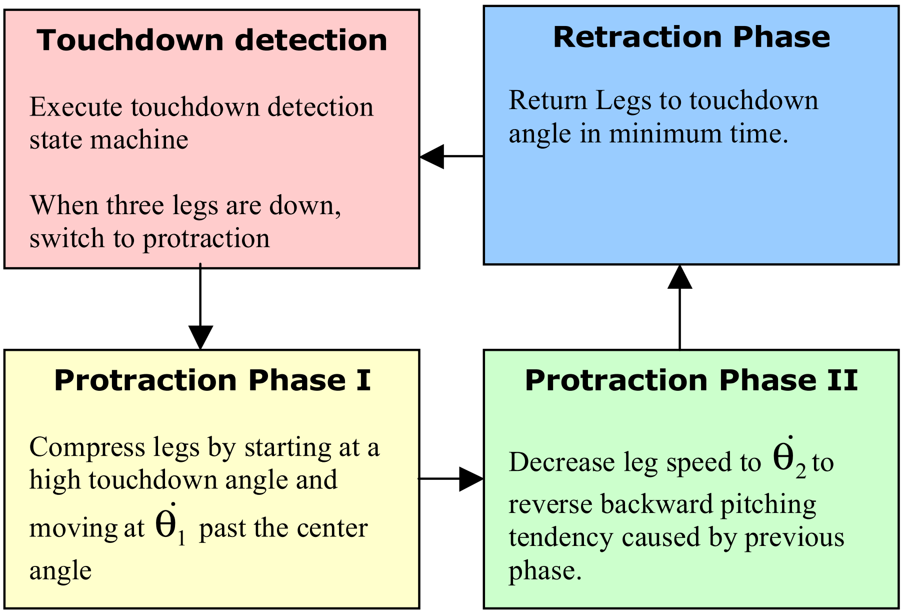
Interestingly, laborious tuning spontaneously resulted in a Protraction Phase I duration of 43 ms, very close to half the observed stance time for the robot. It was also observed that for the majority of the second protraction phase the front four legs were airborne; only the back legs were in contact with the ground.

The high-level trajectory generation state machine is described in Figure 2, along with corresponding plots of leg trajectories and estimated motor currents in Figure 3. Protraction phases I and II execute for $\alpha \cdot t_{swp}$ and $(1-\alpha) \cdot t_{swp}$ seconds, respectively, so that the total protraction duration is t_{swp} seconds.

3.4 Control Parameter Selection

Control parameters for a stable, reasonably fast, pronk were derived empirically. Increasing the touchdown angle for all legs had the effect of increasing the hopping height and power consumption, but also rendering the gait more stable. The touchdown angle was therefore kept as low as possible, but high enough to allow consistent ground clearance and stability. This bears resemblance to [6], in which a trade-off was achieved between forward speed and hopping height could be achieved by moving a monopod's touchdown toe position relative to its center-of-gravity print on the ground.

Protraction phase I and II sweep rates were chosen to provide adequate compression of the legs and compensation for the resulting body pitch error at the end of stance. The idea is that by slowing the legs enough in protraction phase II the rear legs drag just enough on the ground to limit the body pitch increase, but not so much that they slow the robot’s motion substantially.



Touchdown detection

Execute touchdown detection state machine

When three legs are down, switch to protraction

Retraction Phase

Return Legs to touchdown angle in minimum time.

Protraction Phase I

Compress legs by starting at a high touchdown angle and moving at $\dot{\theta}_1$ past the center angle

Protraction Phase II

Decrease leg speed to $\dot{\theta}_2$ to reverse backward pitching tendency caused by previous phase.

Figure 2: State machine for pronking controller

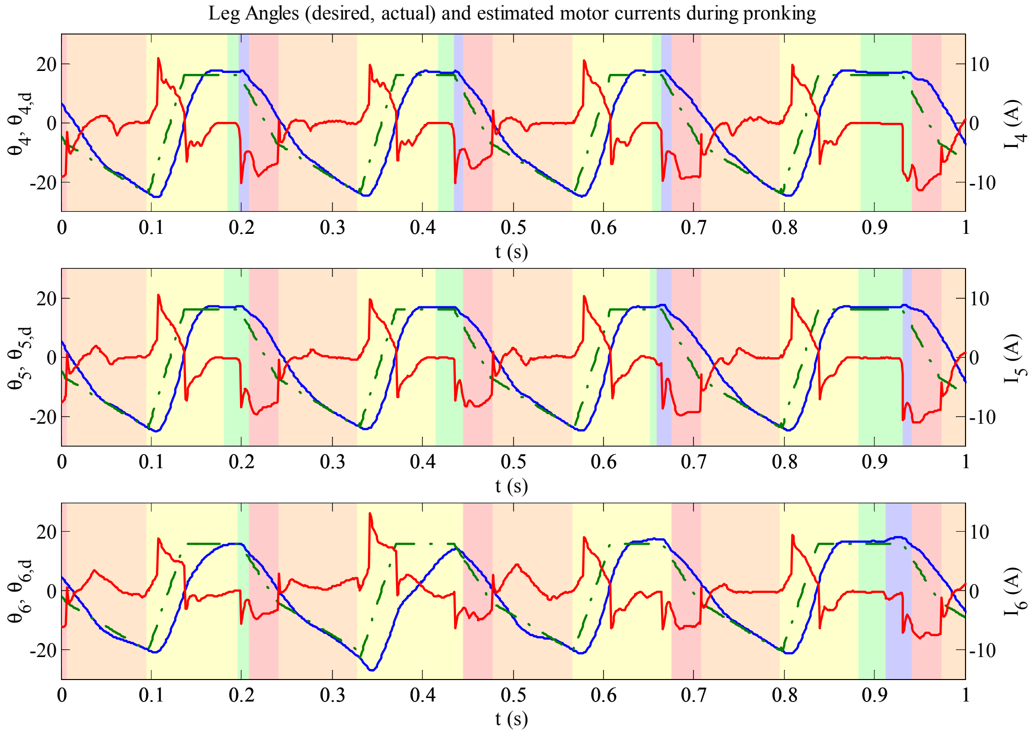


Figure 3: Leg angles and estimated motor currents for right side legs (left side legs not significantly different, and omitted for brevity)

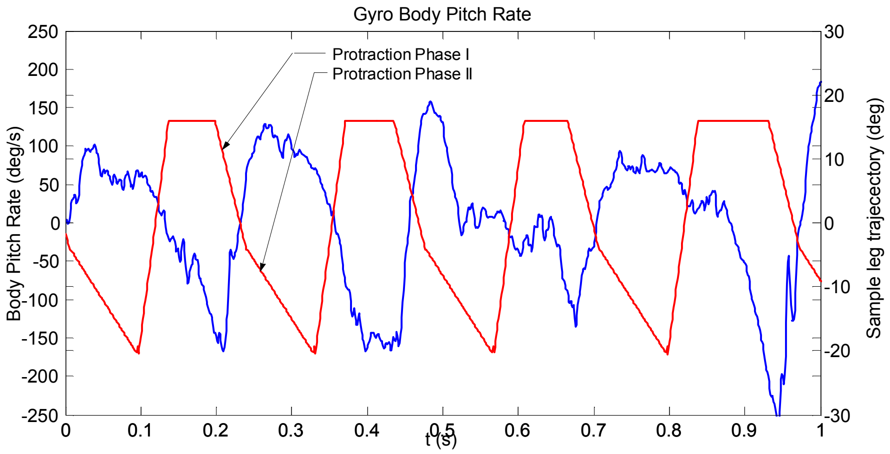


Figure 4: Pitch rate and sample leg trajectory. (Pitch rate acquired with Fizoptika VG941-3AM fibre optic rate gyro)

4 RESULTS

Using the controller described above, the robot was able to pronk at a variety of speeds on linoleum, carpet and snow-covered concrete.

To obtain statistical performance data on specific resistance and speed the robot was run over a 2 m test area with linoleum surface twenty times, with the control parameter settings listed in Table 1. Table 1 also shows the average speed over the successful runs of 0.974 m/s, the average electrical power of 140 W, and the resulting specific resistance. For each run, the elapsed time and electrical power consumed were recorded by the robot's data acquisition and logging system. Runs in which the robot stumbled and halted were counted as failures and discarded from the averages calculated below. However, unsuccessful runs are reflected in the success rate in the right-hand column in Table 1.

Table 1: Results on 2 m linoleum test bed (average of fifteen successful runs)

Controller		**Parameters**					**Speed (m/s)**	**Power (W)**	**ε**	**Success Rate (%)**
		θ_{td}	$\theta_{dot\ 1}$	$\theta_{dot\ 2}$	α	t_{swp}				
Fast	Front 4	18	560	180	0.33	0.130	0.974	140	1.85	75
	Back 2	15	480	180						

Energy efficiency strongly affects the robot's run time and is a key performance parameter for any autonomous mobile robot. Figure 6 compares RHex pronking and walking energetic performance, based on the specific resistance

$$\varepsilon = \frac{P}{mgv}$$

where P is the average total electrical power consumed (in this case, electrical power output of the batteries, as shown in Figure 5), m is the total mass of the robot, v is forward velocity, and g is the acceleration of gravity. The comparison shows that pronking improves both the robot speed as well as the energy efficiency.

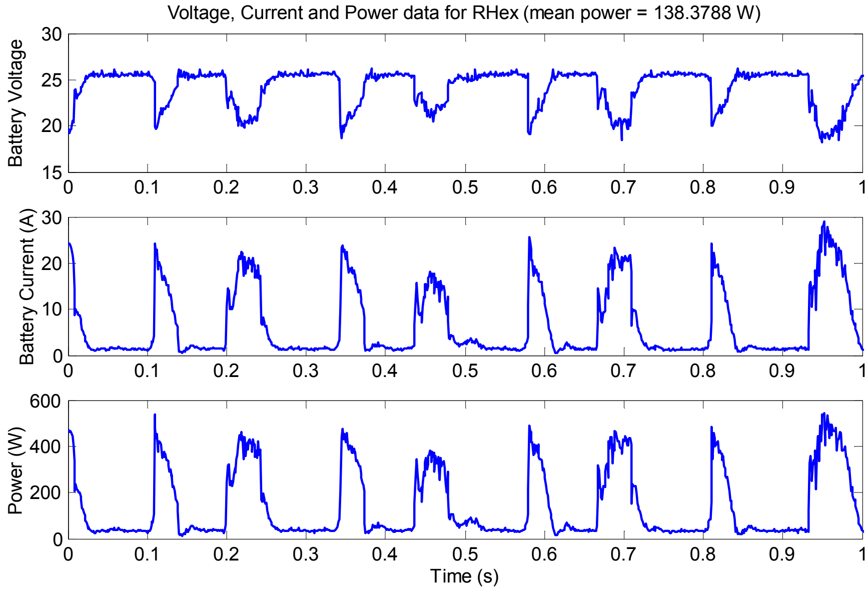


Figure 5: Battery Voltage, Current and Power data during one trial

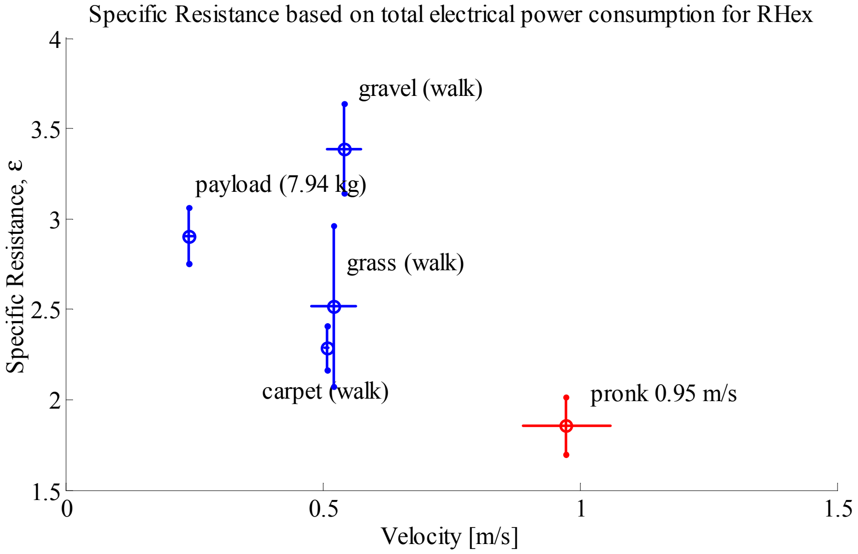


Figure 6: RHex specific resistance during walking and pronking

5 CONCLUSIONS AND FUTURE WORK

We presented an empirically derived pronking controller for RHex that exploits the robot's passive dynamics and achieves pronking at about 1 m/s, with a specific resistance of 1.85, and a success rate of 75% over a 2 m stretch. We have shown that the pronking running gait can increase our robot's forward speed above the maximum speed achievable by its tripod walking gait, while improving locomotion efficiency.

Clearly, the stability (success rate) of the gait described is not yet high enough to be of practical utility. This is likely due to the combination of the open loop nature of the controller and the low inherent damping in the system. The purpose of this paper is to describe the running performance attainable with minimal feedback in our power autonomous, dynamic hexapod. One possible path towards improving the stability of the described controller would be simply to increase the damping in the legs. However, this would also reduce the energy efficiency, and we prefer instead to add active stabilization based on sensing of body pitch and ground forces. This is the subject of ongoing and future work.

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