“Cheap” Rapid Locomotion of a Quadruped Robot: Self-Stabilization of Bounding Gait

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Abstract. The legged animals are capable of rapid, energy efficient, and adaptive locomotion in a complex environment. Toward a comprehensive understanding of the nature of such ecologically balanced legged locomotion, in this paper, we propose a novel method to achieve a form of bounding gait for a quadruped robot by using a minimalistic approach. Although this method uses a simple sinusoidal position control with no global sensory feedback, it is shown that the rapid bounding is possible in a relatively robust manner by properly exploiting the intrinsic dynamics and the interaction with the environment. The behavioral analyses with the robot experiments show that this relatively complicated dynamic locomotion is achieved even with a simple controller mainly because of a self-stabilization mechanism. Moreover, by exploiting this mechanism of self-stabilization, we propose a unique approach to control the forward velocity of the locomotion.

1 Introduction

The locomotion capability is one of the most essential functions for an adaptive robot. However, in order to understand the nature of adaptability, locomotion cannot be seen in isolation, rather a multi-functional perspective is crucial. From this viewpoint, a set of design principles have been proposed for the autonomous agents, which include the principle of “cheap design” [6]. This principle suggests that if a robot could properly exploit the given ecological niche, the control effort could be significantly simplified. The studies of the passive dynamic walking have nicely illustrated this principle [4]. Even without any control and actuation, a robot can achieve a relatively complicated behavior of dynamic walking if it is properly designed for its ecological niche. Another good example is the rapid legged locomotion, since the use of cheap design is particularly important when the temporal constraint of the system is demanding.

The bounding gait is a form of legged locomotion, which is generally observed when a quadruped animal is running at the highest speed. In this gait, the animal lands with both of its front feet and brings the hind legs forward, then lands with both of the hind feet to swing the front legs forward for the next leg step. Biomechanics studies have extensively investigated the mechanisms of this running behavior of the legged animals. The use of the elastic components in the muscle-tendon system has been analyzed and a theoretical model of legged animals, the so-called “spring-mass model” was proposed [1] [5]. In this model, it was hypothesized that an animal’s leg could be approximated by a spring loaded inverted pendulum. Interestingly the studies of the spring-mass locomotion models have shown that, with a proper implementation of the self-stabilization mechanisms, many aspects of rapid legged locomotion can be passive or they require extremely simple controls (e.g. [3] [9]). Based on these biomechanical investigations, the study of running robots has been conducted during last couple of decades, and the mechanism of running behavior has been successfully engineered. The pioneering work by Raibert [8] has shown that the task of a hopping machine can be decomposed into three problems, namely (1) regulating periodic hopping height; (2) maintaining body attitude; and (3) controlling the desired forward speed. Then these control problems can be solved by switching between two control strategies for stance and flight phases. During the stance phase, the robot controls for problems (1) and (2), and during the flight phase, the problem (3) is dealt with. On the basis of this principle, monopod, biped, and quadruped robots have demonstrated dynamical hopping/running behaviors [8]. By following a similar approach, it has been shown that, only by regulating the appropriate angle of attack at touchdown during a flight phase, a quadruped can maintain its balance and control the forward velocity[7]. All these studies are based on a method in which there are two independent control phases. Therefore the robot needs to identify the phase at every computational step by using contact detectors on the feet.

By following the hypothesis of the spring loaded inverted pendulum model, the challenge addressed in this paper is whether it is possible to achieve the bounding behavior of a quadruped robot without sensory feedback at the level of global body function, i.e. no sensory feedback from, for example, gyros, inclinometers and contact detectors. In order to realize such a locomotion method, we have to carefully consider the intrinsic body dynamics which self-stabilizes into a periodic stable gait. Compared to the phase based control scheme, this approach provides a physiologically cheaper design, i.e. no wire transmitting sensory signals is required, and a coherent controller, which reduces the computational cost. Moreover, as shown later in this paper, the coherent control scheme provides the significant flexibility in controlling the locomotion behaviors such as the forward locomotion velocity.

The structure of this paper is as follows. In section 2, we describe the design and control of our quadruped robot which is used for the experiments explained in section 3. Issues leading to further design principles will be discussed in section 4.

2 Design and Control of a Quadruped Robot

2.1 Morphological Design

The robot is designed based on a musculoskeletal model of a canine animal as shown in Figure 1. The physical dimensions of the robot body are as follows: It is 170mm long, 135mm wide and approximately 200mm high (refer to Table 1 for more detailed specifications). The robot has 8 standard digital servomotors (Hitec HS-5945MG) in the shoulder, elbows, hip, and knees. Batteries and a micro controller are also implemented in the robot body, which results in a body weight of 1.5 kg. We employ a three-segment model of animal legs, where two motors and one springy passive joint in the ankle are implemented. We have applied exactly the same leg design to all four legs for the sake of simplicity, whereas the hind and fore legs of animals are generally very different.

In the experiments shown in the following section, we deliberately installed slippery materials on the soles of the robot. The intention of this slippery interaction is two fold: On the

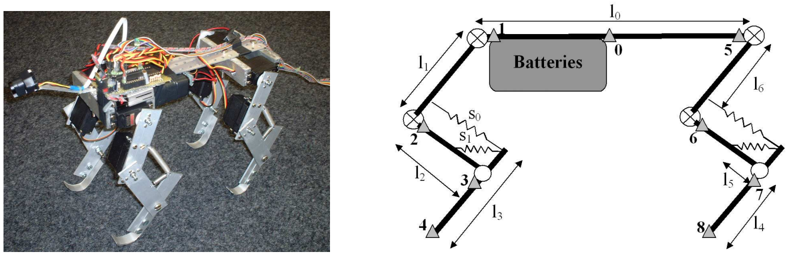

Figure 1: Left: A photograph of the quadruped robot. Right: A schematic of the robot. The circles denote passive joints and the circles with a cross inside denote the joints controlled by the servomotors. The triangles with a number show the locations of LEDs which are used for visual tracking of the body geometry during the locomotion experiments.

Table 1: The specification of the robot mechanical structure

Param.	Description	Value
l_0	length of body	170 mm
l_1	length of upper leg limb	70 mm
l_2	length of middle leg limb	80 mm
l_3	length of lower leg limb	120 mm
l_4	point of lower joint attachment	70 mm
l_5	point of s_1 attachment	45 mm
l_6	point of s_0 attachment	30 mm
s_0	spring constant	13.9 g/mm
s_1	spring constant	20.8 g/mm
m	mass of the robot	1.5 kg

one hand, the informal experiments showed that the robot locomotion requires more torque and it is unstable if the robot has non-slippery interaction. On the other hand, for the running/hopping behavior, the high friction force would not always be required, because of the relatively high vertical force against the ground induced by hopping dynamics. Although it is difficult to quantitatively measure the slipperiness during dynamic interaction between legs and ground, a good estimate could be the coefficient of friction. The static and dynamic coefficients of friction are approximately 0.20 and 0.13, respectively.

2.2 *Controller*

In this paper, we focus only on the hip and shoulder motor controls, i.e. the motors in the elbows and knees are fixed. For the control of shoulder and hip motors, we employ a simple oscillatory position control, and the motor commands are symmetric in terms of the sagittal plane, i.e. the control of two fore legs is the same. The target motor positions are determined as follows.

$$P_f(t) = A_f sin(\omega t) + B_f \tag{1}$$

$$P_h(t) = A_h sin(\omega t + \phi) + B_h \tag{2}$$

where P_f and P_h indicate the target angular positions of the fore (shoulder) and hind (hip) motors, respectively. A and B determine the amplitudes and the set points of the oscillation, and ϕ determines the phase delay between these two oscillations of the fore and hind legs.

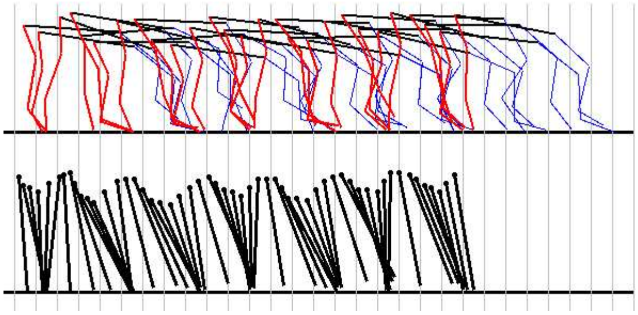

Figure 2: Behavior analysis of a running experiment. The upper graph shows the behavior of whole body extracted from the visual tracking of LEDs attached to the leg joints. The lower graph shows the trajectory of a virtual linear hind leg.

The parameters used in the following experiments are heuristically determined as follows. $A_f = A_h = 25$(degree), $B_f = 20$(degree), $B_h = 10$(degree), $\omega = 7.0$ (1/sec, 0.90 Hz). The coordinate of these set points is set to perpendicular with respect to the spine. This control method does not require any global sensory feedback: The controller does not need to distinguish stance and flight phase, the body attitude or leg angles with respect to the absolute ground plane. Therefore, the main interest of the following experiments is how the robot could self-organize into a periodic gait primarily by the intrinsic body dynamics and its interaction with the environment.

3 Experiments

In this section, firstly, we explain the methods of experiments and behavior analysis. Then, we analyze how the stabilization of the periodic bounding gait can be achieved in the proposed locomotion control. Finally, by exploiting the stabilization mechanism, a control scheme of forward locomotion velocity is proposed.

3.1 Experimental Method

We conducted behavior analysis of the robot movement during the running behavior. In this analysis, first, we attached 9 LEDs at every joint as visual tracking points labeled LED 0 to 8 as shown in Figure 1. Then we recorded the running behavior from a side view by using a standard video camera. These tracking points were extracted by visual tracking processing at 25 frames per second. Figure 2 shows a typical running behavior of the robot as acquired from this visual tracking analysis.

For further analyses explained in this section, we use “a virtual linear (hind) leg”, i.e. a virtual line between the hip joint and toe (LED 5 and 8). For reasons which become clear later in this paper, the running behavior of the robot is well characterized by analyzing the virtual linear leg, instead of using all of the joint trajectories including knees and ankles. A typical behavior trajectory of the virtual linear (hind) leg is shown in Figure 2.

A set of experiments have been conducted in terms of the phase parameter ϕ in equation 2. The reason to focus on the phase parameter is that the self-stabilization mechanism and its use are very well characterized as explained in detail later. In the following experiments, we

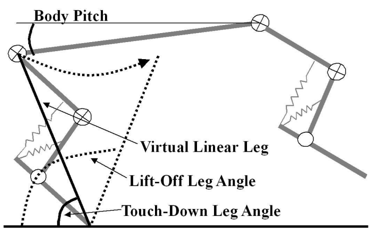

Figure 3: The definitions of touchdown, lift-off angles and body pitch used in the analysis.

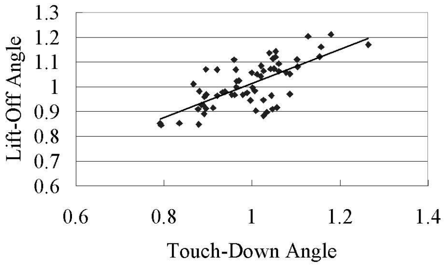

Figure 4: The relation between touchdown and lift-off angles. The touchdown angles and lift-off angles are normalized by the corresponding mean touchdown and lift-off angles.

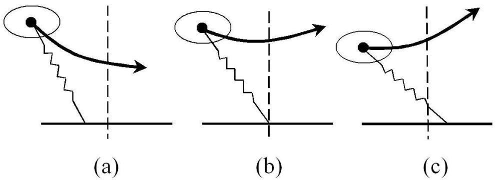

Figure 5: The conceptual illustration of foot placement. If the touchdown angle is appropriate, the trajectory of body mass can be symmetry as shown in (b). Otherwise the lift-off angle can be higher (a) or lower (c).

analyzed the behavior of 6 leg steps from a side view. We repeated the same experiments by changing the phase parameter ϕ from -1.6 to 0.2 (radian) by 0.2 step. This range of the parameter is chosen based on informal experiments, in which a stable bounding gait is possible.

3.2 Stability Analysis

To achieve the stable periodic gait, the legs need to touchdown and lift-off at constant angles with respect to the ground plane. In this subsection, we first analyze the behavior of a hind leg and elaborate the self-stabilization mechanism of the bounding gait. More specifically, by analyzing touchdown and lift-off angles of a virtual linear leg, we explain how the controller is interacting with the environment which leads to the stable gait. Secondly we focus on how the self-stabilization mechanism could result in a whole body coordination by analyzing the dynamics of body pitch. (The touchdown, lift-off angles and the body pitch are explained in Figure 3.)

Self-stabilization during the Stance Phase

In the first analysis, we measured the touchdown and lift-off angles of the virtual linear hind leg with respect to the ground plane (the absolute coordinate) by using joint geometries gained from the visual tracking. The touchdown angles and the successive lift-off angles (the lift-off angles following the corresponding touchdown angles) of 60 leg steps are normalized by the mean touchdown and lift-off angles respectively, and are plotted in Figure 4. As shown in the figure, the lift-off angle is, on average, proportional to the touchdown angle, i.e. the lower touchdown angles result in lower lift-off angles, and vice versa.

It has been found that the angle of attack at touchdown is one of the most important parameters for a legged running behavior [8] [9]. The basic principle is illustrated in Figure 5. In this principle, if the touch down angle of a linear springy leg is appropriate, the trajectory

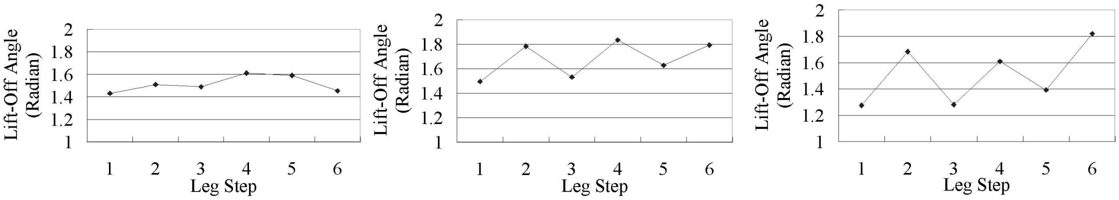

Figure 6: Typical transitions of lift-off angles with different phase parameters. (The phase 0.2 (Left graph), 0.8 (Middle), and 1.0 (Right) radian.)

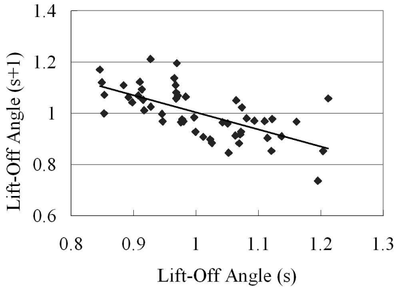

Figure 7: Relation between the normalized lift-off angles of two successive leg steps. The variable s represents the index of leg step.

of the body mass can be symmetric with respect to the vertical line at the foot contact, as shown in the middle illustration. Otherwise the lift-off angle can be lower or higher. Figure 4 shows that this principle holds also for the experimental results of the virtual linear leg.

Self-stabilization during the Flight Phase

In the next analysis, we analyze the stabilization of locomotion during the period of several leg steps by using the same joint geometry data above. As shown in Figure 6, the fluctuations of successive lift-off angles against the ground are generally maintained within a certain range. To show this more clearly, the relation between two successive lift-off angles is plotted in Figure 7. This figure shows that, when a lift-off angle is lower than average, the subsequent lift-off angle tends to be larger, and vice versa. Given the relation between touchdown and lift-off angles during the stance phase, the leg behavior during the flight phase is typically such that a lower lift-off angle leads to a higher touchdown angle and vice versa, which results in the stable gait over multiple leg steps.

It has been shown that the principle of foot placement can be used for the speed control of some legged hopping robots by adjusting the touchdown angle during a flight phase [8] [7]. However, in this experiment, the angle of attack was not controlled but self-stabilized without sensory feedback; the robot cannot recognize flight/stance phase nor the body pitch to estimate the touchdown angle of the legs.

Full Body Coordination

By using the same joint geometry data above, we analyzed the movement of the body pitch. The body pitch is measured as the angle of spine with respect to the ground plane as shown in Figure 3. Figure 8 shows a few typical angular movements of the body pitch. As shown in these graphs, the spine rotation is changed from a steep zigzag movement to a relatively stable flat movement depending on the phase. The average angular velocity against the phase

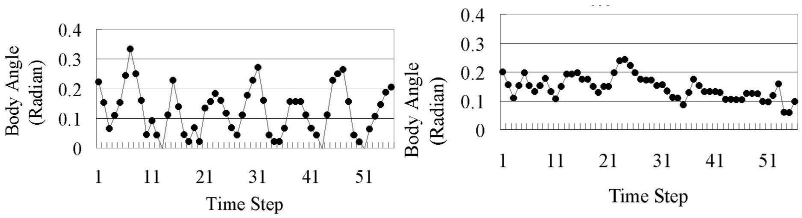

Figure 8: Typical time series movement of body pitch with respect to the ground plane. The phase parameter of 0.2 (Left graph) and -0.8 (Right) radian.

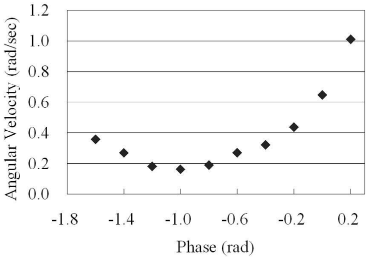

Figure 9: Average body rotational angular velocity versus the phase parameter.

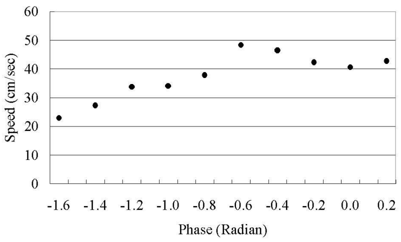

Figure 10: Average speed versus the phase parameter.

parameter is plotted in Figure 9, which shows that the movement of body pitch as measured by angular velocity accurately corresponds to the phase between front and hind leg oscillations. This is possible only when the front and hind legs are self-stabilizing their touchdown angles. More precisely, to maintain a constant touchdown angle with respect to the ground plane, the motor angles of hip at touchdown, i.e. $P_h(touchdown)$ in equation 2, should be changed according to the phase parameter, which would result in this characteristics of body pitch movement.

3.3 Forward Speed Control

In this section, the forward locomotion speed with respect to the phase parameter ϕ is analyzed. The velocity is also visually estimated by using the center of the body (LED 0), where we measured the horizontal distance traveled and the duration during 6 leg steps for the values of the phase parameter ϕ. As shown in Figure 10, the speed can be controlled in the range from 20 to 50 cm/sec by changing the phase. A possible explanation of the speed difference shown in this figure could be that, considering the fact that relatively higher velocity is achieved at a larger body movement, i.e. the phase range from -0.4 to 0.2, the fluctuation of body pitch could provide smaller touchdown angle even with the same amplitude of motor oscillation, which is required for the faster legged locomotion. An explanation of the relation between the phase and the forward locomotion speed need to be corroborated, but, at least, this experimental result shows that the speed of locomotion can in principle be controlled by changing only the phase parameter.

4 Discussion

The findings discussed in this paper are of potential interest to both engineers and biologists. One of the most significant contributions is that the proposed control scheme adds another variation of rapid bounding locomotion method. In most of the existing controllers for the bounding behavior, the controllers need to detect two states, i.e. flight and stance phases, whereas it requires no need of the global state recognition in the proposed method.

From an information theoretic viewpoint, there are a number of interesting aspects. Firstly, the flow of information is unidirectional and there is no signal feedback loop running all through the body, but the loop is only local, i.e. only in the servomotors. This experimental result achieved by a synthetic investigation could help understanding the physiological nature of legged rapid locomotion. Secondly, the control of speed cannot be computationally cheaper than the proposed phase control, since there is no sensory feedback, on the one hand, and the phase is equivalent to a low-pass filter or a simple time delay, on the other. Given the fact that the property is possible mainly due to the self-stabilization mechanism, the design of controller strongly depends on the stabilization mechanism including the morphological design of legs and body. From this perspective, although we only focus on a simple sinusoidal position control, the adaptability of the controller (e.g. the biological controller models investigated by [2]) would be another interesting topic to be investigated in the future. Thirdly, it is also worth to mention that, owing to the self-stabilization mechanism, there are many other parameters such as the frequency, the set points, and the spring constants (if possible) which can potentially control the forward velocity in addition to the phase parameter. The diversity and the flexibility of the proposed control scheme is another interesting aspect to be explored further.

Acknowledegements

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