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Velocity Control of a Bounding Quadruped via Energy Control and Vestibular Reflexes

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Abstract

In this paper a bio-inspired approach of velocity control for a quadruped robot running with a bounding gait on compliant legs is set up. The dynamic properties of a sagittal plane model of the robot are investigated. By analyzing the stable fixed points based on Poincare map, we find that the energy change of the system is the main source for forward velocity adjustment. Based on the analysis of the dynamics model of the robot, a new simple linear running controller is proposed using the energy control idea, which requires minimal task level feedback and only controls both the leg torque and ending impact angle. On the other hand, the functions of mammalian vestibular reflexes are discussed, and a reflex map between forward velocity and the pitch movement is built through statistical regression analysis. Finally, a velocity controller based on energy control and vestibular reflexes is built, which has the same structure as the mammalian nervous mechanism for body posture control. The new controller allows the robot to run autonomously without any other auxiliary equipment and exhibits good speed adjustment capability. A series simulations and experiments were set to show the good movement agility, and the feasibility and validity of the robot system.

Keywords: legged robots, biologically-inspired robots, biomimetics, energy control, vestibular reflexes

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Nomenclature

m	Body mass	kg
I	Body inertia	kg·m^2
K	Spring stiffness	N·m^{-1}
B	Damping coefficient	N·m^{-1}·s^{-1}
x	C horizontal pos.	m
y	C vertical pos.	m
θ	Body pitch angle	rad
φ	Leg angle relative to the body	rad
γ	Leg angle relative to the vertical	rad
α	Body yaw angle	rad
β	The action angle	rad
l_0	Leg resting length	m
l	Leg length	m
τ	Torque at hip	Nm
L	Half body length	m
W_{in}	The system energy input	J

Subscript

td	Leg touch down
end	Ending impact
f or r	Front leg or rear leg
k	The number of step
d	The desired state

1 Introduction

Running is a form of legged locomotion characterized by traveling at high speed and by periods of ballistic flight during which all feet leave the ground[1]. There are two main reasons for exploring dynamically stable running control methods for locomotion, namely mobility and to gain an understanding of animal locomotion[2].The basic control task is to establish a pattern of leg and body motion that stabilizes the attitude and movement of the body while propelling it in the desired direction at the desired speed[3]. The characteristics of high speed and ballistic flight suggest that dynamics and active stability are important for accomplishing this control task and improving our general understanding of running.

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A number of quadruped robot prototypes capable of dynamically stable running have been built using various control approaches[4–7]. Unlike statically stable robots, dynamically stable robots can be controlled to tolerate departure of the center of mass from the support polygon formed by the legs in contact with the ground[8]. Raibert's monopod hopper was the first dynamically stable running robot[2]. Contacting with the leg stance phase is typically modeled with the Spring-Loaded Inverted Pendulum (SLIP) model[2], whereby the spring stores the potential and kinetic energy in the first portion of the stride, and releases it in the second portion to produce leg liftoff. Using this basic theory, Raibert revolved around the three-part controller principles, which control hopping height, forward velocity and body posture to make complex gaits possible in one-, two-, and four-legged robots[9–11], and even in the BigDog system[12].

One recent design for dynamically stable legged robots is used in the KOLT quadruped robot[13,14], which uses direct adaptive fuzzy control to operate one leg at speeds necessary for gallop[15], and successfully execute high-speed turns over a range of speed and turning rate[16,17].

SCOUT II was the first physical robot to achieve stable galloping with under-actuated compliant legs[18–21]. It achieved stable running at speed of up to 1.3 m·s^{-1} by positioning the legs at a desired touchdown angle. In another robot, PAW, a Levenberg-Marquardt learning algorithm was used to modify Raibert's velocity controller to allow adequate tracking of the velocities between 0.9 m·s^{-1} and 1.3 m·s^{-1} during bounding[22,23]. It was shown that even compliant movement and a simple controller can be used to stabilize running.

Currently, SCOUT II uses touchdown and liftoff angles, hip torques as the control input for the stable bounding[24]. The robot's controllers modify these elements to adapt to the desired velocity, desired turning rates, and the terrain. The influence of impact is also considered as a control parameter[25]. Raibert defined forward velocity as the key parameter in adjusting robot locomotion, and other researchers have discussed the possibility of controlling hopping height for overcoming obstacles. However, the control of forward velocity of the robot is an appropriate starting point and the main purpose for dynamically stable locomotion[23].

The purpose of this study is to find a way of controlling the velocity of a robot, which contains the similar functions as the mechanisms of the mammal's locomotion adjustment. We have built a robot, shown in Fig. 1a, inspired by SCOUT II for testing purposes. The robot consists of a spine with four compliant legs, and is equipped with an Inertial Measurement Unit (IMU, Crossbow NAV420) to sense the robot's locomotion state, and a linear potentiometer for each leg that senses the length of the leg to judge touchdown and liftoff events thereby detecting the movement phase[8].

In sections **2** and **3**, the energy control idea is introduced, and the effects of various hip torques and impact angles on the robot's motion under the idea of controlling the energy input are discussed. In section **4.1**, the function of the vestibular reflexes during quadruped bounding is discussed, and the correlation between vestibular feedback and the bounding states is ascertained through data analysis. In section **4.2**, a bio-inspired velocity control method is built based on energy control and vestibular reflexes to generate a stable and speed-adjustable bounding gait. Finally, in section **5**, the simulations of velocity feedback and vestibular reflex bounding are compared, and the results demonstrate the simplicity, feasibility and validity of the velocity control method.

2 Passive dynamics of bounding

2.1 Bounding model

The template model for the passive dynamics of robot bounding is shown in Fig. 1b, and was discussed in a previous paper[8]. According to the virtual leg concept[2], the front and rear physical legs can be replaced by single front and rear virtual legs, respectively.

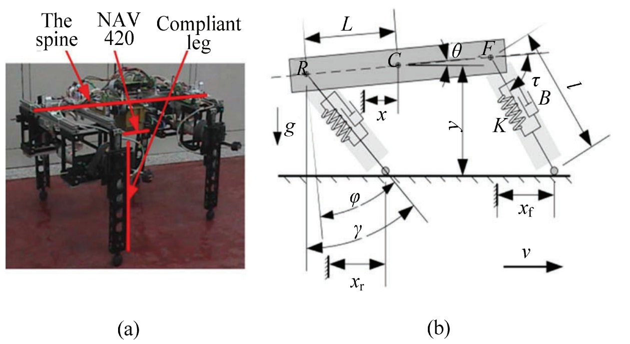

Fig. 1 (a) Photograph of quadruped robot used for exercise and (b) the sagittal plane running model. The variables in this figure are listed in Nomenclature and Subscript.