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A Parallel Actuated Pantograph Leg for High-speed Locomotion

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Abstract

High-speed running is one of the most important topics in the field of legged robots which requires strict constraints on structural design and control. To solve the problems of high acceleration, high energy consumption, high pace frequency and ground impact during high-speed movement, this paper presents a parallel actuated pantograph leg with an approximately decoupled configuration. The articulated leg features in light weight, high load capacity, high mechanical efficiency and structural stability. The similarity features of force and position between the control point and the foot are analyzed. The key design parameters, K_1 and K_2, which concern the dynamic performances, are carefully optimized by comprehensive evaluation of the leg inertia and mass within the maximum foot trajectory. A control strategy that incorporates virtual Spring Loaded Inverted Pendulum (SLIP) model and active force is also proposed to test the design. The strategy can implement highly flexible impedance without mechanical springs, which substantially simplifies the design and satisfies the variable stiffness requirements during high-speed running. The rationality of the structure and the effectiveness of the control law are validated by simulation and experiments.

Keywords: high-speed, parallel actuated pantograph leg, optimization, virtual SLIP model, active force

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Nomenclature

m (kg)	Mass
J (kg·m^2)	Inertia
x (m)	C horizontal position
y (m)	C vertical position
θ (rad)	Angle
l (m)	Leg or leg component length
L (m)	Length
τ (N·m)	Torque at hip
u (m·s^{-1})	Horizontal speed
d (m)	Distance
F (N)	Output force or applied force
ρ (kg·m^3)	Material density
A (m^2)	Cross-sectional area
S (m^2)	Area
h (m)	Hopping height
$\bar{I}$ (kg·m^2)	Average inertia
$\bar{I}'$ (kg·m^2)	Simplified average inertia
D (m)	Inner diameter of the cylinder
T (s)	Period
v (m·s^{-1})	Speed
α	Minimum value
β	Maximum value
$\boldsymbol{M}$	Inertia matrix of the leg

Subscript

t	Thigh
s	Shank
td	Leg touch down
h	Horizontal hydraulic cylinder
v	Vertical hydraulic cylinder
x	Direction of x axis
y	Direction of y axis
Ω	Maximum foot trajectory
i	Point name, $i \in \{O,P,Q,A,B\}$
k	Sub target k
scap	Scapular
step	Step length
SLIP	Virtual leg
thrust	Thrust along the virtual leg
st	standing phase

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1 Introduction

High-speed running is one of the most important topics in the field of legged robots which requires strict constraints on structural design, control and state perception. Many research groups have made substantial effort to achieve this goal[1–4]; and Boston Dynamics set a new speed record for quadruped robot galloping of 47.15 $km \cdot h^{-1}$. However, few quadruped robots rival the high-speed running of animals. The fastest animal – the cheetah – could accelerate from a static position to nearly 120 $km \cdot h^{-1}$ in 5 s with each step of approximately 6 m to 7.6 m. Cheetahs exchange their legs from 2.5 Hz to 4 Hz when running at 72 $km \cdot h^{-1}$. The average ground contact time, which is extremely short, is approximately 60 ms to 70 ms[5]. To solve the challenging problems, such as high acceleration, high energy consumption, high pace frequency, ground impact[6], and strong nonlinear coupling, many researchers have explored leg design by learning from nature.

A high speed running requires a high pace frequency with a low duty ration of the standing phase[7], and the pace frequency is closely related to the configuration of the leg. A leg configuration with the properties of light weight, low inertia and energy-efficiency is required to reduce the backswing time, minimize body pitching motion in the flight phase, and reduce energy consumption to maintain a long running period.

Some researchers focus on reducing the mass of a leg and converging the mass to the proximal part of the body[8–10]. Lewis tried to combine lightweight actuators with passive elements to imitate the highly explosive force mechanism of cheetah leg by abruptly releasing the energy that is stored in springs and compressed gas[8]. In the Cheetah-Cub robot[9], leg actuators were installed in the body *via* a cable-type transmission mechanism. However, a cable-type transmission or pressed air actuators may bring compliance to the system and reduce the control accuracy. The MIT-cheetah developed by Hyun *et al*. employed link mechanism to move the leg actuators up to the hip joints, making 90% of the leg mass converged to the hip joints, and achieved a maximum speed of 24.12 $km \cdot h^{-1}$[11].

Besides the mass, power consumption of the hopper determines the physical sizes of the actuators that will also affect the structure design. As the fundamental step, hopping gaits should be achieved with minimal power consumption by mechanical design. However, most existing legged robots adopt a serial-actuated articulated leg design with each joint correspond to one actuator independently. The coupling movement between the hip and the knee renders it inefficient during running, whereas the decoupled configuration may be a better choice for leg movement. Waldron *et al*. noted the internal energy dissipation problem of serial driving[7]. Cleather *et al*. introduced a ‘parallel actuated’ mechanism inspired by biarticular muscles of animals to achieve high-efficient movement, within which an actuator spans two joints[12]. Using the straight leg model of Cartesian coordinate form, Alexander stated the relation between decoupled configuration and working efficiency[13]. Based on the key points, a ramification of four-bar linkage termed ‘pantograph’ is introduced into robotic fields[14]. It is light weight, low inertia and decoupled driving. The parallelogram linkages and homothetic triangle mechanism are assembled together to enable the foot to follow the control point in constant proportion. The quadrilateral links connect the hip and knee joints to prevent a singular configuration and knee inversion. These properties are concordant with Fischer’s study on multi-joint muscles in mammals[15], which have similar ability of enhancing stability. The ‘pantograph mechanism’ was also extensively applied to many other robotic systems such as biped[16], quadruped[17], hexapod[7] bionic robots and industrial robot arms. Yang *et al*. investigated the pantograph mechanism of a non-traditional manipulator structure[18]. However, the majority of ‘pantograph’ legs have only been applied to static gaits at low speed, and a completely decoupled configuration of horizontal and vertical actuators has been used to minimize energy loss. A maximum working space is pursued based on the application demand for detecting unknown environments. In contrast, the step length and pace frequency are more important for high-speed locomotion. A completely decoupled configuration of separated control points will also produce relatively loose shoulder/hip shapes with great body weight. Boston Dynamics initially introduced the ‘pantograph leg’ to high-speed running with an adjustment of combining control points in 2012[19]. Relevant design details and control information have not been released, and MIT-cheetah adopted a similar three-segmented pantograph leg.

To construct a configuration and control framework