Available online at www.sciencedirect.com
ScienceDirect
Journal of Bionic Engineering 12 (2015) 352–360

Innovative Design and Performance Evaluation of a High-speed Bionic Mechanical Leg

Hua Nie, Ronglei Sun, Chaoke Guo, Guohua Qin, Huiyang Yu

State Key Lab of Digital Manufacturing Equipment and Technology, *Huazhong University of Science and Technology*, *Wuhan* 430070, *China*

Abstract

For most legged robots the drive-motors are mounted on the joints of legs, which increase leg's mass and rotary inertia. When mounted on legs, the drive-motor has to rotate clockwise and anticlockwise periodically to swing a leg back and forth. Larger inertia of the leg, as well as the ever-changing status of frequent acceleration and deceleration of the motors, limits the moving speed of the legged robots. This article proposes an improved mechanical design to overcome such problems. All the drive-motors are installed on the robot body to reduce the rotary inertia of the legs. Then a crank-rocker mechanism is used to transform continuous rotation of motors to back and forth motion of the leg. With this scheme, the motor may reach higher rotation speed since it drives a lighter leg with no change of the rotation direction. In addition, an elastic tendon is attached to the ankle to reduce the pulse stress on the leg. Kinematics and dynamics analysis demonstrates that the new design enlarges end-workspace, reduces driving torque and increases ground reaction force, which means the new robot has lager stride and higher swing frequency of leg to achieve faster moving.

Keywords: high-speed, mechanical design, bionic leg, dynamics

doi: 10.1016/S1672-6529(14)60127-X

1 Introduction

In the last decades, bionic legged robots have been developed to increase robots' adaptation to different environments such as grassland, snowfield, muddy road, *etc*. Since 2000, legged robots like Aibo[1], BISAM[2], KOLT[3], Tekken[4], TITAN[5,6], LittleDog[7] and HYQ[8,9], Baby Elephant[10] and MBBOT[11] have been developed in succession, of which BigDog[12,13] is the most representative one. It possesses the ability of strong anti-interference to adapt different ground surfaces. The stability and gait are major concerns of these legged robots. Since driving actuators mounted on the leg joints, which increase leg-mass and rotary inertia, the speed of these robots is low.

Recently, more attentions are drawn to cheetah-like robot because of its ability of achieving high-speed running. Generally speaking, two methods contribute to the high speed of cheetah robot. One effective way is to change the leg morphologies, such as decreasing the inertia of the distal leg and introducing compliance. Another feasible way is the utility of high-power actuators[14,15]. Our study focuses on the leg morphology of motor-driven cheetah robot. Many researches have been carried out in such field. MIT Robotic Cheetah[16–19] could run up to 10 mph and jump over a 33 cm high obstacle. ASLP cheetah-cub[20–23], whose speed could reach 6.9 times of its body length, is the fastest one among robots with less than 30 kg mass. These two robots achieve high-speed running mainly by two techniques. One is reducing the leg mass. All motors of these two robots are mounted directly on the body, which reduces leg masses. Second is using mechanical compliance to reduce the leg impedance. MIT Robotic Cheetah adopts the tendon-bone co-location architecture and ASLP cheetah-cub uses a passively spring loaded (diagonal spring) mechanism to increase the leg's compliance. However, motors of these robots require clockwise and anticlockwise rotation periodically when the leg swings back and forth, which reduces the working efficiency of the motors. Improving working mode of the motor could further enhance the speed of the

Corresponding author: Hua Nie
E-mail: niehua@hust.edu.cn

cheetah robot.

Based on the above analysis, our research focuses on mechanical design of the high-speed bionic mechanical leg from the aspects of reducing leg mass, introducing compliance and improving working mode of the motor. Kinematics and dynamics model are built to analyze the performance of the new leg model. The rest of this paper is as follows: Section **2** describes mechanical design of the high-speed bionic leg. In section **3**, three performance indexes are proposed to evaluate the performance of the new leg. Furthermore, the leg prototype manufacturing and physical experiments are shown in section **4**. The conclusion and possible future research are given in section **5**.

2 Mechanical design

2.1 Mechanical improvements and transmission

It is known that decreasing the mass of the leg and improving the working mode of the motor are important to increase the swing speed of the mechanical leg. According to these two principles, three mechanical improvements are proposed. First, all motors are mounted on the body instead of the legs of the robot to reduce the leg mass. The motor driving the knee joint weights almost 700 g in our study, which is more than half of the total weight of one leg. A sprocket mechanism is thus designed to transmit the driving torque to the knee joint (Fig. 1). Second, a crank-rocker mechanism (Fig. 1) is added to each motor shaft. Previous motor shaft was connected to the joint axes directly. Motors need constantly forward and reverse rotation when the leg swings back and forth. This kind of movement limits the moving speed of the leg. To avoid this defect, a crank-rocker mechanism is added between the motor and the joint, which can transform the continuous rotation of the motor to the swinging back and forth of the leg. Third, a parallel four-bar linkage is designed to add a joint of the leg. Inspired by the skeletal structure of cheetah[17,20], most researchers choose the three-segment swinging model to design the leg. As two active Degree of Freedoms (DOFs) are sufficient for the end to reach any position on the plane, a parallel four-bar linkage is added to couple knee joint and ankle joint.

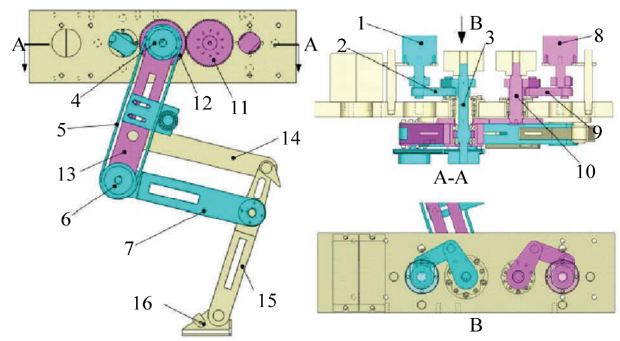

Fig. 1 The assembly drawing of the leg: 1-knee motor, 2-knee crank rocker, 3-spindle, 4-driving sprocket, 5-chain, 6-driven sprocket, 7-tibia, 8-hip motor, 9-hip crank rocker, 10-gear shaft, 11-driving gear, 12-driven gear, 13-femur, 14-parallel four-bar linkage rod, 15-tarsus, and 16-phalange.

Our leg morphology is designed based on the skeletal structure of the cheetah. A three-segmented, pantograph is implemented for the leg. Each leg is actuated by two servo motors which are mounted directly on the body. The role of the hip motor is protracting (swing forward) and retracting (swing backward) the leg. The knee motor provides flexion-extension motion of the leg. For further description, two transmission chains, one of which drives hip joint and another drives knee joint, are marked pink and blue respectively in Fig. 1. Blue chains: the knee motor (1) energizes the knee crank-rocker (2). The rocker of knee crank-rocker and driving sprocket (4) are fixed with both ends of the spindle respectively. Thus rotation of rocker drives the tibia through the driving sprocket. Pink chains: the hip motor (8) energizes the hip crank-rocker (9). The energy is transmitted to the femur (13) through the gear shaft (10) and a set of gear, where the driving gear (11) is fixed with the gear shaft and the driven gear (12) is fixed with the femur. At last, the tarsus (15) driven by the parallel four-bar linkage moves along with the tibia.

2.2 The tendon mechanism

Biological researches[24,25] found that the animal tendon (Fig. 2c) could improve the stress condition of the tarsus, buffer the ground impact, reduce the stiffness of the leg and enhance the motion performance. Based on the merits above, an elastic tendon is added between the tarsus and the phalange (Fig. 2b). The tendon starts at the tiptoe (A), bypasses point (E), the phalangeal joint, and finally connects to heel (D).

To better illustrate the role of the tendon, the stresses in the components of the leg caused by the ground reaction force will be calculated. Fig. 2a and Fig. 2b describe the design of the leg without and with a tendon. The stresses of the tarsus with and without the tendon are calculated, which are respectively presented