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Modeling, motion planning, and control of one-legged hopping robot actuated by two arms

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Abstract

A new underactuated one-legged hoping robot model is proposed for researching the utilization of the elastic energy of underactuated flexible mechanical system repeatedly, and researching the motion control method for underactuated hopping robots with dynamic balance. Only two arms actuate the hopping robot, the single elastic leg of the robot has no actuator, thus the coupling between the arms and the unactuated leg controls the hopping motion. The modeling, motion planning, and control method are investigated for this kind of hopping robot. A new time-varying feedback control algorithm is suggested based on the nonlinear transformation of inputs locally. It is shown that controlling the orientation and vibration of the leg would be essential for hoping stably, and controlling the motion of center of mass of the system can control the moving speed in horizontal direction. Some numerical simulations verified some aspects of the feasibility of the proposed model and control method.

Keywords: Hopping robot; Underactuated; Nonholonomic; Dynamic control

1. Introduction

Hopping robot has better mobility in a natural environment for the motion style, with intermittent stance and flight. It can move with great speed and maneuverability even on rough terrain. A great capability in evading obstacles indicates that the hopping robot may be suitable for reconnaissance tasks [1]. The dynamic balance and special motion style of the hopping robot can provide a fundamental research bed for passive walking robot or running robot [2–6]. The simple mechanical construct of a one-legged robot also provides a perfect test bed for studying on the control theory of nonholonomic mechanical systems. The hopping robot holds many scholars interests in recent years, and had been reported in many publications.

One-legged system is the main research focus for hopping robot in the past three decades. Raibert and his coworkers have significant contribution in the development of hopping robot. They had fabricated several

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experimental robot systems such as 2D [2,3], 3D [4] one-legged hopping robot and biped gymnastic robot [5,6] in order to understand the legged systems that hop and run. Since then, many new hopping and running robots with complex kinematics have been proposed based on the Raibert's research. For instance, Hyon and Mita designed a biologically inspired hopping robot-''Kenken'' that is actuated by hydraulics [7]. Leavitt and his coworkers designed an acrobot-like hopping robot that is actuated pneumatically [8]. Taghirad designed a hopper that is actuated electrically [9]. Iida et al. designed a pendulum driven hopping robot [10]. Hyon and Emura designed a passive one-legged hopper [11]. Shimoda designed a hopping robot for microgravity environment [12]. Gregorio et al. designed an electrically actuated hopping robot ''ARL Monopod'' [13]. Zeglin fabricated a bow leg hopping robot [14]. Stoeter and Papanikolopoulos fabricated a small cylindrical jumping scout robots [15]. Most these studies have used Raibert's controller based on the Spring Loaded Inverted Pendulum (SLIP) model [16]. The SLIP model, which consists of a point-mass on a springy leg, is the minimum model for running. The dynamic balance principle and motion control method can be investigated more thoroughly for the simple mechanical system. For instance, Vakakis and Burdick et al. investigated the chaotic motions in the dynamics of point mass hopping robot, and a strange attractor was developed [17,18]. They find the strange attractor can be controlled and eliminated by tuning an appropriate parameter corresponding to the duration of applied hopping thrust. Burdick and Fiorini also proposed a novel approach to the design and deployment of small and minimally actuated jumping or hopping robots suitable for exploring the unstructured terrains of celestial bodies [19]. For increasing energy autonomy of the hopping robot, Papadopoulos and Cherouvim find that there exists a particular passive gait which leads to the least dissipated energy [20,21]. The result is based on the research of Ahmadi and Buehler [22]. In recent years, Collins, Ruina and their coworkers [23] built the first three-dimensional, kneed, two-legged, passive dynamic walking machine that extended the work of McGeer [24], in which McGeer introduced a new concept of passive dynamics firstly. The passive dynamic walker has no actuator but can walk downhill with human-like gait, and can walk on level-ground when one substitutes gravitational power with a suitable small actuator [25]. However, neither a full passive dynamic walker [24] nor a passive hopping robot is an animalized robot system, because of their limited movement capability.

Since the SLIP is represented by a point mass at center of mass (COM), the dynamic coupling of multi-degree of freedoms (DOFs) mechanical system is not considered. Nevertheless, the dynamic coupling is helpful for improving the dynamic property of jumping or running robot in some circumstances. For example, swing of arm of human being can help balance in walking and running, and augment the stride in walking, running and jumping. In track and field sports such as high jump, long jump, trampoline, diving, discus, shot, javelin, etc., swing the arms affects the result effectively. Thus researching on the dynamic coupling of hopping or running robot with non-SLIP model can get better understanding the dynamic balance and motion control method for legged systems.

In this paper, we proposed a new hoping robot model, which moves in vertical plane. Two arms of the hopping robot are actuated, but the elastic telescopic leg is not equipped with an actuator. The dynamic coupling between the arms and the leg controls the motion of the system. Thus the hopping robot is underactuated and the main aim is to find a method that can control the system by internal coupling. Works, similar to that which lead to this paper, is reported in Ref. [10], in which a pendulum driven hopping robot was studied. Since the pendulum driven hopping robot has four feet, the system can stable stand statically. However, differing from work introduced in [10], the hopping robot in this paper is unstable statically. The two arms must control the motion of the system with dynamic balance simultaneously.

2. The model

Fig. 1 shows the model of the hopping robot, of which the single telescopic leg consists of two segments. One segment of the leg is nonzero mass and another is massless. The length of the segment with nonzero mass is l_1, the mass of it is m_1, and the center of mass lies in the middle of the length. The massless segment has length, l_2, is connected to the former by linear spring serially with same axis line. The stiffness of the linear spring is k. The length of the two arms is the same as r, and the mass is m_2, respectively. The center of mass of the arm lies at its end. The two arms are hinged at the top of the nonzero mass segment of leg. Defining the general coordinates of the model are $(x_0, z_0, l_2, \varphi, \theta_1, \theta_2)$, of which (x_0, z_0) is the position of the foot toe in the