Mechatronics 29 (2015) 1–12

Contents lists available at ScienceDirect

Mechatronics

journal homepage: www.elsevier.com/locate/mechatronics

Modeling, design, and implementation of a baton robot with double-action inertial actuation

Joe Zoghzoghy, Junkai Zhao, Yildirim Hurmuzlu *

Mechanical Engineering Dept., 3101 Dyer St, Dallas, TX 75275, USA

ARTICLE INFO

Article history:
Received 14 February 2014
Accepted 19 April 2015
Available online 23 May 2015

Keywords:
Inertial actuation
Baton
Locomotion
Control
Robotics

ABSTRACT

In this paper, we present a baton locomotor capable of generating tapping gait. A baton is a system that consists of two masses joined with a massless rod. We use a new double-action inertial actuation scheme to drive this system. This scheme employs two spinning pendulums at one end, turning in opposite directions with the same angular velocity. One can control the direction and magnitude of the resultant inertial force that propels the system by changing the rendez-vous angle and the angular velocity of the spinners. In this paper, we first present the modeling of the system with actuation on both ends. Then, we use a numerical approach to simulate and analyze the tapping gait of the inertially actuated baton. In addition, we developed a new prototype, Pony II robot, to establish the practicality of the concept. This prototype consists of the double-action spinners mounted on both ends of the baton. The mechanical and electronic components of the robot are also presented in full detail. Finally, we demonstrate that the robot can successfully generate periodic tapping gait.

1. Introduction

One of the earliest mobile robots developed in the literature were hopping machines [1,2]. The motion of these robots can be described as continuous jumping and landing in the vertical direction. Alternatively, people also developed legged machines that can produce locomotion similar to that of biological organisms such as bipeds and quadrupeds, [3–12]. These robots rely on the action of the legs to achieve progression.

Spring-based mechanical systems have been used to generate jumping. In general, a motor stores potential energy in a spring, such as the 7 g Miniature robot [13]. A spring-like shell is used in the case of the Jollbot [14]. A release mechanism produces the impulsive forces, at the level of the legs, sufficient to generate a jump. Even with the high power-to-weight ratio of springs, these systems are not very successful in producing consecutive hopping motions. This is mainly due to a long actuation cycle, premature jump before the full energy transfer to the legs, or the difficulty of the robot to land on its legs.

Fluid-power based jumpers employ for example pneumatic actuators that provide controlled high forces with fast actuation cycles. The main inconvenience with such systems is the dependence on a compressed fluid, which leads to a tethered robot or adds a heavy high-pressure tank/compressor. The Sandia Hopper [15] is a fluid-power based jumper that uses combustion of propane in a cylinder to push a piston against the ground. Although capable of generating high jumps, this system faces many difficulties: obtaining a favorable fuel-to-air ratio, requires heat dissipation, and produces semi-random jumping directions. Hence, this robot lacks the capability to produce consecutive jumps.

Inertia-based systems rely on transfer of momentum to initiate a jump. An example of momentum-initiated jump is when a human being jumps vertically while swinging their arms in a pendulum-like motion. Lees et al. [16] have shown that this motion can enhance the jump by up to 28%. This pendulum like motion have been utilized in several designs [17–23]. Although successful, the produced jumps and progression velocities were too small compared to the size of the actual robot.

In this article we consider a new robotic system which relies on inertial actuation. This robot represents a baton system, which was previously developed in [24] based on the theory presented by Tavakoli and Hurmuzlu in [25]. A baton is a member of a family tree of robotic mechanisms. It consist of two masses joined by a connection rod. Using a highly simplified model, it was demonstrated that this locomotor can generate different gait types, when placed on an inclined plane (passive locomotion [26]), or actuated with impulsive forces (active locomotion [27]). Several gaits generated by the baton can neither be characterized as hopping nor legged locomotion. In fact, they are hybrid of the two. These gaits

* Corresponding author.
E-mail addresses: joezogh@gmail.com (J. Zoghzoghy), junkaiz@smu.edu (J. Zhao), hurmuzlu@smu.edu (Y. Hurmuzlu).

http://dx.doi.org/10.1016/j.mechatronics.2015.04.015
0957-4158/

could be enumerated as follows: front tapping, back tapping, back-and-forth tapping, hopping, galloping, and tumbling. Subsequently, a preliminary prototype, Pony I, was developed to emulate baton's motion. This robot employs inertial actuation instead of the impulsive one proposed in [26,27]. We found out that there are serious challenges in developing impulsive actuators [28]. The inertial actuation system of Pony I consists of a spinning mass/pendulum mounted at one end of the baton. A numerical model of Pony I and the prototype presented in [24] indeed generated tapping gait with forward progression. This type of gait can be described as one end of the baton is hopping, while the other is in contact with the walking surface.

As was discussed above, different types of actuation can be used to navigate robots on various terrains. These typical actuation schemes require direct contact with the ground. In contrast, inertially actuated locomotion enables us to separate the ground contact points from actuation points. The actuation mechanism can be for instance encapsulated inside the robot. With this scheme, one can even actuate a robot during the flight phase. This type of robotic systems can achieve locomotion on low friction surfaces and uneven terrain, can easily generate multi-modal locomotion (such as hopping, tapping, and galloping), and can potentially generate higher velocity tumbling gaits.

The success of the inertial actuation we used in the first generation of Pony robots led us to the development of an improved system. This actuation mechanism is called the double-action actuation. This actuation scheme employs two spinning pendulums at one end, turning in opposite directions. One can control the direction and magnitude of the resultant inertial force by changing the rendez-vous angle (the angle at which the spinning masses meet) and the angular velocity of the spinners. To the best of our knowledge, we never seen such mechanism used in the actuation of robots before.

In the ensuing article, we present a model of a baton system actuated inertially on both ends. We use numerical modeling to simulate and analyze the tapping gait of this system. A prototype, Pony II robot, was also developed to implement the new double actuation system. This prototype consists of double-action spinners mounted on both ends of the baton. The mechanical and electronic components of the robot are also presented in full detail.

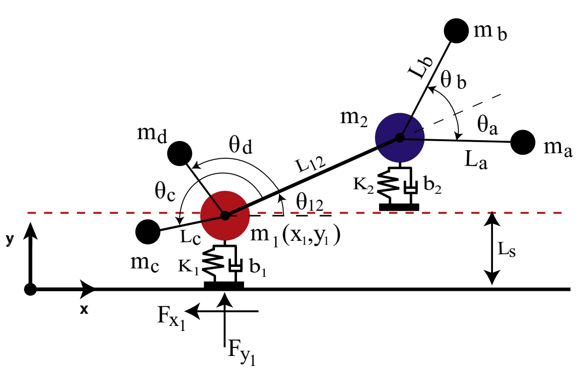

Fig. 1. Double spinners on both ends.

2. Modeling of baton with the double-action system

2.1. Description of the double-action system

A generalized model of the baton with the double-action is shown in Fig. 1. The 5-link 6-mass system consists of two masses, m_1 and m_2 connected with a massless rod L_{12} (m_1 and $m_2 \gg m_{rod}$) representing the baton. This system is called the Pony II.

The two masses m_1 and m_2 account for the weight of the two motor assemblies and the rest of the robot. The interface between the ground and each of these masses is modeled using a spring-damper system. The eccentric masses m_a, m_b, m_c, and m_d, represent the pendulum-like actuation mechanism, with massless connectors of respective lengths: L_a, L_b, L_c, and L_d. Note that at the instant shown in Fig. 1, m_1 (trailing end) is interacting with the ground and m_2 (leading end) is in the air. The forces F_{x_1} and F_{y_1} represent the friction and the reaction forces at the ground contact of the trailing end. The horizontal dashed line represents the undeformed length of the springs, L_s, and sets the level at which the baton's ends start interacting with the ground. For the single-pendulum actuator described in [24], the inertial force generated by the rotation of the pendulum-like arm has a magnitude of $|F_{c_a}| = m_a L_a \omega_a^2$. The direction of that force points towards the eccentric mass, varying with the rotation angle.

In the single-action system, the forced applied to the baton is a radial force that has the same angle of rotation. In contrast, the double actuation system provides a mechanism to apply the inertial force in a desired direction. Thus, employing two masses of equal weight, rotating in opposite directions at the same angular velocity leads to an alternating resultant force $\overrightarrow{F_c}$. This force is the result of the inertial forces $\overrightarrow{F_c a}$ and $\overrightarrow{F_c b}$), created by the masses m_a and m_b respectively, as shown in Fig. 2. The direction of these forces can be presented by the normalized vectors $\overrightarrow{e_{2a}}$ and $\overrightarrow{e_{2b}}$, describing the links between the spinning masses, and the center of rotation. The resultant force $\overrightarrow{F_c}$ points in the direction $\overrightarrow{e_\beta} = \overrightarrow{e_{2a}} + \overrightarrow{e_{2b}}$ of the rendez-vous angle β as presented in (1). Hence, one can have control over the direction and magnitude of the inertial force generated by this actuation mechanism.

$$
\begin{aligned}
&\overrightarrow{F_{ca}} = m_a L_a \omega_a^2 \overrightarrow{e_{2a}} \\
&\overrightarrow{F_{cb}} = m_b L_b \omega_b^2 \overrightarrow{e_{2b}} \\
&\overrightarrow{F_c} = \left\{ |\overrightarrow{F_{ca}}| cos(\theta_a) + |\overrightarrow{F_{cb}}| cos(\theta_b) \right\} \overrightarrow{e_\beta} \\
&m_a = m_b = m; \quad L_a = L_b = l; \quad \omega_a = \omega_b = \omega \\
&|\overrightarrow{F_c}| = 2ml\omega^2 (cos(\theta_a) + cos(\theta_b))
\end{aligned}
\tag{1}
$$

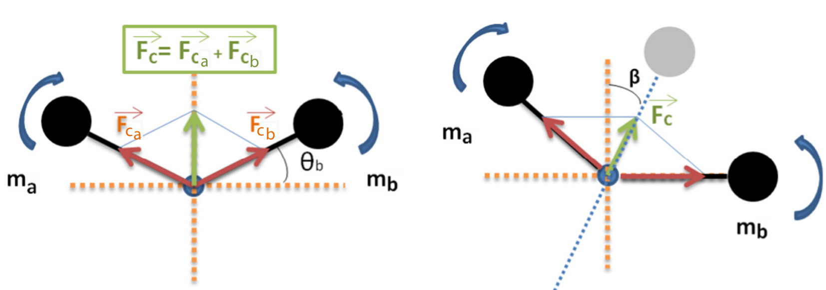

Fig. 2. Double-action and inertial reaction forces.