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Trajectory planning of a rolling robot of closed five-bow-shaped-bar linkage

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ABSTRACT

A morphological rolling robot of closed five-bow-shaped-bar linkage is presented in this paper. The exterior of each bow-shaped-bar represents a portion of a circle, and then the robot could be propelled forward by displacing the center of mass of the robot relative to the contact point between the rounded exterior of the link and the ground. Herein, we present the mechanical design, kinematics modeling and the analysis of dynamic rolling constraints including the mechanical configuration and motion continuity. And then four schemes of rolling laws limited by the constraints are used to plan the joint paths and analyze the stability with zero moment point (ZMP) criterion. As the results of the trajectory planning with the principle of minimal module between the joint position and the reference trajectory, the rolling laws without sharp transition, such as sinusoid and modified trapezoidal curve, are more appropriate for the dynamic rolling on the robot. Furthermore, dynamic rolling experiments on the prototype are used to verify the trajectory planning. The experimental results show that the rolling locomotion of this robot has favorable characteristics in speed, compliance and continuity.

1. Introduction

Mobile mechanism has a great significance in the performance of speed, stability, accuracy and efficiency in the mobile robot. Therefore, particular mobile mechanism has become to be a hot research topic in robotics, and studying from nature is always to be an important research method in the innovative work. The bionic research shows that there is a special rolling locomotion in nature. The rolling organisms, such as the Tumbleweed plant, Web-toed Salamander, Namib Golden Wheel Spider, Woodlouse, Mother-of-Pearl Moth caterpillar and Stomatopod shrimp, can acquire the rolling locomotion by using their torsos and limbs as rolling element in some situations [1]. The Web-toed Salamander curls itself into a hoop shape, with its dorsal side outermost, and rolls down slopes with rocky surfaces far faster than would be possible by simply running down the slope [2]. The Namib golden wheel spider cartwheels down sand dunes at a speed of 1 ms^{-1} when attacked by its nemesis [3]. The Nannosquilla decemspinosa is a type of shrimp with elongated body and short laterally projecting legs. They cannot walk but adopt an uninterrupted backward somersault returning to the water at a speed of 40 cms^{-1}, when a wave washes them from their burrows onto the beach and out of the water [4].

Inspired by the nature, researchers have developed a variety of rolling robots in view of the advantages of speed and consumption in the rolling locomotion. Many examples of rolling robots exist in the literature, and there are two main categories relevant to our work.

The first category includes the spherical robots where the control components and other devices could be sealed in the sphere shell, resulting in a superb dynamic stability performance while encounter with obstacles. Whereupon, spherical robots are very suitable for working in the abominable environments such as desert, corrosion, amphibious surroundings. The first of the spherical robots was developed by Halme et al. [5], who proposed a mechanism encased in a plastic sphere that uses a motor-driven wheel to tip the internal mechanism and propel the sphere in the desired direction. Michaud and Caron developed a spherical toy called Roball [6,7] that has motors connected to the spherical shell of the robot for propulsion and a counterweight used for steering. Mukherjee et al. [8] proposed systems where masses placed on four linear actuators are used to control the net center of mass and, therefore, the torque, position, and orientation of the robot as it rolls. Another rolling method proposed by Bhattacharya and Agrawal [9] involves a driving mechanism that consists of two mutually perpendicular rotors inside a sphere that cause the sphere to roll via conservation of momentum. However, because of the special spherical shape and omnidirectional rolling mode, manipulators and other executive devices are hard to be installed on the spherical robot, thus limiting the practical application. In order to realize operation ability, a spherical mobile robot called BYQ, which has a two degrees of freedom (DOF) telescopic manipulator and a standing stabilizer, was developed by the Space

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Robot Laboratory of Beijing University of Posts and Telecommunications [10,11].

The second category consists of robots with noncircular rolling cross sections formed by multilinked modular robots [12–16]. The GRASP laboratory of Pennsylvania University put forward a modular loop robot called CKBOT [17,18], which can roll forward by control of its shape to maintain the center of gravity (COG) in front of the contact point with the ground. Y. Tian et al. [19] proposed a deformable polyhedron robot, which has two types of motions: a linear rolling motion and a reconfiguration motion that allows the robot to change its moving directions. T. Yamawaki et al. [20] proposed a self-reconfigurable parallel robot with the abilities of getting over a bump and carrying an object by configured to 4R and 5R closed kinematic chains. The unifying principle of this category is that rolling can effectively be produced by morphing the shape of the robot to displace the COG with respect to its point of contact with the ground, which is a rolling technique denoted as structural morphing locomotion. However, the robots based on conventional structure link will be affected by the impact of ground that could be enhanced by the rolling speed, and then the resulting motions are not as smooth as cylindrical or spherical rolling [20].

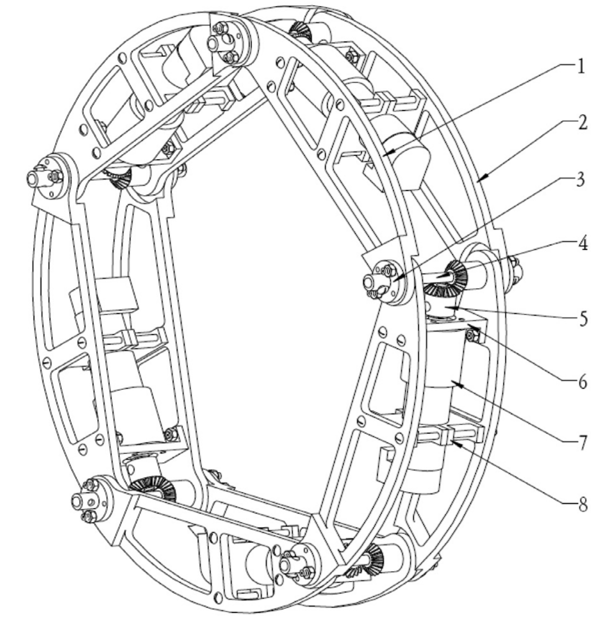
And then, M.A. Minor et al. [21] developed a rolling disk biped robot (RDBR) with the abilities of walking, rolling, climbing and the rolling locomotion without the need for resources beyond those required for climbing and walking. The rolling locomotion is realized using four circle links in an open loop. While walking or transforming between two motion models arbitrarily, it is balanced by electro-magnets which are installed on the two foots. To mimic the caterpillar rolling, B. Trimmer et al. [22–24] put forward a soft-bodied rolling robot called GoQBot, which has a monolithic silicon polymer body actuated by shape memory alloy (SMA). Inspired by the wheel spider, T. Nemoto et al. developed a reconfigurable quadruped robot, which can perform walking and rolling locomotion by using bow-shaped legs [25]. Besides, they proposed a hexapod robot to realize the bionic wheel spider rolling locomotion by raising the COG of the robot and shifting it forward on the overturned posture [26].

In order to avoid the suffering of impact force from the ground and extend the application, a quadruped robot with the abilities of walking and rolling, which is evolved from the closed five-bow-shaped-bar linkage, was proposed in our previous work [27]. Further, the abilities of incline climbing and obstacle negotiation of the closed five-bow-shaped-bar linkage were investigated with quasi-static method [28,29]. Thereupon, this paper is aim to realize smooth dynamic rolling locomotion through the control of the joints to form surface-compliant configuration due to the usage of bow-shaped links.

The paper is organized as follows. Section 2 first outlines the mechanical structure, and then followed by the kinematics modeling and the analysis of dynamic rolling constraints in Section 3. Section 4 describes the trajectory planning algorithm with the optimal principle of minimal module between the joint position and the reference joint trajectory, then the generation of joint paths according to four kinds of robot's rolling laws and stability analysis with zero moment point (ZMP) criterion. Section 5 presents the experimental results on a prototype. The conclusions and future work are discussed in Section 6.

2. Mechanical structure

The overall concept of the mechanical structure is to design a robot with the ability to adapt itself to rolling coherently by its morphological structure. In view of the spherical robots and structural morphing robots, we design the robot using the bow-shaped-bars, rather than traditional structure links. Circular exoskeletons were selected over other design alternatives, such as wheeled mechanisms. The robot consists of five modularized links in a closed loop, where the exterior of each link represents a portion of a circle. Consequently, the cross-sectional area of the robot is symmetrically segmented by the links, resulting in a round exterior profile of the robot with a regular pentagon inside at the normal posture. The robot may then be propelled forward by displacing the center of mass of the robot relative to the contact point between the rounded exterior of the link and the ground. In this way, we put forward a rolling robot based on the morphology circular exoskeletons, as shown as Fig. 1.



1,2—bow-shaped plank；3—potentiometer；4—joint axle；
5—bevel gear；6,8—supporting part；7—motor

Fig. 1. Overall view of the rolling robot.

To establish symmetrical rolling, the mass of the robot is balanced among the links so that the COG of the robot exactly coincides with the centroid at the normal circular posture. There are two strategies used for weight balancing. The first is that each modular link is installed with a DC motor equipped with a planetary gearbox. Because that the robot's shape is controlled by two of the joints, only two active joints are actuated by relevant motors and then the redundant motors could be used for balancing. The situation that if the unactuated joints were actuated, the robot would be over-actuated, is not discussed here. Another strategy is adding counter weight. As the results of the weight balancing, each modular link has the same mass with the center locating at the midpoint of the adjacent joints.

The driving principle of the joint design, shown in Fig. 2, is to create the smallest diameter joint while allowing for the largest possible joint torque. To that end, each joint is actuated using bevel gearing. Motors may be mounted perpendicular to the joint axle, resulting in smaller link widths and direct joint drive. Matching up with the gearbox equipped with the motor, bevel gearing provides significant gear reduction in a small amount of space, and thus, allows for a small joint diameter. The compact configuration makes the robot more suitable for confined environments, such as narrow crevices, and also appropriate to be adapted into a quadruped [27]. Additionally, because of the high gear ratio and the bevel gearing, the joints are nonbackdrivable, which is advantageous for uniform rolling as it does not require the motors to operate in this case. Joint position measurement is accomplished through potentiometer installed at the joint axle. This joint design is duplicated for each joint of the robot to reduce the number and complexity of manufactured parts.