Mechanism and Machine Theory 111 (2017) 39–65

Contents lists available at ScienceDirect

Mechanism and Machine Theory

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

Research paper

A reconfigurable multi-mode mobile parallel robot

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ARTICLE INFO

Keywords:
Parallel mechanism
Folding mechanism
Quadruped robot
Reconfigurable robot
Rolling motion
Multiple locomotion modes

ABSTRACT

In this paper we put forward the idea of deforming the geometry of a parallel mechanism such that it can operate either as an equivalent rolling robot or quadruped robot. Based on it, we present a novel mobile parallel robot that can change its locomotion modes via different equivalent mechanisms. The robot is in essence a four-arm parallel mechanism in which each arm contains five revolute (R) joints. The axes of the three internal R joints in any arm are parallel and are orthogonal to those of the end joints. Based on singularity and deformation analysis, we show that the upper platform has four practical operation modes, (i.e., translation, planar, rotational, and locked-up modes). Using these operation modes, the robot can realize rolling, tumbling and quadruped locomotion modes by deforming into switching states. The switching configurations of the robot are further identified in which the robot can switch among different locomotion modes, such that the robot can choose its mode to adapt complex terrains. To verify the functionality of the robot, we present the results of a series of simulations, and perform the locomotion modes' experiments on a manufactured prototype.

1. Introduction

There are many classes of mobile robots with different characteristics. Legged robot can achieve walking, crawling, running and jumping by alternatively changing the supporting legs on the ground. This enables it to flexibly explore different environments, but its walking efficiency is lower and the control system is usually very complicated [1–3]. To enhance the walking capability of the robot in different working environments, hybrid robot was presented that constructed by integrating different walking devices together (e.g., wheel-legged robots [4–10], track-legged robots [11], wheel-track-legged robots [12]). But such a combination usually increases the weight and volume of the robot, which makes it less swift [3].

Different from hybrid robots, several mobile robots can realize different locomotion modes by using reconfigurable methods, which can switch among the locomotion modes of rolling, walking and snake-like crawling, by changing the topology of the robot properly [13–16]. However, the DOFs of a these robots are usually very large, and the modules are required to divide and re-connect to change their locomotion modes. This highly limits the switching speed and increases the control difficulty.

Without modular units, some deformable mobile robots can obtain multiple locomotion modes by deforming their bodies or entire shapes into various topology structures. For example, soft robots composed of multiple loops, can roll, crawl, or jump by changing the shapes of loops [17,18]. Some legged robots can switch their locomotion modes by deforming the legs into a wheel [19],

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http://dx.doi.org/10.1016/j.mechmachtheory.2017.01.003
Received 8 October 2016; Received in revised form 19 December 2016; Accepted 6 January 2017

disk [20] or sphere [21], such that the legged robots can achieve wheeled or spherical rolling motion.

In additional, parallel mechanisms have also been used to realize different locomotion modes (e. g., walking mode [22–24], biped mode [25–28], rolling mode [29–33], crawling mode [34,35], and worm-like mode [36]). However, the locomotion mode of each of these mobile robots is fixed and the working space is very small, that strictly limits the robot in accommodating different road conditions. To improve the capability of parallel mechanisms, a plenty of parallel mechanisms with multiple operation modes were presented [37, 38]. Several lower DOF parallel robots can realize multiple motion modes, e.g. rotational, translation, planar, or spherical motions etc. Based on different operation modes, we further presented two mobile parallel robots with two different locomotion modes [39, 40]. We also used metamorphic methods to make single loop linkages realize different locomotion modes by changing their gestures. For example, we presented a mobile parallelogram mechanism that can slide or crawl on the ground [41], and used a spatial 8 R linkage to realize biped and rolling locomotion [42].

In this paper, we present a parallel robot that can deform into a rolling and quadruped robot, which can significantly improve the capability of a mobile robot. We mainly focus on the mechanical design and the locomotion analysis of the robot. We will show that the robot can be deformed into equivalent open-chain mechanisms or planar closed-loop mechanisms by controlling its singularity positions. Using different mechanisms, this robot can mobile by rolling, tumbling, and quadruped modes. Each of these modes can be quickly switched at its singularity positions for adapting different environments. Furthermore, our robot can be folded into three compact forms, which may be useful for storage or hiding itself in performing some dangerous tasks.

The rest of the paper is organized as follows. The design and operation modes analysis of the parallel mechanism are introduced in Section 2. Section 3 analyzes the different locomotion modes of the robot. Section 4 gives the switching methods of the rolling, tumbling and quadruped modes. Section 5 presents the results of locomotion tests and folding functions on a physical prototype. The conclusions and brief discussions close the paper in Section 6.

2. Mechanism design

In this section, we first introduce the design of the mobile parallel robot. Then, based on the mobility and singularity analysis, we show that the upper platform has four typical operation modes. Using these modes, the robot can be viewed as a parallel manipulator to realize some special movements.

2.1. Description of mechanism

The proposed robot is illustrated in Fig. 1. It is basically a symmetric parallel mechanism with two equal platforms and four equal arms (Fig. 1(a)). For ease of description, the two platforms are called the upper platform ($E_1E_2E_3E_4$) and lower platform ($A_1A_2A_3A_4$) respectively, Here E_i and A_i are the endpoints of an arm, and both are R joints with their axes collinear. For the upper platform, $||oA_1|| = ||oA_2|| = ||oA_3|| = ||oA_4||$, and $A_1A_3 \perp A_2A_4$. Each arm consists of five R joints at A_i, B_i, C_i, D_i, and E_i. The positions of R joints on an arm are as follows:

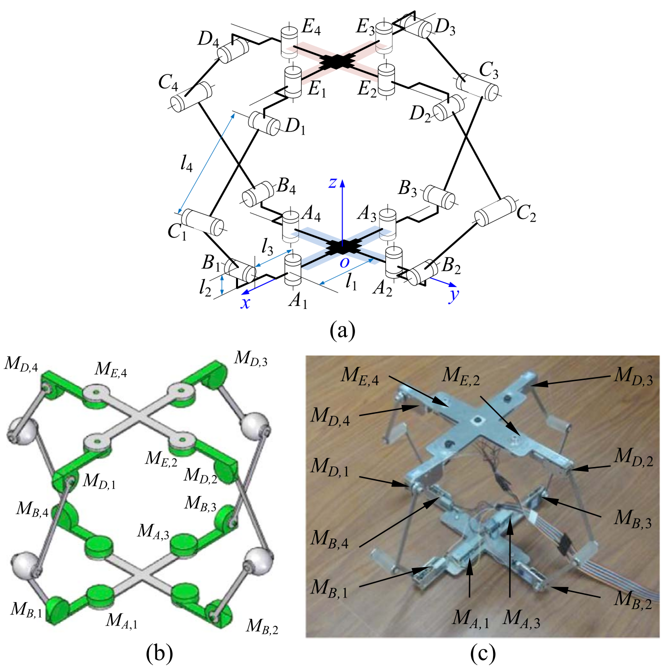

Fig. 1. (a) The sketch of the parallel mechanism, (b) the positions of motors on a 3D model, (c) the prototype of the mechanism.