Mechanism and Machine Theory 130 (2018) 567–584

Contents lists available at ScienceDirect

Mechanism and Machine Theory

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

Research paper

Type synthesis of a 3-mixed-DOF protectable leg mechanism of a firefighting multi-legged robot based on G_F set theory

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ARTICLE INFO

Article history:
Received 4 January 2018
Revised 6 June 2018
Accepted 28 August 2018

Keywords:
Firefighting robot
Multi-legged robot
Protectable leg mechanism
Parallel mechanism
Hybrid mechanism

ABSTRACT

The biggest hurdle to applying multi-legged robots to firefighting is the protection of the motors driving their legs and the motors' accessories. A series of protectable leg mechanisms (LMs) are thus proposed to remove this obstacle. First, the relationships between the motion characteristic of the rigid body and one point on this body are revealed based on generalized function ($\boldsymbol{G}_F$) set theory. The motion characteristics of the LM and ankle, which enable the robot body to achieve six-dimensional movement, are determined. Then, the structure layout of the protectable LM is designed, and two composition schemes for a protectable LM are proposed. In addition, 13 types of walking mechanisms (WMs) and their motion input points are presented. Considering the protective design of the motors and their accessories, two rules of type synthesis of the driving mechanism (DM) are set. Based on the motion characteristics of the motion input points of the WMs and foot end-points, seven rules are given to solve the characteristics of DM and connecting joint. 23 types of protectable DMs are synthesised. Finally, 23 types of 3-mixed-DOF protectable LMs are obtained, and examples of protectable LMs are presented. One of these LMs was successfully used in the design of a six-legged firefighting robot.

1. Introduction

Mobile carrier machines include wheeled vehicles, tracked vehicles and multi-legged robots [1,2]. Wheeled and tracked vehicles can only move across continuous ground [3,4]. Compared with wheeled and tracked vehicles, multi-legged robots are able to move across both continuous and discontinuous ground [5]. Moreover, multi-legged robots exhibit better flexibility and adaptability on uneven terrain, such as uplands, forests and stairways [6]. Therefore, in environments that wheeled and tracked vehicles cannot traverse, multi-legged robots can help humans perform special tasks [7]. Various types of multi-legged robots have been proposed. For instance, Honda released a robot in 2011 named 'ASIMO2011' [8]. Boston Dynamics manufactured a bipedal robot named 'ATLAS' [9] and two quadrupedal robots named 'BigDog' [10] and 'Cheetah' [11]. Ding et al. [12] developed a hexapod robot named 'NOROS'. Hawkes et al. produced a bio-gecko robot named 'StickyBot III' [13]. Rong et al. developed a hydraulic quadrupedal robot named 'SCalf' [14]. Gao et al. developed a quadrupedal robot named 'Baby Elephant' [15] and a hexapod robot named 'Octopus' [16]. The FESTO Company released a bio-kangaroo hopping robot in 2013 [17].

When multi-legged robots walk, their mechanical legs alternate between swinging and supporting phases. Therefore, the performances of multi-legged robots are evaluated according to their mechanical legs. In the research field of

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https://doi.org/10.1016/j.mechmachtheory.2018.08.026
0094-114X/

multi-legged robots, the study of type synthesis of leg mechanisms (LMs) is extremely important. At present, many type synthesis approaches, such as displacement sub-group theory [18], graph theory [19], screw theory [20–23], linear translation [24–26], position ad orientation characteristic (POC) set theory [27] and $\boldsymbol{G}_{\mathrm{F}}$ (generalized function) set theory [28], can be used to address this problem. Numerous novel LMs have been obtained by these approaches. For example, Rong et al. [14] designed a 3-degrees-of-freedom (DOF) hydraulic actuated LM and applied it as the LM of a quadruped robot. Tian et al. [29] proposed different 3-DOF hybrid LMs. Kern and Woo [30] designed a 2-DOF under-actuated LM. He and Gao [31] studied the type synthesis of a bionic quadruped robot systematically and introduced a variety of legs with a parallel topology based on G_F set theory. Uluc et al. [32] introduced a single-DOF LM actuated by one motor. Rong et al. [33,34] proposed a 3-DOF LM and a 5-DOF decoupled LM. Wang et al. [35] proposed a reconfigurable LM based on a 6-SPU parallel mechanism (PM). Henrey et al. [36] designed a LM consisting of a 3-DOF series mechanism and a foot pad with dual-layer dry adhesives that can climb smooth vertical surfaces. Furthermore, many scholars [37] have designed various LMs with different DOFs based on a series mechanism.

Based on the abovementioned LMs, the workspace of the endpoint of a single-DOF LM is a curve [32], that of a two-DOF LM is a surface [30] and that of an LM with three or more DOFs is a three-dimensional volume [33–37]. Hence, when an LM has fewer than three DOFs, the LM has low flexibility. When the DOFs are not fewer than three, the LM has good flexibility, but with the change in the degrees of freedom, the orientation adjustment between their feet and the ground differs. For example, a 3-DOF LM adjusts the orientation between the foot and ground by one passive spherical ankle connected to the end of the LM [29,33,37]. A 4-DOF LM adjusts the orientation between the foot and ground by one active DOF of the LM and one passive universal ankle connected to the end of the LM [38]. Analogously, 5-DOF and 6-DOF LMs adjust the orientation with two and three active DOFs, respectively [31,34]. In this way, the feet can actively adapt to the ground, and their adaptability increases with the increase of degrees of freedom. However, as the number of DOFs increases, the volume and weight of LMs become larger. Correspondingly, manufacturing cost and control difficulty become greater. For these reasons, 3-DOF LMs have good application prospects.

Firefighting is a hazardous occupation. Firefighters are injured, suffer work-related illnesses, are hospitalised, are forced into early retirement or die at higher rates than most other workers in the world [39,40]. Therefore, robots are expected to replace firefighters and carry out dangerous tasks [41]. Wheeled and tracked vehicles are currently used to perform firefighting tasks [42]. However, they cannot be used on rugged and discontinuous ground because their mobility is limited on uneven terrain [43]. Multi-legged robots have better flexibility and mobility in uneven terrain than wheeled or tracked vehicles. Therefore, multi-legged robots are considered potentially powerful tools for protecting firefighters' lives [40]. Although great progress has been made in research on multi-legged robots [44,45], few have been applied in firefighting. One of the reasons for this problem is that existing multi-legged robots' motors and their accessories are easily damaged in high-temperature environments [46,47]. The motors and their accessories of the LM of existing multi-legged robots are fixed to the leg. They move with the LM, which makes it difficult to design protective enclosures that are suitable for severe environments. Therefore, to improve the protection of multi-legged robots and promote the application of multi-legged robots in the field of firefighting, it is essential to synthesise novel LMs whose motors and motors' accessories are protected.

In this paper, we investigate the structural layout and rules of the type synthesis of a protectable LM and explore a type synthesis approach for a protectable LM based on G_F set theory to obtain LMs that can be applied to a firefighting multi-legged robot. The remainder of this paper is organised as follows: in Section 2, the relationship between the motion characteristic of a rigid body and one point of the limb is described, and the independent translational and accompanying translational characteristic are expressed. In Section 3, the structural layout of a protectable LM is designed, and the rules of the type synthesis of the protectable LM are established. In Section 4, a type synthesis approach for a protectable LM is proposed. Many protectable LMs are synthesised based on the proposed type synthesis approach. Section 5 reports an application example. Section 6 concludes the paper.

2. Relationships between the motion characteristic of a rigid body and one point on the rigid body

Generally, the translational characteristic of a mechanism consists of the independent translational characteristic and the accompanying translational characteristic. The independent translational characteristic is caused by a prismatic joint or an equivalent prismatic joint [48,49,51]. The accompanying translational characteristic is formed by revolute joints [49]. In general, a rigid body, such as the end-effector of a series limb or the moving platform of a parallel mechanism, is considered to be formed by a number of closely linked points. The translational characteristic of one point on the rigid body can be caused by the prismatic, equivalent prismatic or revolute joints. The translational characteristic of a rigid body is the intersections of the translational characteristic of all points that make up the rigid body. In a limb, because the vectors from the centre of the same revolute joint to different points on a rigid body are different, the same revolute joint can generate different accompanying translational characteristics at different points of the rigid body. Therefore, the intersection of the accompanying translational characteristics of the different points on a rigid body is an empty set. In contrast, the same prismatic joint or equivalent prismatic joint in the limb can generate the same independent translational characteristic at different points of the rigid body. For these reasons, the translational characteristic of one point of the rigid body is related to the prismatic joints, equivalent prismatic joints or revolute joints. However, the translational characteristic of the rigid body is only related to the prismatic joints or equivalent prismatic joints. For example, in Fig. 1, because the vector $\boldsymbol{RA}$ is not equal to the vector $\boldsymbol{RB}$, the accompanying translational characteristic of the R joint at point A is not equal to that at