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Structural synthesis of two-layer and two-loop spatial mechanisms with coupling chains

Huafeng Ding [a,b], Wen-ao Cao [a,b], Ziming Chen [b], Andrés Kecskeméthy [c]

[a] School of Mechanical Engineering and Electronic Information, China University of Geosciences (Wuhan), 430074 Wuhan, China
[b] Hebei Provincial Key Laboratory of Parallel Robot and Mechatronic System, Yanshan University, 066004 Qinhuangdao, China
[c] Chair for Mechanics and Robotics, University of Duisburg–Essen, 47057 Duisburg, Germany

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ABSTRACT

Structural synthesis is one of the most important tasks in the creative design of mechanisms. In the past decades, spatial parallel mechanisms have been extensively synthesized. However, structural synthesis of more complex spatial mechanisms with coupling chains is seldom addressed. This paper aims to propose a general method for synthesizing a class of important spatial mechanisms with coupling chains, called two-layer and two-loop (TLTL) mechanisms, which are the basic units for constructing multi-layer and multi-loop mechanisms with more complex couplings. First, the motion screw equation of TLTL mechanisms is derived, with which mobility or degree-of-freedom (DOF) of the class of mechanisms can be analyzed and rigid substructures can be detected. Then, a general method for structural synthesis of TLTL mechanisms is proposed on the basis of the principle of mobility analysis. Finally, TLTL mechanisms with fourteen kinds of degrees of freedom are synthesized, illustrating the effectiveness of the method.

1. Introduction

Structural synthesis plays an important role in the conceptual design of mechanisms. In the process, a large number of feasible kinematic structures can be generated for designers to choose. In the past decades, strong interest has been shown in structural synthesis of spatial parallel mechanisms. Huang and Li [1] developed the constraint synthesis method based on screw theory and synthesized systematically lower-mobility spatial parallel mechanisms with symmetrical structures. Kong and Gosselin [2], and Fang and Tsai [3] also studied structural synthesis of parallel mechanisms based on constraint screws. Herve [4], Fanghella and Galletti [5], and Rico et al. [6] proposed the structural synthesis method for spatial parallel mechanisms based on group theory. Later, Li et al. [7] and Meng et al. [8] further extended the relevant research based on differential manifold. Gogu [9] synthesized spatial parallel mechanisms based on linear transformation. Gao et al. [10,11] proposed the concept of G_f set to synthesize parallel mechanisms. Dai and Rees Jones [12] proposed the concept of metamorphic mechanisms and then structural synthesis associated with this kind of mechanisms has been investigated by many researchers [13–15]. Kong [16] synthesized parallel mechanisms with multiple operation modes and metamorphic mechanisms. Tanev [17] presented a type of hybrid mechanism consisting of two parallel mechanisms connected serially. Alizade et al. [18,19] synthesized multiple platform manipulators according to their new structural formula.

However, structural synthesis of spatial mechanisms with coupling chains can be found in relatively little literature. A typical topology of the kind of mechanisms is shown in Fig. 1(a). Generally speaking, spatial mechanisms with coupling chains have higher rigidity and greater load-carrying capacity than corresponding spatial parallel mechanisms, and can output some special motion for

E-mail address: dhf@ysu.edu.cn (H. Ding).

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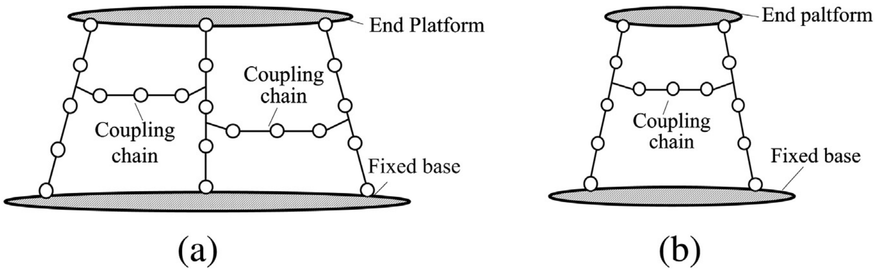

Fig. 1. (a) The topology of a spatial mechanism with coupling chains and (b) the topology of a TLTL mechanism.

specified requirements. A few of them have been applied to industrial equipment and handicrafts, such as forging manipulators [20], the Hoberman switch-pitch ball [21] and magic cubes [22].

Differing from the constitution of parallel mechanisms, the coupling chains of such complex spatial mechanisms connect with other chains rather than the fixed base and the end platform. That means the constraints and motions provided by the coupling chains directly exert on other chains rather than the end platform, so that the existing methods for parallel mechanisms based on constraint screws or displacement groups cannot be directly used to analyze the influence on the mobility and motion pattern of the end platform exerted by the coupling chains. Based on constraint screws along with some equivalent approaches, Huang et al. [23] analyzed the mobility of the Hoberman switch-pitch ball, and Dai et al. [24] analyzed the mobility of a complex structure ball. Zoppi et al. [25] analyzed the mobility and velocity of two spatial mechanisms with coupling chains by complementing the additional constraints from logical derivations. Kong [26] analyzed kinematic influence coefficients of some complex spatial mechanisms. Zeng and Ehmann [27] designed parallel hybrid-loop manipulators with kinematotropic property and deployability based on displacement group and logical proposition.

Up to now, some key issues for structural synthesis of spatial mechanisms with coupling chains have not been solved effectively, such as mobility analysis of mechanisms, mobility and motion pattern analysis of the end platform, and detection of rigid substructures, so that a general method has not been developed for synthesizing the class of mechanisms systematically.

Since spatial mechanisms with coupling chains are great in quantities and varieties, this paper aims to develop a general method to synthesize a class of important spatial mechanisms with coupling chains, called two-layer and two-loop (TLTL) mechanisms, whose topology is shown in Fig. 1(b). The classes of mechanisms are basic modules for constructing more complex multi-layer and multi-loop mechanisms. The paper is organized as follows. In Section 2, some basic concepts of screws and mobility are recalled briefly. In Section 3, the principle of establishing the twist equation of TLTL mechanisms is derived. In Section 4, a method for the detection of rigid substructures is concerned based on the twist equation. In Section 5, a method for mobility analysis of TLTL mechanisms is proposed. In Section 6, a general approach to structural synthesis of the class of mechanisms is proposed and TLTL mechanisms with fourteen kinds of degrees of freedom are synthesized.

2. Basic knowledge

2.1. Basic concepts of screw theory

In screw theory [23,28], a unit screw $\boldsymbol{S}$ is defined as

$$\boldsymbol{\$} = \begin{pmatrix} \boldsymbol{S} \\ \boldsymbol{S}_0 \end{pmatrix} = \begin{cases} \begin{pmatrix} \boldsymbol{S} \\ \boldsymbol{r} \times \boldsymbol{S} + h\boldsymbol{S} \end{pmatrix} & \text{if } h \text{ is finite} \\ \begin{pmatrix} \boldsymbol{0} \\ \boldsymbol{S} \end{pmatrix} & \text{if } h \text{ is infinite} \end{cases} \tag{1}$$

where $\boldsymbol{S}$ denotes the direction vector of the screw axis, $\boldsymbol{r}$ denotes the position vector of any point of the screw axis with respect to a reference frame, and h is called pitch. Both the unit twist (motion screw) of a revolute pair and the unit wrench (constraint screw) of a constraint force are denoted as $(\boldsymbol{S}, \boldsymbol{r} \times \boldsymbol{S})^T$ with $h = 0$, called a line vector. Both the unit twist of a prismatic pair and the unit wrench of a constraint couple can be denoted as $(0, \boldsymbol{S})^T$ with $h = \infty$, called a couple.

2.2. Motion pattern of the end effector

A set of bases spanning the twist system of an end effector is used to represent the motion pattern (called mobility property as well) of the effector. Generally, couples and linear vectors are preferred as the bases. If a set of bases consist of ζ line vectors, τ couples and λ general twists, the motion pattern of the end effector may be described by ζ rotations, τ translations and λ screw motions. Further, the rotations can be classified into the follows two types: If the line vectors of the bases are always through a specified point or line, the corresponding rotations are called continual rotations. Otherwise, they are called non-continuous (instantaneous) rotations.