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Research paper

Design and analysis of a metamorphic mechanism cell for multistage orderly deployable/retractable mechanism

Kun Xu[a], Long Li[a], Shaoping Bai[b], Qiaolong Yang[c], Xilun Ding[a,*]

[a] School of Mechanical Engineering and Automation, Beihang University, 37 Xueyuan Road, Beijing, 100191, China
[b] Department of Mechanical and Manufacturing Engineering, Aalborg University, Fibigerstraede 16, Aalborg 9000, Denmark
[c] Beijing Institute of Spacecraft System Engineering, 102 Youyi Road, Beijing, 100094, China

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ABSTRACT

Normal kinematic joint can be transformed to variable kinematic joint(VKJ), which refers to a kinematic joint that is capable of topological variation in a mechanism, by utilizing effect of friction and self-locking. In this paper a metamorphic mechanism cell which can realize deploying, self-locking, unlocking, retracting and interlocking with other cells, is designed by incorporating VKJs. Self-locking margin is proposed to estimate the self-locking capability. The variable topology configurations of this cell are presented and the mobility of this cell is analyzed. With the new metamorphic cell, a cable-driven telescopic model with 3 tubes is built, and its motion simulations are conducted to verify the design method. The results demonstrate that the impact in transformation is mitigated and multistage orderly deployable/retractable mechanisms can be built by this method.

1. Introduction

A class of mechanisms whose topology configurations are changeable to meet different task requirements is called metamorphic mechanism [1], also known as the mechanism with variable topologies(MVTs) [2,3]. The mobility of this class of mechanisms is accordingly changed with their configuration variation. These mechanisms are generally functioned by the variable kinematic joints(VKJs) whose types and/or representative orientations are changeable during a cycle of motion [4,5]. Several types of these joints were illustrated by Yan and Kuo [5]. Gan et al. [6] presented the reconfigurable Hook (rT) joint and two types of metamorphic parallel mechanisms assembled with this rT joint.

The MVTs or metamorphic mechanisms have been widely studied. Matrix representation [7] and topological graph [8–10] are two main methods used to represent the topological configuration. Pucheta et al. [11] analyzed the topological configuration using the graph theory method and their synthesis method has been successfully applied to design a family of low-voltage circuit breakers. Li and Dai [12] presented a method of structure composition of single-driven metamorphic mechanisms based on augmented Assur groups. Balli and Chand [13,14] proposed a method for the synthesis of five-bar motion with variable topology and an analytical method of synthesis of a planar seven-link mechanism with variable topology.

The realization of MVTs can depend on the friction effects which change the motion of the kinematic joint. The frictional force causes self-locking which leads to change of topology of a mechanism. Oledzki [15] described the classification of self-locking drives and proposed a physical model of a self-locking kinematic pair. Leonesio and Bianchi [16] proposed a definition of self-locking for multi-DoF(Degree of Freedom) mechanisms and presented an algorithm for computing the

* Corresponding author.
E-mail address: xlding@buaa.edu.cn (X. Ding).

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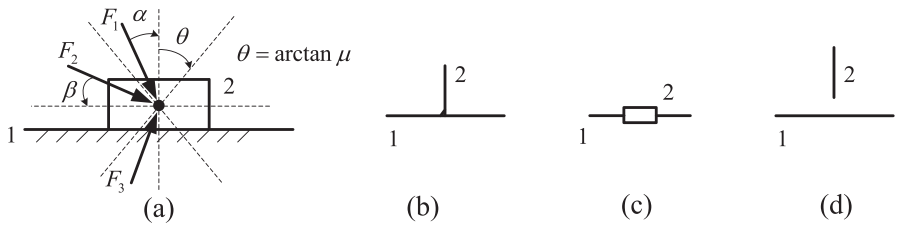

Fig. 1. Friction models of planar pair under different driving, (a) planar pair, (b) equivalent fixed pair, (c) equivalent prismatic pair, (d) equivalent separated pair.

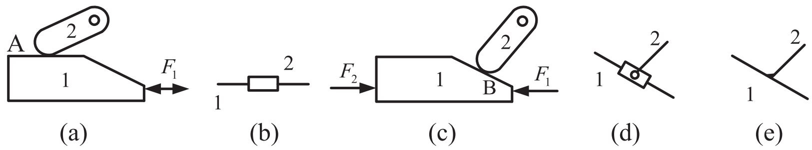

Fig. 2. Friction models of cam pair under different conditions, (a) cam pair coupled at line A, (b) equivalent prismatic pair, (c) cam pair coupled at line B, (d) equivalent prismatic pair and revolute pair, (e) equivalent fixed pair.

geometrical locus that corresponds to a specific self-locking configuration. Xu and Ding [17,18] studied walking robot as metamorphic mechanisms by assuming the constraints between supporting foot and ground with different hinges. Ding and Li [19] developed a deployable/retractable mechanism using the joint friction effect.

Deployable/retractable mechanisms can be used in aerospace field. Relevant examples include the extendable retractable telescopic mast [20], the deployable optical telescope [21], the CFRP Boom and the DLR Boom [22], the Sula Boom for the Cibola Flight Experiment Satellite [23], and the FAST mast for the international Space Station [24]. The MVTs/metamorphic mechanisms can be used to construct multistage deployable mechanisms and new designs can be proposed.

In this paper, several variable kinematic joints are analyzed with consideration of effects of friction and the driving forces. By making of variable kinematic joints, one metamorphic mechanism cell which can be self-locking and inter-locking with other cells is designed. Self-locking margin is proposed to assess the self-locking capability, upon which the mobility of this cell is analyzed. Moreover the expansion designs of the metamorphic mechanism cell in parallel and in serial are described. A design example of cable driven mechanism which can be orderly deployable/retractable is presented with simulations to demonstrate the design method.

2. Metamorphic mechanism cell design for self-locking, interlocking and unlocking

2.1. Specific variable kinematic joints using friction effect

Equivalent kinematic pair is often used in mechanism analysis [25,26]. Using equivalent kinematic pair friction effect and driving direction can make a normal joint transformed to a variable kinematic joint. As shown in Fig. 1(a), body 1 and body 2 form a planar pair. If the driving force F_1 was applied in friction lock area (inside the friction cone), there are no relative movements between body 1 and body 2. The equivalent joint is shown in Fig. 1(b). When driving force F_2 was applied in sliding area, body 2 could slide on body 1, the equivalent joint is a prismatic pair, shown as Fig. 1(c). If the driving force F_3 was applied in separating area, body 2 would move away from 1, the equivalent joint is a separated pair, shown as Fig. 1(d).

Similarly, considering effects of friction, specific cam pair can be equivalent to variable kinematic joints. A cam pair composed of bodies 1 and 2 is shown in Fig. 2. The contact surface is represented by two lines: line A and line B. When bodies 1 and 2 are coupled at line A as shown in Fig. 2(a), they can slide on each other under the driving force F_1. Its equivalent joint is a prismatic pair as shown in Fig. 2(b). As shown in Fig. 2(c), bodies 1 and 2 are coupled at line B. If body 1 is driven by F_1, they can slide on each other and body 2 can rotate by its axis. So the equivalent joint is a combination of a prismatic pair and a revolute pair, as shown in Fig. 2(d). When body 1 is driven by F_2 and no friction lock is satisfied, the equivalent joint is the same as Fig. 2(d). When body 1 is driven by F_2 and friction lock is satisfied, its equivalent joint is a fixed pair, as shown in Fig. 2(e).

A wedge planar pair composed by bodies 1 and 2 is shown in Fig. 3(a). If driving force F_1 is applied, the relationship between bodies 1 and 2 can be seen as a prismatic pair as shown in Fig. 3(b) without considering the friction. When the friction effects are taken into account, the relationship between bodies 1 and 2 will vary. The equivalent joint can be seen as a fixed pair as shown in Fig. 3(c) while friction lock is satisfied. Under this condition if driving force F_2 is applied as shown in Fig. 3(a), its equivalent joint transforms into a prismatic pair as same as the one without friction.