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The whole family of kinematic structures for planar 2- and 3-DOF fractionated kinematic chains

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ABSTRACT

Fractionated planar mechanisms, apart from the non-fractionated ones, are also widely used in engineering machinery and various robots, especially those with two or three degrees of freedom (DOFs). This paper proposes an automatic approach to synthesize the whole family of the kinematic structures of 2- and 3-DOF fractionated planar kinematic chains. Isomorphism-free algorithms for the combination of two or three non-fractionated topological graphs are proposed first. Then based on the algorithms and the atlas databases of the topological graphs of non-fractionated mechanisms [H.F. Ding, F.M. Hou, A. Kecskeméthy, Z. Huang, Mech. Mach. Theory 2012 47(1) 1–15], a general approach for the generation of fractionated topological graphs and the corresponding atlas database for 2- and 3-DOF fractionated planar kinematic chains is proposed. Isomorphism identification, one of the most difficult problems in structural synthesis, is rendered unnecessary with this synthesis approach. The whole family of the kinematic structures of 2- and 3-DOF fractionated planar kinematic chains up to seven basic loops is obtained for the first time.

1. Introduction

Multi-DOF mechanisms are widely used in various mechanical products such as industrial robots, engineering machinery, high precision surgical tools, and micro electromechanical systems. It is well known that structural synthesis in mechanism and machine theory has played an important role in the synthesis of mechanisms with different degrees of freedom [1–3] and a lot of kinematic structures of current robots are created as a result of structural synthesis [4–6].

The systematic approaches for the generation of the kinematic structures of kinematic chains and mechanisms began in the 1960s with the introduction of the graph theory to the study of the topological structure of kinematic chains. Adopting the graph theory in their approach, Freudenstein [7] and Crossley [8] generated 16 kinematic structures for 8-link, 1-DOF kinematic chains. Woo [9] synthesized 230 10-link, 1-DOF kinematic chains based on the contracted graphs. In order to reduce computational complexity, Sohn and Freudenstein [10] proposed the dual graph to represent the topological graph of kinematic chains and developed a corresponding structural synthesis method on the basis of the dual graph. By using the multiple link adjacency matrix to represent kinematic chains, Yan et al. [11–15] proposed the permutation group based approach for the structural synthesis of generalized kinematic chains. Hwang and Hwang [16] used the contracted link adjacency matrix to represent kinematic chains and developed a corresponding synthesis approach. Rao [17,18] employed the Hamming number technique for

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structural synthesis by using *F*-DOF, (*N*-2)-link chains as the basic chains to synthesize *F*-DOF, *N*-link chains. Mitrouchev [19] proposed the notion of logical equations to synthesize planar kinematic chains. Tuttle [20] first generated all possible bases and then used the bases to synthesize kinematic chains, and the theory of symmetry group is used to eliminate isomorphism in the synthesis of both bases and kinematic chains. By constructing proper simplified graphs, Butcher and Hartman [21] listed the numbers of 12- and 14-link planar single degree-of-freedom kinematic chains. Recently, Ding, etc. [22,23] proposed a fully-automatic method to synthesize the whole family of planar non-fractionated kinematic chains with different links, and the corresponding atlas databases containing all the classified topological graphs were also established.

However, based on the structure characteristics kinematic chains with two or more DOFs can be divided into non-fractionated and fractionated structures. Some approaches tackled both the non-fractionated and fractionated structures while the others only generated the non-fractionated structures. That partly accounts for the contradiction among the results obtained by various synthesis approaches [24]. Based on a canonical labeling of kinematic chains, Tischler et al. [25] proposed an orderly generation algorithm to synthesize both the non-fractionated and fractionated 3-DOF kinematic chains up to 10 links. Adopting the idea of the Assur group, Martins, Simoni and Carboni [26,27] proposed a new approach for the generation of fractionated kinematic chains, and planar fractionated kinematic chains up to four independent basic loops were synthesized.

This paper proposes a fully automatic method to synthesize the whole family of planar fractionated kinematic chains with two and three DOFs on the basis of the atlas databases of planar non-fractionated kinematic chains and the isomorphism-free combination algorithms. The overall structure of the paper is organized as follows. In Section 2, the classification of kinematic chains and the graph-based representation model are addressed. In Section 3, isomorphism-free algorithms for the combination of two or three non-fractionated topological graphs are proposed. In Section 4, the synthesis rules for planar 2- and 3-DOF fractionated kinematic chains are addressed. In Section 5, a human–machine interactive synthesis program is developed, and planar 2- and 3-DOF fractionated kinematic chains up to seven independent basic loops are synthesized automatically, and their classified atlas database is obtained for the first time, showing the effectiveness of the method.

2. Basic concepts

2.1. Classification of kinematic chains

In the structural synthesis of kinematic chains, usually all joints of a kinematic chain are assumed to be revolute joints [1,3]. A kinematic chain is said to be a *fractionated kinematic chain* if it can be separated into two or more independent kinematic chains at a link or joint. Fractionation in a kinematic chain can be divided into two basic types: link-fractionation and joint-fractionation. Any fractionated kinematic chain is either one of the two or a combination of them. For example, Fig. 1(a) can be separated into two independent kinematic chains at link 4, namely two six-link kinematic chains, so it is a link-fractionated kinematic chain. Similarly, Fig. 1(b) is a joint-fractionated kinematic chain. Fig. 1(c) is a kinematic chain with two fractionated links, links 4 and 6.

A fractionated kinematic chain is said to have a *multiple fractionated link* if two or more of its fractionated links coincide, i.e. the chain can be separated into three or more independent kinematic chains at the *multiple fractionated link*.

A *non-fractionated kinematic chain* (or a *basic closed-loop kinematic chain*) is a closed-loop kinematic chain which cannot be separated into two independent kinematic chains at any link or joint.

2.2. Graph-based models

In order to realize the fully-automatic structural synthesis of fractionated kinematic chains, the graph theory is adopted here. The kinematic structure of a kinematic chain can be uniquely represented by a topological graph in the graph theory whose

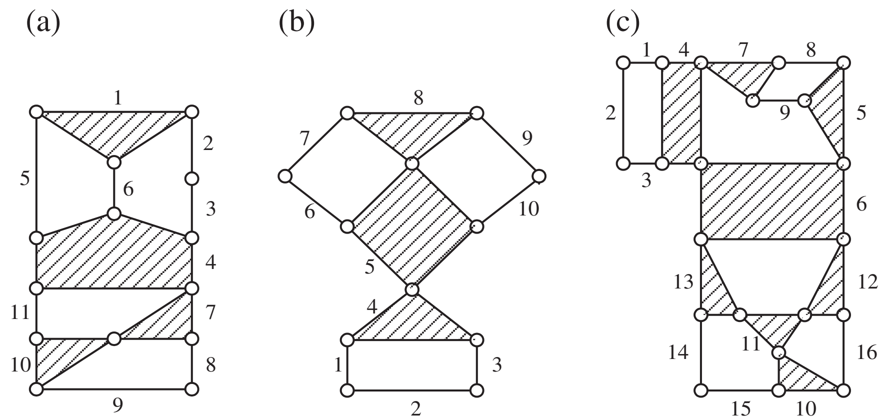

Fig. 1. (a) A link-fractionated kinematic chain, (b) A joint-fractionated kinematic chain, (c) A kinematic chain with two fractionated links.