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Research paper

A new method for the automatic sketching of planar kinematic chains

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ABSTRACT

In the synthesis of kinematic chains, especially using computerized methods, the synthesis results are usually represented in the numerical form. Sketching the synthesis results as visual kinematic chains is helpful for the creative design of mechanisms. This paper proposes a new method for the automatic sketching of planar kinematic chains, by converting the corresponding topological graphs with the aid of line graph. The first objective is to completely eliminate extraneous edges in the line graph. To achieve this, the joints in the multiple link are sequenced and the multiple link is sketched as a closed polygon. The second objective is to correct defective multiple links in the kinematic chain. To achieve this, a new concept called the Inner Angle of joint is defined, based on which a new correction algorithm is proposed to eliminate the unnatural link crossing and concave angle in the defective multiple link. The present work is helpful for enhancing the efficiency of design of mechanisms.

1. Introduction

The structure synthesis of kinematic chains is important for the conceptual design of mechanisms. Since the 1960s, numerous methods have been developed and successfully used to synthesize various kinds of kinematic chains.

In 1966, Davies and Crossley [1] applied the Franke's condensed notation to synthesize kinematic chains. In 1986, Sohn and Freudenstein [2] applied the dual graph concept to enumerate the kinematic structures of mechanisms. In 1992, Hwang and Hwang [3] developed a method using the contracted link adjacency matrix to synthesize kinematic chains. In 1996, Tuttle [4] developed an approach based on finite symmetry group to generate kinematic chains, as well as kinematic chain inversions. In 1997, Rao [5] presented the Hamming number technique to enumerate kinematic chains. In 2005, Butcher and Hartman [6] used the hierarchical representation method to synthesize kinematic chains. In 2006, Sunkari and Schmidt [7] developed a method by using the Mckay-type algorithm to synthesize kinematic chains. In 2010, Martins et al. [8] developed an Assur group based method for the generation of fractionated kinematic chains. In 2012, Nie et al. [9] utilized the addition method with 2 links and 3 pairs to synthesize kinematic chains. In 2013 and 2014, Yan and Chiu [10,11] developed a method using the multiple link adjacency matrix to synthesize generalized kinematic chains. Recently, Ding et al. [12–14] developed the perimeter loop based algorithms to synthesize simple joint and multiple joint kinematic chains, and the longest loop was selected as the peripheral loop to sketch topological graphs.

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In the synthesis of kinematic chains [1–14], the topological structure is usually represented in the numerical form, such as the adjacency matrix and number code. For the reason that, the numerical representation is easy to be computerized to derive all possible topological structures, and detect isomorphic and rigid structures.

The synthesis work is closely followed by the sketching of kinematic chains, for the convenience of designing mechanisms. The sketching work aims to generate visual kinematic chains, which are helpful for the designer to visualize the link-joint inter-relationship of the enumerated results, and carry out the dimension calculation and kinematic analysis.

Because the number of synthesis results is usually very large, the sketching of kinematic chains is desired to be automated to improve the efficiency. Kinematic chains are viewed to have high quality if they meet the following aesthetic criteria, namely minimizing link crossings, maximizing symmetry, and avoiding bends and concave polygons. Among the criteria, minimizing link crossings is the most important one. In 1985, Olson et al. [15] presented a procedure for sketching kinematic chains by acquiring the line graph of topological graph. The procedure was applied to some simple kinematic chains. In the ensuing decades, the procedure was frequently adopted or improved by other researchers in the sketching algorithms. In 1990, Chieng and Hoeltzel [16] developed a method based on joint-to-loop location relation and loop-to-loop location relation to sketch kinematic chains. In 1994, Belfiore and Pennestri [17] sketched the topological graph without edge crossings and then converted the graph into kinematic chain using the concept of line graph. The loops in the topological graph were sketched as convex polygons to avoid link crossings in the kinematic chain. The method was verified by the atlas of 8- and 10-link 1-DOF (degree of freedom) kinematic chains with planar graphs. In 1996, Mauskar and Krishnamurty [18] developed a loop configuration method to sketch kinematic chains. The method was applied to some kinematic chains with up to 12 links. In 2003, Mruthyunjaya [19] reviewed the automatic sketching methods and considered [18] as the most promising method for integrating with the computerized synthesis. In 2007, Nie et al. [20] developed a method based on the independent loops addition or subtraction to sketch kinematic chains. In 2012 and 2013, Pucheta et al. [21,22] developed a loop permutation method to sketch kinematic chains. The link crossings were tested by verifying all possible edge crossings in each two adjacent links, and eliminated by moving the involved joint. The method was applied to kinematic chains with up to 14 links. In 2013, Bedi and Sanyal [23] directly selected the longest loop as the peripheral loop to sketch kinematic chains. However, the link crossings cannot be avoided in many cases. Yan and coworkers [10,11,24,25] applied the concept of line graph to sketch the generalized kinematic chains, illustrated by those chains with up to 8 links. Recently, Yang et al. [26] developed an automatic method to determine the optimal layout of topological graphs. This work can serve as the basis of sketching of kinematic chains.

Most of the existing sketching methods were only applied to some simple kinematic chains with no more than 12 links. These methods can hardly guarantee success for complex kinematic chains. Based on the layout of topological graph acquired in [26], this paper aims to develop a new method for the automatic sketching of planar kinematic chains, including those chains with both planar and non-planar topological graphs. In order to demonstrate the efficiency and validity, the method will be verified by both simple and especially complex kinematic chains. The method can be seamlessly integrated with the computerized synthesis method, and enhance the overall efficiency of design of mechanisms.

The entire paper is arranged as follows. In Section 2, some basic concepts and the basis of the present sketching work are introduced. In Section 3, the process of eliminating extraneous edges in the line graph is developed. In Section 4, the concept of Inner Angle of joint is defined, and a new correction algorithm is proposed to eliminate the unnatural link crossing and concave angle in the defective multiple link. In Section 5, some example kinematic chains are automatically sketched to demonstrate the ability of the method. Besides, the practical application and main merits of the method are discussed.

2. Basic concepts and the basis of the sketching work

2.1. Kinematic chain, topological graph and adjacency matrix

The widely used face-shovel hydraulic excavator shown in Fig. 1(a) is taken as the example machinery. The schematic diagram of the excavator is shown in Fig. 1(b), which is a 12-link 3-DOF mechanism. Links 1 and 12 are respectively the frame and end-effector.

In the conceptual design of mechanisms, the mechanism is usually represented by its kinematic chain. The frame of the mechanism is represented by an appropriate link and all joints are assumed to be revolute joints. The kinematic chain of Fig. 1(b) is shown in Fig. 1(c). In the topological graph, vertices and edges respectively denote the links and joints of the corresponding kinematic chain. The topological graph of Fig. 1(c) is shown in Fig. 1(d). For the convenience of being processed by computer, the topological graph is usually represented by its adjacency matrix in the computerized synthesis. The adjacency matrix is a symmetric matrix with the element $a_{ij} = 1$ if vertex i is adjacent to vertex j, and $a_{ij} = 0$ otherwise. The adjacency matrix of Fig. 1(d) is shown in Fig. 1(e).

2.2. The line graph of topological graph

The line graph has vertices in one-to-one correspondence with the edges of the topological graph. The vertex of the line graph is usually located at the midpoint of the corresponding edge of the topological graph. Two vertices of the line graph are connected by an edge if the corresponding edges of the topological graph are adjacent [15]. For example, Fig. 2(a)