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AN IMPROVED APPROACH TO AUTOMATIC SKETCHING OF MECHANISM BASED ON LOOP CONFIGURATION AND ITS IMPLEMENTATION

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Abstract: An improved approach to automatic sketching of planar kinematic chain from its adjacent matrix is proposed in this paper. The basic loops of the graph, which correspond to the adjacent matrix of kinematic chain, are derived by means of breadth-first spanning tree, then these loops are standardized and configured according to some steps. Finally, the graph of kinematic chain is automatically sketched in terms of the configured loops. In addition, the comparison between the proposed approach and existing ones is made. Through some application examples, its effectiveness as well as completeness is verified, the corresponding computer prototype system is also implemented.

INTRODUCTION

In the mechanical creative design (Johnson and Ray, 1978) field, various methodologies (F. Buchsbaum and F. Freudenstein, 1970; R. Ravisankar and T. S. Mruthyunjava, 1985; H. S. Yan, 1992) had been proposed for the computerization and automatization of whole design process. However, the results of these methods, which are usually presented in numbers or symbols, are not visible for designers. As a result, designers have to take great pains to sketch the mechanisms manually. This problem is especially profound in the type synthesis process of higher order mechanisms, in which there are a large number of candidate solutions. Therefore, it is of great significance to develop an automated approach to mechanism sketching, which will enable designer to systematically visualize the link-joint relationship of the enumerated candidate mechanisms and improve the efficiency of computer-aided mechanisms design.

In 1967, Freudenstein and Dobransky began to research on this problem, whereas their routine did not address the issue of non-crossing of links. After that, Woo (1972), Olsen et al. (1985), Hoetzal and Chieng (1990), Belfiore and Pennestri (1994) made some further study, while all those approaches proposed had respective defects, which limited the application in mechanism type synthesis. In 1996, Mauskar and Krishnamurty developed a new method, through which mechanisms with more than ten links and single or multi degree of freedom can be sketched successfully based on loop configuration. However, the way to generate loops and determine the relations between loops in their approach is too complex. In this paper, the idea of loop configuration is referred and an improved simple approach to generate and rearrange loops is proposed to improve the efficiency and completeness of automatic sketching.

PROCEDURE OF THE PROPOSED APPROACH

The goal of type synthesis process is to get the basic kinematic chains and the corresponding mechanisms that satisfy topological requirements, as well as the determination of distinct inputs, outputs and joint type based on functional requirements. Different methods had been proposed to realize the automation and computerization of type synthesis process, the results of them are usually presented by link-link adjacent matrix, which well indicate the inter-relationship between links of mechanism, or numerical representation of adjacent matrix such as standard code (Shin and Krishnamurt, 1994). To make these results visible, graph theory (Gibbons and Alan, 1985) is widely adopted. The approach proposed by Mauskar and Krishnamurty was based on configuration of independent loops, which can fully express the topological information of mechanism, and the kernel of it was the generation of loops and determination of the inter-relationship between loops. In this paper, the improved approach is also based on loop configuration. However, independent loops are generated from the corresponding Breadth-First Spanning Tree (BFST for short) of adjacent matrix, in addition, the inter-relationship between loops is derived from several simple rules. The procedure of the proposed approach is shown in Fig. 1.

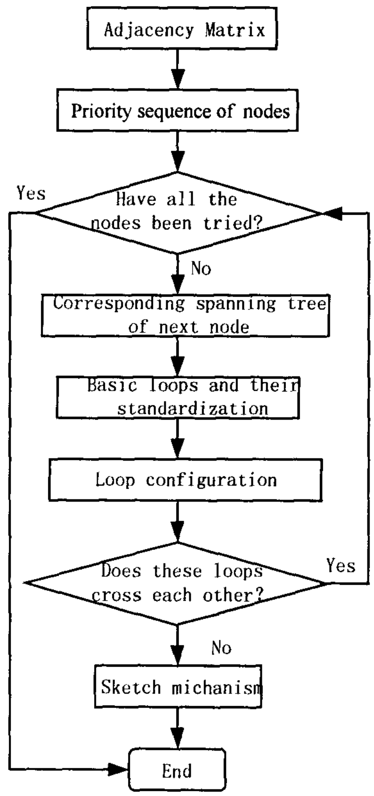
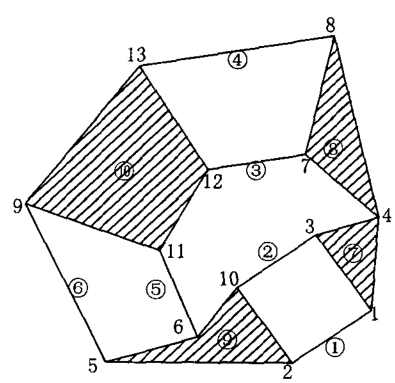


Fig.1 Flow chart of the proposed approach based on loop configuration

PRINCIPLE OF THE PROPOSED APPROACH

Generation of Basic Loops

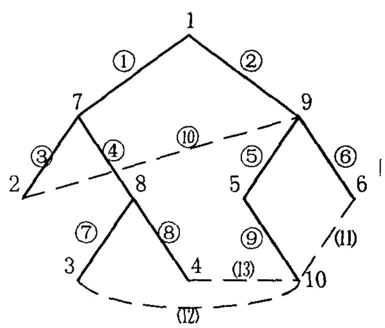
According to the adjacent matrix $M_{n \times n}$, an arbitrary link is selected as the root of spanning tree, then a BFST, in which nodes denote links and branches denote joints, is attained based on breadth-first algorithm. Let T be a BFST and e be an edge in $\overline{T}$, the cotree of T, then according to the graph theory, T and e form a loop and it is independent of other loops generated in the same way. Therefore, the basic loops of mechanism can be derived from corresponding adjacent matrix. For convenience, we number the branches in BFST according to principle of breadth-first, edges in the cotree are numbered after the branches according to the corresponding loop. In addition, we assume the direction of loop is counter-clockwise. For example, the kinermatic chain with ten links and thirteen joints is shown in Fig. 2(a), the corresponding adjacent matrix is shown in Fig. 2(b). Take link 1 as the root of BFST, we can get the corresponding BFST shown in Fig. 2(c), Fig. 2(d) shows the four independent loops, which form the basis for mechanism sketches.



(a) Kinermatic chain
(Standard Code-2570 10652896)

$$M_{10\times 10} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 \\ 1 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 & 0 & 0 & 1 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 \end{bmatrix}$$

(b) Link-link adjacent matrix



(c) BFST whose root node is node 1

	node sequence	edge sequence
L_1:	[1 7 2 9]	[1 3 10 2]
L_2:	[9 5 10 6]	[5 9 11 6]
L_3:	[1 7 8 3 10 5 9]	[1 4 7 12 9 5 2]
L_4:	[1 7 8 4 10 5 9]	[1 4 8 13 9 5 2]

(d) Independent loops

Fig.2 Generation of basic loops of a ten bar mechanism with one degree of freedom

Standardization of Basic Loops

Definition 1: If the node sequence of a basic loop does not contain the root node of corresponding BFST, then this basic loop is called local loop. On the contrary, a basic loop with a node sequence that contains the root node is called global loop.

Definition 2: If a basic loop is a local one, there must be one global loop that contains most common edges in it. Use other edges in the local loop to replace those common edges in the global loop, then the new loop formed is used to take the place of original local loop, this operation is called the standardization of local loop and the loop generated is called the standardized loop of original local one.

Since basic loops are independent from each other, the standardized loops are still independent from each other. Obviously, the standardization operation keeps the global loop unaltered.

According to the loop configuration idea of Mauskar and Krishnamurty, it is the necessary condition of non-crossing sketching that all the loops must have a common node. The standardized loops are independent from each other, which also contain the root node of BFST, thereby the conditions of non-crossing sketching is satisfied. In order to decrease the complexity of computation, the less the number of local loops is, the better is the result. Therefore, before the loop configuration process, the corresponding local loops number of each node, when it is regarded as the root node of BFST, is calculated, and then all the nodes are reordered according to them and form a priority sequence of nodes. Note that the nodes whose degree is bigger than 2 may cause the standardized loops to have no common edge, so these nodes are deleted from the priority sequence of nodes firstly.

For example, the loop L_2 in the four basic loops shown in Figure 2(d) is a local loop; it has common edges (e_5 and e_9) to loop L_3. After standardization operation, the four loops are L_1: [1 3 10 2], *L2*: [1 4 7 12 11 6 2], *L3*: [1 4 7 12 9 5 2], *L4*: [1 4 8 13 9 5 2].

Loop Configuration of Standardized Loops

Loop configuration is a symbolic representation of the relationship between the independent loops in a mechanism. The relationship that loop L_i is exterior to loop L_j can be expressed symbolically as $L_j<L_i$, and such relationship can be extended to mechanism with any number of loops. Let L_e denote the most exterior loop current, then the relationship between the independent loops can be derived according to the following steps.

Step 1: Select a node from the priority sequence of nodes as the root node of BFST, and then generate the corresponding standardized loops.

Step 2: Select the loop that has the minimum number of edges as the first loop, viz. this loop is the most interior loop.

Step 3: Search a loop from the loops that have been assigned a definite relationship with other loops, if L_i has the maximum number of common edges to L_e, then $L_e< L_i$ and L_i becomes the new L_e. If there are some loops that have the same maximum number of common edges to L_e, select a loop whose edge number is smaller than other ones as the new L_e. Continue this step until all the standardized loops have definite relation with each other.

Step 4: if $L_j< L_i$, mark the all the edges that in L_j but not in L_i, then check whether the outer loops contain those edges or not. If yes, there must be cross between this group of standardized loops, go back to step1; Otherwise, the loop configuration attained in step 3 can be used to sketch non-crossing mechanism, stop.

Step 3 can determine the relation between standardized loops. According to the character of BFST, the common edges between two non-crossing loops only locate at the two ends of loops, i.e. the edges that near the root node. Therefore, we can make use of the depth information of common edges and put the loop that have the smaller depth of common edge to internal loop. Therefore, the steps of loop configuration are reasonable.

Step 4 is used to detect whether there are cross between loops. If $L_i<L_j< L_k$ and L_k contain edges that in L_i but not in L_j, it's clear that L_j and L_k cross each other.

For example, the loop configuration result of the four standardized loops shown in Fig. 2(d) is $L_1 <L_2 <L_3 <L_4$, and there is no cross between these four loops.

Automatic Sketching According to Loop Configuration Result

According to the result of loop configuration, it is easy to sketch the mechanism. Mauskar and Krishnamurty had discussed this method in detail, so it is omitted here. In their paper, they also addressed three potential issues, i.e. self-crossing, inter-loop crossing and link self-crossing. In the software system named SKETCH described in Section 6, links, joins can be dynamically draggled, and such problems are easy to be avoided.

SOME ANALYSIS AND DISCUSSION

Comparing with the approach proposed by Mauskar and Krishnamurty, the improved approach has the following advantages:

(1) Optimal strategy is adopted in this improved approach and the complexity of calculation is decreased. In the paper of Mauskar and Krishnamurty, heuristics was used. A joint was taken as the common joint at random to construct incidence matrix, oriented loop matrix, and then to get the corresponding loop configuration result, if cross exists between loops, try another joint again. Obviously there are some redundant loop generation and configuration whose mean number is $n/2-1$, in which n denotes the number of independent loops. Furthermore, in the process of identify the cross between loops, two rules are used to check every three loops, so the complexity of this process is $2C_n^3$ and the complexity of their approach is $O(n^4)$. In this paper, however, priority sequence of nodes is attained firstly and some redundant calculations are avoided. Mostly, only one time of loop generation and configuration is enough. In addition, the complexity of cross-identifying process is C_n^2, so the complexity of the approach in this paper is $O(n^3)$ and greatly improved the computing efficiency, the comparison of computing complexity between the two algorithms can be seen in Fig. 3.

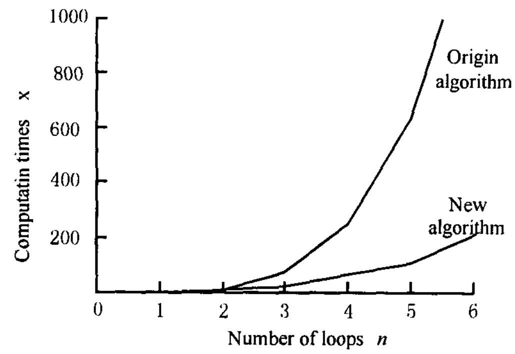


Fig.3 The comparison of computing complexity between the two algorithms

(2) The proposed approach has better completeness. In the paper of Mauskar and Krishnamurty, heuristics rather than definite rules were adopted in loop calculation of those loops that do not contain the common joint, i.e. the local loop defined in this paper. It works well when the number of independent loops is small; however, it may take the valid candidate groups of loops as invalid when the number of independent loops becomes lager. Such problem can be solved successfully with the standardization operation in this paper. As a result, the completeness of the improved approach is improved.

In next section, an example is given to show the advantages of our approach.

AN EXAMPLE OF AUTOMATIC SKETCHING

The basic steps involved in the improved algorithm are illustrated with the aid of a 12 bar one degree of freedom mechanism. The input is its standard code 1313297,36832270, and the corresponding link-link adjacent matrix is shown in Fig. 4(a).

(1) Take each node as the root node to construct the corresponding Breadth-First Spanning Trees, then count the number of local loops in each tree, and then a priority sequence of nodes in sort ascending is attained according to these numbers. In this example, priority sequence of nodes is {2, 3 ,8 ,10 ,12, 4, 5, 6, 7, 11, 1, 9}, corresponding numbers of local loops is {0, 0, 0, 0, 0, 1, 1, 1, 1, 1, 2, 2}. After delete the node whose degree is more than two, the priority sequence of nodes at last is {2, 3, 4, 5, 6, 7, 1}.

(2) Take a node from the priority sequence above to generate basic loops. In this example, the BFST whose root node is node 2 should be considered first, because the number of local loops in this tree is zero, the basic independent loops in this tree do not need standardization operation. In order to illustrate the generality of the improved approach, node 1,the corresponding local loops number of which is two, is taken as the root node, the result of loop generation is L_1[3 8 12 5]、L_2[5 9 13 6]、L_3[1 3 8 14 7 2]、L_4[1 3 8 15 9 5 2]、L_5[1 3 8 11 16 10 7 2], Fig. 4(b) shows the Breadth-First Spanning Tree with the root node 1.

(3) The standardization of the five basic independent loops. In this example, the result of standardization operation is: L1[1 4 12 14 7 2], L2[1 3 8 15 13 6 2], L3[1 3 8 14 7 2], L4[1 3 8 15 9 5 2], L5[1 3 8 11 16 10 7 2].

(4) Loop configuration. If any cross between standardized loops is detected, go back to step 2, take next node as root node, and continue. In this example, the result of loop configuration is L1< L3 <L5<L4 <L2. In addition, there is no cross between all the standardized loops from L1 to L2.

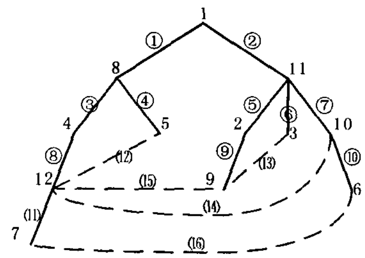
(5) Sketch the mechanism. From the result of loop configuration above, the mechanism is sketched as shown on the left part of Fig. 4(c). In paper of Mauskar and Krishnamurty, node 1 was taken as the common joint to all independent loops firstly, yet the result of loop configuration was regard as an invalid result. In fact, it is valid by using the improved algorithm in this paper. Furthermore, if node 2 is regard as root node, the corresponding sketch (the right part of Fig. 4(c)) is same as the result in paper of Mauskar and Krishnamurty. Thus it can be seen that the higher completeness of the improved approach.

PROTOTYPE SYSTEM

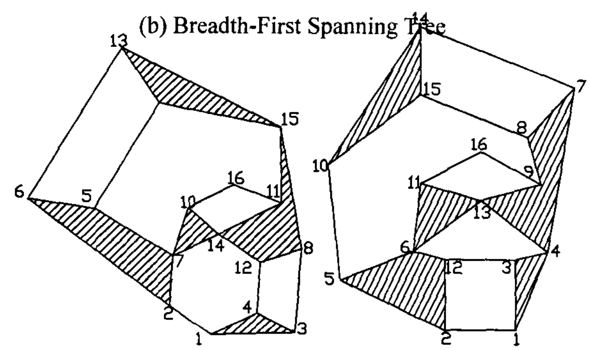
Base on the above work, a prototype system named SKETCH is developed. Furthermore, the system has been tested for all of 6~11 bar single/multi degree mechanisms and several 12 bar ones.

$$\begin{bmatrix}
0&0&0&0&0&0&0&1&0&0&1&0\\
0&0&0&0&0&0&0&0&1&0&1&0\\
0&0&0&0&0&0&0&0&1&0&1&0\\
0&0&0&0&0&0&0&1&0&0&0&1\\
0&0&0&0&0&0&0&1&0&0&0&1\\
0&0&0&0&0&0&1&0&0&1&0&0\\
0&0&0&0&0&1&0&0&0&0&0&1\\
1&0&0&1&1&0&0&0&0&0&0&0\\
0&1&1&0&0&0&0&0&0&0&0&1\\
0&0&0&0&0&1&0&0&0&0&1&1\\
1&1&1&0&0&0&0&0&0&1&0&0\\
0&0&0&1&1&0&1&0&1&1&0&0
\end{bmatrix}$$

(a) Link-link adjacency matrix



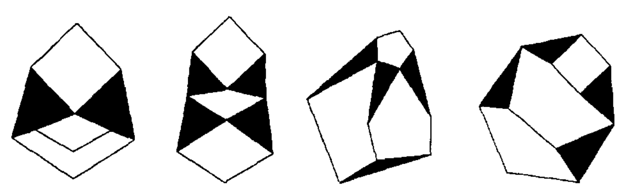
(b) Breadth-First Spanning Tree



(c) Corresponding sketch of the Breadth-First Spanning Tree with root node 1 (left) and 2 (right)

Fig. 4 Result of a 12 bar one degree of freedom mechanism

Fig. 5 shows several mechanism examples. Mechanisms that cannot be sketched without crossing can be identified as well, Fig. 6 shows one such 10 bar mechanism. Fig. 7 shows the interface of the prototype system and the loop configuration result of the mechanism in Fig. 6.



38082635 15114456 9, 25514115 12, 6414610

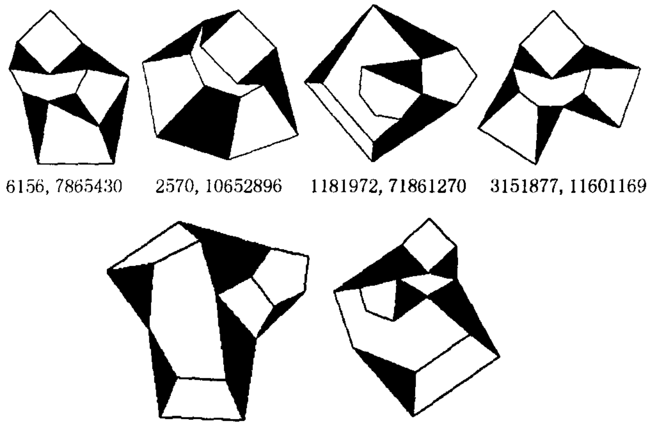


Fig. 5 Examples of sketched mechanisms and their standard code

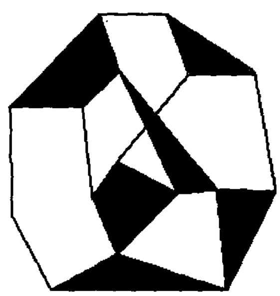


Fig. 6 An Example of a mechanism without non-crossing configurations

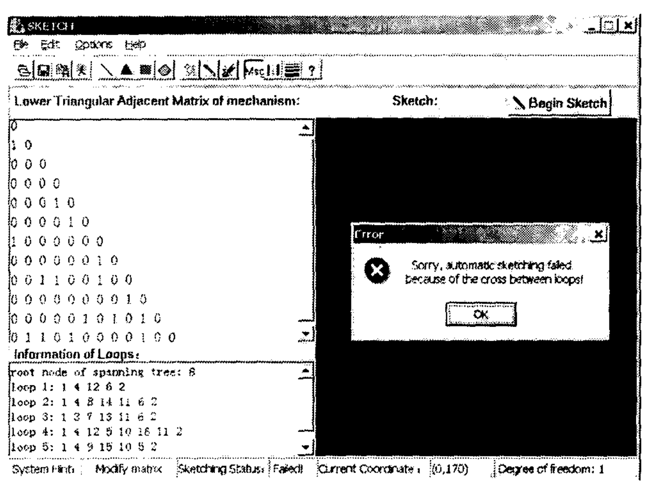


Fig. 7 The interface of prototype system-SKETCH and the loop configuration result of the mechanism in Fig. 5

CONCLUDING REMARKS

An improved approach based on loop configuration is proposed in this paper, which is simple and improves the efficiency and completeness. The results analysis and discussion as well as application examples shows that this method is valid and efficient in the sketching process of arbitrary number of links or degrees of freedom. It is expected to help designer select candidate mechanisms efficiently in the type synthesis process. Moreover, it will serve as a stepping-stone in the automation and computerization of the whole mechanism creative design process.

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