IJRAME
ISSN (ONLINE): 2321-3051
INTERNATIONAL JOURNAL OF RESEARCH IN AERONAUTICAL AND MECHANICAL ENGINEERING

A NEW THEORY (BASED ON INVARIENT LABELING OF LINKS) FOR TOPOLOGICAL STRUCTURE ANALYSIS OF KINEMATIC CHAINS

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Abstract

This work presents a new method to identify isomorphism of kinematic chains and distinct mechanism (DM) derived from the given family of kinematic chains (KCs). The researchers so far have proposed many methods which are mainly based in characteristic polynomial and on some code based method to test the isomorphism among kinematic chains. In this paper a new structured invariant based on link-link shortest path distance and link degree has been developed for a kinematic chains. A unique label using invariant is assigned for each link of kinematic chain. The set of link labels are combined in the form of a numerical label of kinematic chain called Kinematic Chain Label (KCL). KCL is proposed as unique identifier for identification of isomorphism among kinematic chains and also provides the information regarding the distinct mechanism of a kinematic chain. Method is tested on several cases of single degree of freedom planner kinematic chain successfully with simple joints and also tested for nine link two degree of freedom kinematic chains.

Keywords: Isomorphism, kinematic chains, distinct mechanism, link-link shortest path matrix, invariant labelling.

1. Introduction

Detection of isomorphism between kinematic chains and among inversions of a given chain is one of the most important and challenging problem in structural synthesis of kinematic chain. Undetected isomorphism's results in duplicate solutions and an unnecessary effort where as falsely identified isomorphism eliminates possible candidate for new mechanisms. A lot of time and effort has been devoted to develop a reliable and computationally efficient technique. However, scope exists for an efficient and reliable method to detect isomorphism between kinematic chain and among inversions of a given chain.

Various researchers have proposed methods for identification of isomorphism of kinematic chains and identification of distinct inversion. Manolescue[1] reported for the first time a total of 219 distinct mechanisms derived from nine link two degrees of freedom kinematic chain. Mruthyunjaya[2] corrected the above and reported 71, 254 and 1834 distinct mechanisms for eight link single degree of freedom, nine link two degrees of freedom and ten link single degree of freedom kinematic chains. Mrythunjaya and Raghavan[3] used a modified characteristic polynomial for detecting distinct inversions. Ambekar and Agrawal[4] extended the min code approach is identified the inversions corresponding to the original kinematic chain. Patel and Rao[5] presented a method based on velocity graph and motion transfer matrix. The Hamming number technique of Rao and Raju[6] has the potential to disclose the distinct inversions. Chu Jin Kui and Cao Wei Qing[7] extended the link's adjacent chain table for detection of inversions. Yadav et. al.[8] used a new invariant called Arranged Sequence of Modified Total Distance Ranks of all the links(ASMTDRL) incorporating the degree of links, degrees of freedom and types of joint of the kinematic chain to identify the distinct inversions. Sanyal et. al.[9] proposed a link-link probability matrix based method. Fuzzy logic and loop based methods are also presented by Rao and his co-workers[10,11,12]. Srinath and Rao[13] presented a method based on correlation concept for detection of isomorphism among kinematic chains and their inversions. R. Simoni et. al.[14] presented a method based on group theory for enumeration of mechanisms. The symmetry of graphs is identified by a group of autoisomorphism and the set of vertices in same equivalence class is used to identify and symmetrical links - since every kinematic chain can be presented by its graph. Ashok Dargar et. al.[15] used link adjacency values-first and second to identify the distinct inversions. The method has the potential of identifying the isomorphic kinematic chains also. Bedi and Sanyal[16,17] has presented joint connectivity approach for detection of isomorphism and distinct inversions of planner kinematic chains. The method[18] proposed by them also identifies unique joints in a kinematic chain.

Most of the methods reported so far require complex algorithms to carry out the test. A broad review of the methods published was given Mruthyunjaya[19] and it was conclude that quest for computerstionally efficient, reliable and simple methods is still on. Bearing the above in mind, a methodology based on link-link shortest path distance and degree of links of kinematic chain, as invariant link labels are proposed to detect isomorphism and distinct mechanisms.

2. ARCHITECT OF THE PROPOSED METHOD :-

2.1 Degree of link $d(l_i)$ –

The degree of a link actually represents the type of the link, such as binary, ternary, quaternary links etc. Let the degree of i^{th} link in a kinematic chain be designated $d(L_i)$ and $d(L_i)$ = 2, for binary link, $d(L_i)$ = 3, for ternary link, $d(L_i)$ = 4, for quaternary link and $d(l_i)$ = n, for n-nary link.

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a. Labeling of link (V_i) –

Usually, the canonical labels depend only on the connectivity of the links being labelled together with its immediate neighbours. However, in a closed kinematic chain, links are connected by joints so as to form loops and every link has a distinct relation with every other link in the form of distance between them which is constant and presented here by a matrix is called link path matrix of the chain. Bearing this in mind the usual canonical labelling is extended to include all links of the chain. Canonical label **V** of a link of a kinematic chain, defined here, is a sum of path weighted connectivity of the links. Each link **L** is assigned a label $\mathbf{V_i}$ as follows –

$$V_i = \sum_{J=1}^{N} 1/2^{D_{ij}} \bullet W_j \qquad \text{-----------------(1)}$$

Where W_j is the weight of degree of jth link with related to total degree of kinematic chain . And Wj is related weight of degree of the links which is defined as the ratio between of j^{th} link and total degree of kinematic chain given as

$$\mathbf{W_j = d(L_i) / d(KC)} \qquad \text{-------------------------(2)}$$

To include all links but give a higher path weight to those closest to the link L_i being labelled, a factor of ($½^{Dij}$) is included where, D_{ij} is the distance between the links L_i and L_j. This distance is defined as the shortest path between any two links of a chain. N is the total number of links in the chain being labelled.

Consider for example, six – link; single degree of freedom Watt and Stephenson chain shown in Figs., 1(a) and 1(b), respectively. Invariant link labels are calculated as-

For Watt chain shown in Fig. 1(a), relative weights of 6 links using eq. 2 are

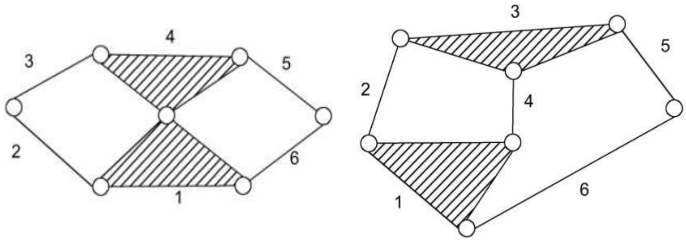


Fig. 1(a) Watt chain **Fig.1(b)Stephenson chain**

1 2 3

4 5 6

0.21428	0.14285	0.14285	0.21428	0.14285	0.14285

And link-link path matrix is

Link	**1**	**2**	**3**	**4**	**5**	**6**
1	0	1	2	1	2	1
2	1	0	1	2	3	2
3	2	1	0	1	2	3
4	1	2	1	0	1	2
5	2	3	2	1	0	1
6	1	2	3	2	1	0

Invarient label for any link is sum of path weight connectivity of all the links. Thus the

$$V_1 = \sum_{J=1}^{N} 1/(2)^{D_{1j}} \bullet W_j$$

---------------------(3)

Thus invariant label $\mathbf{V_1}$ for link 1 of Fig. 1(a).

$= 1/2^0 \bullet 0.21428 + 1/2^1 \bullet 0.14285 + 1/2^2 \bullet 0.14285 + 1/2^1 \bullet 0.21428 + 1/2^2 \bullet 0.14285 + 1/2^1 \bullet 0.14285$.

= 0.5356

Similarly for all the other links, labels can be calculated as shown below.

$\mathbf{V_2}$ = 0.4285, $\mathbf{V_3}$ = 0.4285 , $\mathbf{V_4}$ = 0.5356, $\mathbf{V_5}$= 0.4285, $\mathbf{V_6}$ = 0.4285

So for Watt chain the labels are

[0.5356, 0.4285, 0.4285, 0.5356, 0.4285, 0.4285]

And Squared sum of links labels, defined as kinematic chain label(KCL)

$$KCL = \sum_{i=1}^{N} V_i^2$$

---------------------------(4) and KCL_{watt} is 1.3085

For Stephenson chain shown in Fig.1(b), the labels are [0.5178, 0.4642, 0.5178, 0.4642, 0.4464, 0.4464] and KCL is 1.36564

b. DETECTION OF ISOMORPHISM -

The set of link labels can be directly be used to distinguish kinematic chains. To make it more meaningful the labels calculated above can be combined to generate a numerical code for a kinematic chain. Squared sum of links, defined as kinematic chain label (KCL) is proposed as an index for testing isomorphism. Two chains having identical KCL will be isomorphic to each other.

Application of the concept is illustrated with the help of several examples.

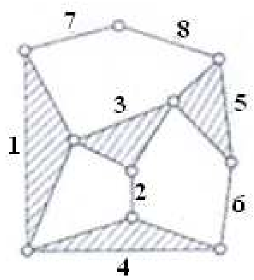
Example 1- Watt and Stephenson chain are shown in Fig. 1 (a) and in Fig. 1(b) respectively. Link labels calculated using equation (1), and (2) for Watt chain is [0.5356, 0.4285, 0.4285, 0.5356, 0.4285, 0.4285] and KCL calculated by equation (3) is equal to 1.3085 and by the comparison of labels of links of kinematic chain (Watt chain) it is found that there two distinct mechanism will be obtained i.e for links (1,4) and for links (2, 3, 5, 6) .

For Stephenson chain the labels are

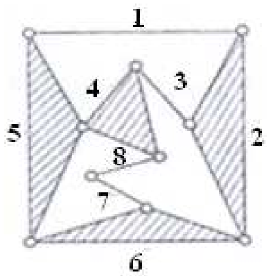
[0.5178, 0.4642, 0.5178, 0.4642, 0.4464, 0.4464] and KCL is 1.365964.

By the comparison of KCL of Watt chain and Stephenson chain it is clear from the result that two chains are distinct.

Example 2 – Consider the two chains shown in Fig.2.



(a)



(b)

Fig. 2 Eight link isomorphic chains

For Fig.2(a), the labels are

[0.4625, 0.375, 0.4625, 0.4375, 0.450, 0.3875, 0.3625,0.3562] and KCL is 1.370820

For Fig.2(b), the labels are

[0.375, 0.4375, 0.3875, 0.45, 0.4625, 0.4625, 0.3625,0.3562] and KCL is 1.370820

The labels and corresponding chain labels for both the figures are identical hence the chains are isomorphic.

Example 3- Consider the two chains shown in Fig 3

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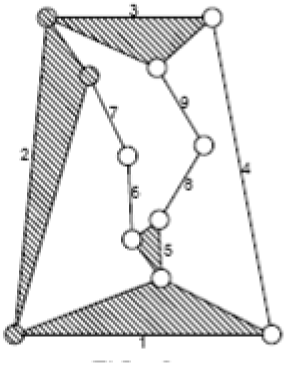
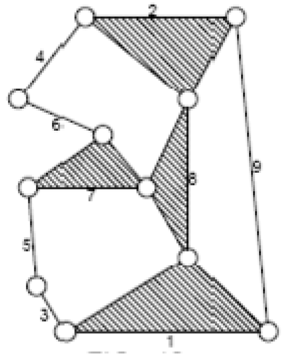


(a)



(b)

Fig.3- 9 links 2 degree of freedom kinematic chains

For Fig.3(a), the labels and KCL are

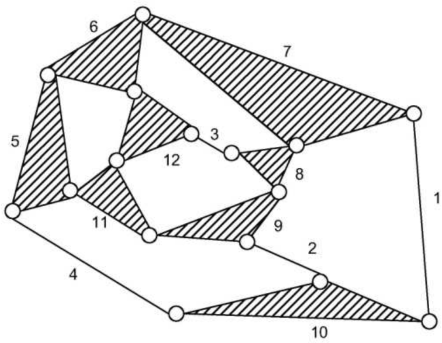
[0.4317, 0.4317, 0.4033, 0.3522, 0.4147, 0.3352, 0.3408, 0.3352, 0.3352] and KCL= 1.2850

For Fig.3(b), the labels and KCL are

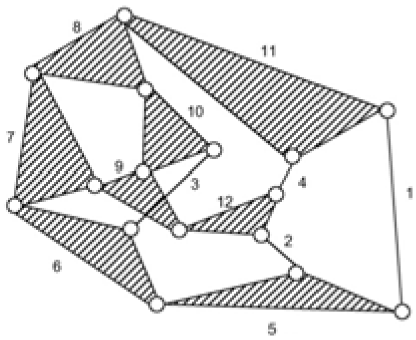
[0.40907, 0.40607, 0.3295, 0.3295, 0.3352, 0.3352, 0.4204, 0.4545, 0.3465] and KCL is 1.20004

The chain label and KCL for Nine link two degree of freedom chain shown in Fig. 3(a) and Fig. 3(b) are non identical, so it is clear from result that two chains are non-isomorphic.

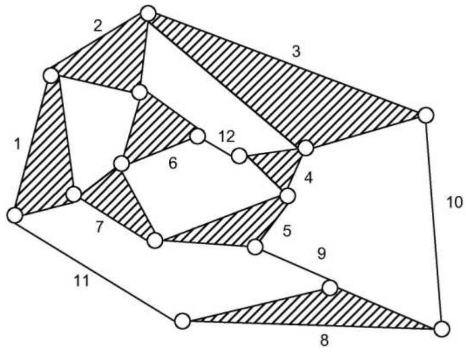
Example 4- Three 12-bars non-isomorphic kinematic chains cited from [12]are shown in Figs.4(a), 4(b) and 4(c) respectively. They have identical characteristic polynomial. The link labels and corresponding chain labels for the fig 4



(a)



(b)



(c)

Fig. 4. Twelve-link 1-dof kinematic chains

Fig.4(a)

Link Labels: [0.2832, 0.2832, 0.2871, 0.2792, 0.3476, 0.3554, 0.3554, 0.3476, 0.3554, 0.3027, 0.3554, 0.3417].

KCL = 1.2764

Fig. 4(c)

Link Labels: [0.3476, 0.3554, 0.3554, 0.3476, 0.3554, 0.3417, 0.3554, 0.3027, 0.2832, 0.2832, 0.2792, 0.2871].

KCL = 1.2764

Fig. 4(b)

Link Labels: [0.2832, 0.2832, 0.2929, 0.2617, 0.3261, 0.3359, 0.3671, 0.3554, 0.3027, 0.33007, 0.3359, 0.3359].

KCL = 1.22147

Chain shown in Fig. 4(a) and 4(c) are isomorphic to each other, only links are relabelled in a different manner. Results clearly show that the invariant is independent of relabeling of links. KCL for Fig 4 is different hence it clearly reflects that the chains are uniquely identified by KCL.

Example 5:- Complete set of 9 links, 2-degree of freedom kinematic chains is shown in Fig. A. The kinematic chain is calculated for each chain and is shown in Table 1. All of these chains have distinct value of KCL. The notation for each family title is given; (number of) pentanaries quaternaries, ternaries and binaries. Thus 1017 stand for one pentanary, zero quaternary, one ternary and seven binaries.

Table: - 1

K.Chain No.	*Chain Family*	*KCL*	*Distinc Mechanism*
	Six links single degree of freedom kinematic chains		
Watt chain	024	1.3085	(1,4), (2,3,5,6) = 2
Stephenson chain	024	1.365964	(1,3), (2,4), (5,6) = 3
	Eight links single degree of freedom - Total no. of D.M = 71[20]		
	Nine links two degree of freedom kinematic chains		
1	0045	1.282528	(1,2,3,4),(5,6,7,8),9 = 3
2	0045	1.28094	(1,3),2,4,5,6,7,8,9 = 8
3	0045	1.2796	(1,2),3,(4,5),(6,7,8),9 = 5
4	0045	1.22616	(1,2),(3,4),(5,6),(7,9),8 = 5
5	0045	1.2384	(1,2),(3,4),(5,6),(7,8),9 = 5
6	0045	1.2158	(1,2),(3,4),(5,6),7,8,9 = 6
7	0045	1.27158	1,2,3,4,5,6,7,8,9 = 9
8	0045	1.23049	(1,2),(3,4),(5,6),(7,8),9 = 5
9	0045	1.2850	(1,2),3,4,5,(6,8,9),7 = 6
10	0045	1.20004	(1,2),(3,4),(5,6),7,8,9 = 6
11	0045	1.27826	(1,2),(3,4),(5,6),(7,8),9 =5
12	0045	1.22755	1,2,(3,7),4,5,6,8,9 = 8
13	0045	1.22601	1,2,3,(4,7),5,6,8,9 = 8
14	0045	1.27458	(1,2),(3,4),(5,6),(7,8),9 = 5
15	0045	1.318934	(1,2),(3,4),(5,6),(7,8),9 =5
16	0045	1.32358	1,2,(3,4),(5,6),7,8,9 = 6
17	0045	1.3281	(1,2),(3,4),(5,6),(7,8),9 = 5
18	0045	1.21977	(1,2,3,4),(5,6),(7,8),9 =4
19	0045	1.306408	(1,2,3,4),(5,6),(7,8),9 = 4
20	0126	1.325658	1,2,3,4,5,6,7,8,9 = 9
21	0126	1.310389	(1,7),2,3,4,5,6,8,9 = 8
22	0126	1.3219	(1,2),3,4,5,6,7,8,9 =8
23	0126	1.29337	(1,2),(3,4),(5,6),7,8,9 = 6
24	0126	1.227572	(1,2),(3,4),5,6,7,8,9 = 7
25	0126	1.219074	(1,2)3,4,,5,6,7,8,9, = 8
26	0126	1.35047	1,(2,4),3,5,6,(7,9),8 = 7
27	0126	1.329102	1,2,3,4,5,6,7,8,9 = 9
28	0126	1.259084	(1,2,3,4),(5,6),(7,8),9 = 4
29	0126	1.384818	1,2,3,4,5,6,7,8,9 = 9
30	0126	1.3005897	(1,2),(3,4),(5,6),(7,8),9 = 5
31	0126	1.414255	(1,2),3,(4,9),5,6,7,8 = 7
32	0126	1.30669	(1,2),3,4,5,6,7,8,9 =8
33	0126	1.267876	(1,2,3),4,5,6,7,8,9 = 7
34	0126	1.316317	(1,20,(3,4),(5,6),(7,8),9 = 5
35	0126	1.353471	(1,2),(3,4),(5,6),7,8,9 = 6
36	0207	1.36425	(1,2),(3,4),(5,6),(7,8),9 = 5
37	0207	1.416156	(1,2,3,4,5,6),(7,8),9 = 3
38	0207	1.361932	(1,2,3,4),(5,6),(7,8),9 =3
39	1017	1.363144	(1,2),(3,4),5,6,7,8,9 = 7
40	1017	1.35003	(1,2,5.6),(3,4),7,8,9 =5

			Total D.M. 245

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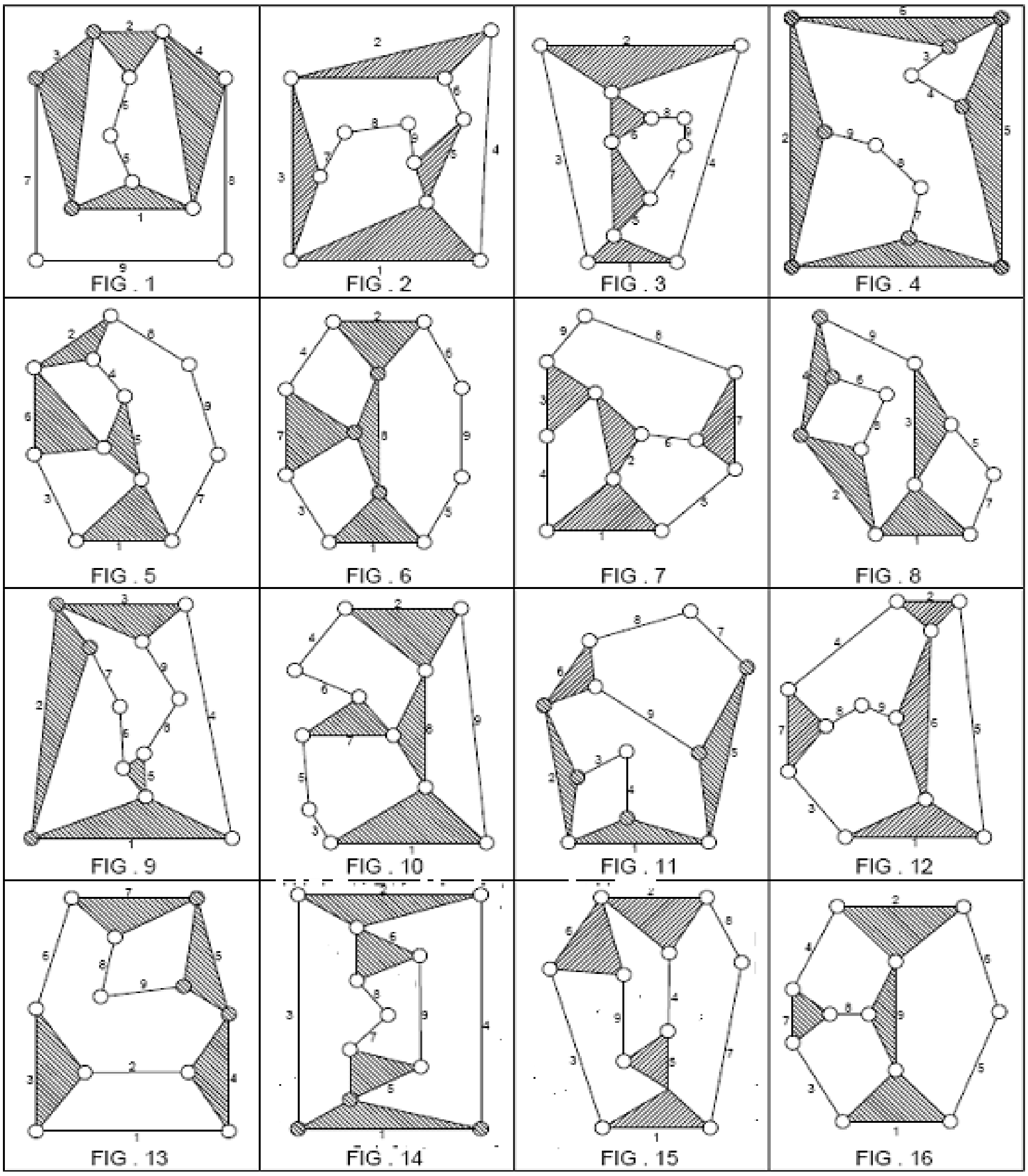
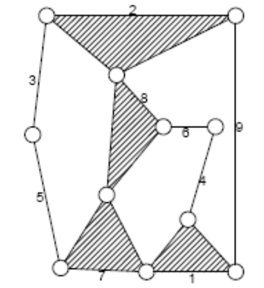
FIG. – A, **(Nine links 2 Degree of freedom kinematic chains)**

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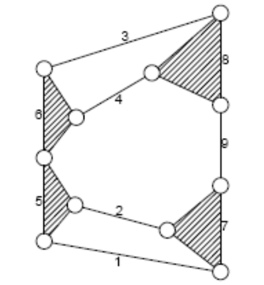
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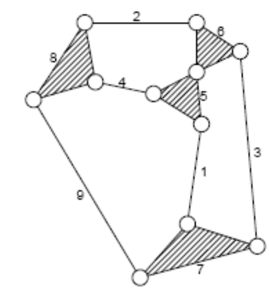
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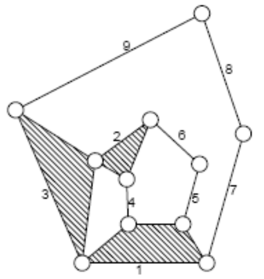
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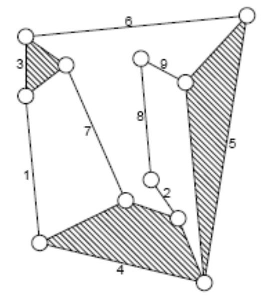
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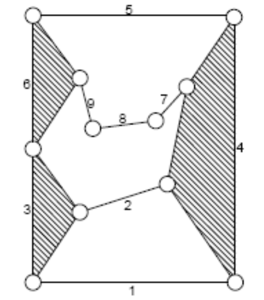
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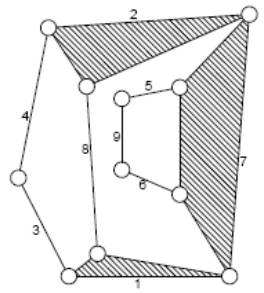
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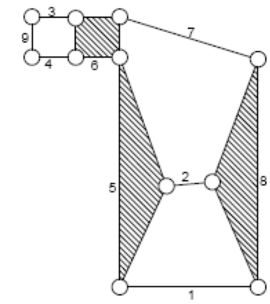
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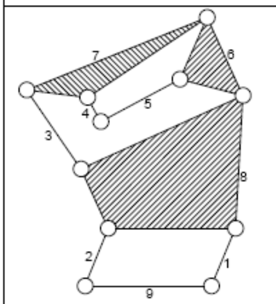
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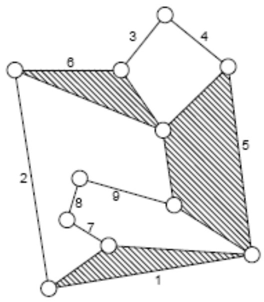
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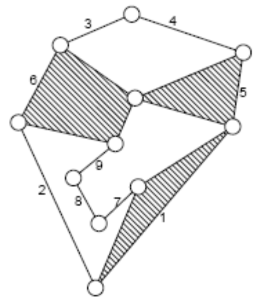
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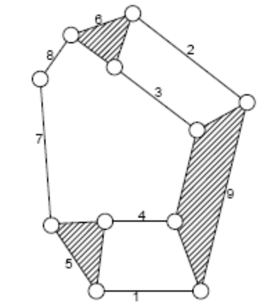
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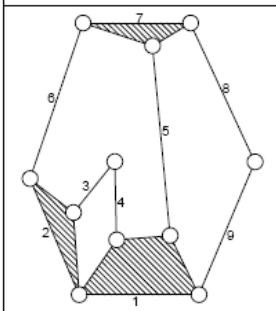
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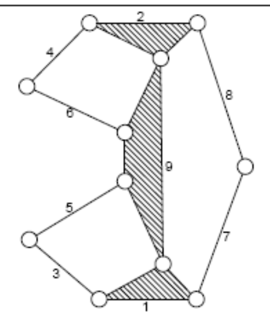
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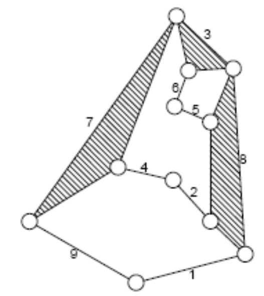
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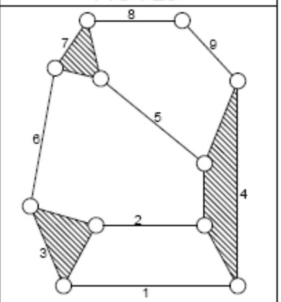
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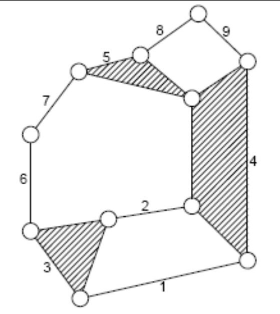
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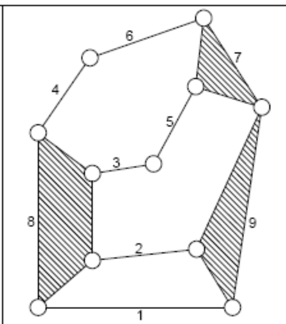
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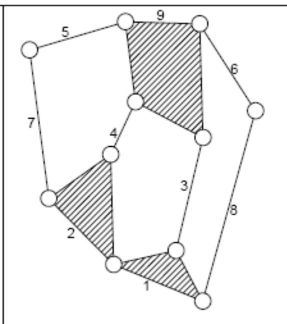
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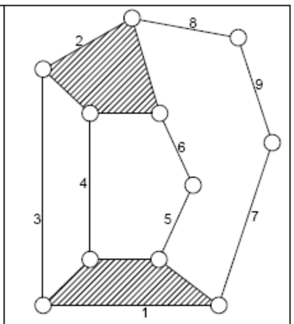
FIG . 36

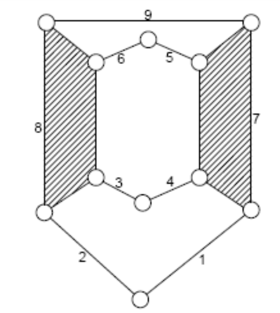
FIG . 37

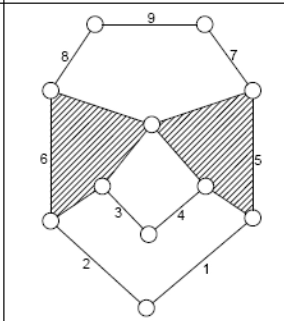
FIG . 38

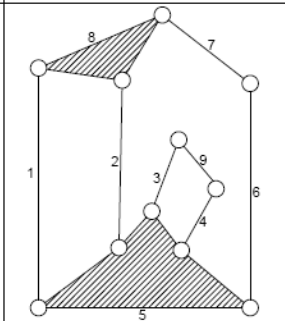
FIG . 39

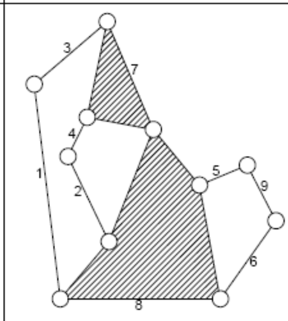
FIG . 40

RESULT AND CONCLUSIONS:-

In this paper a heuristic method for detection of isomorphism and D.M of related family of kinematic chains is presented. The proposed method is tested to obtain isomorphism and all D.M derived from a family of kinematic chain. By present method isomorphism of kinematic chains can be checked with single numerical invariant i:e KCL. And it is found that it is more useful and reliable for detection of isomorphism of any type of family of kinematic chain. Also D.M of kinematic chains are derived from the family of 6 links, 8 links single degree of freedom and 9 links 2 degree of freedom of kinematic chains it is found that results of identification of D.M of single degree of freedom of kinematic chain are accordance with result given by Mruthyunjaya[(2)], but varied for kinematic chains more than one degree of freedom. Proposed method is simple and reliable for identification of isomorphism of any kind of kinematic chain and can be easily be implemented on computer. Table 1 shows the result of 6,8 links single degree of kinematic chains and KCL and D.M of family of 9 links kinematic chains.

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