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Comparative Study of Isomorphism Detection of Kinematic Chains

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***Abstract**: one of the most essential and challenging step in the structural synthesis of any kinematic chain is to detect the possible structural isomorphism to avoid the repetitive work. Over past few decades many researchers reported different techniques to identify the isomorphism of different kinematic chains. In this study, an attempt has been made to compare few of these methods by considering different kinematic chains. It was observed that results obtained from these methods do not concur for all the kinematic chain inversions.*
***Keywords:** Kinematic chain, Inversion, Least path matrix, Isomorphism*

I. INTRODUCTION

One of the most important aspects of structural synthesis is to identify all the possible unique arrangements of kinematic chains for a specific number of links, joints and degrees of freedom, so that the most efficient and optimum mechanism can be obtained. In this course of development of kinematic chains and mechanisms, the major problem will be to identify the possible isomorphism. An undetected isomorphism chain may lead to duplication and unnecessary effort. To avoid this, many researchers have proposed different methods to detect the isomorphism of kinematic chains.

Ambekar et al. [1,2] established a method to check the isomorphism of kinematic chain pair by their canonical coding of corresponding adjacent matrices. Although many researchers [3-5] have worked to improve and modify, this method appears to be less efficient [6]. Rao et al. [7,8] introduced the conception of hamming distances to study kinematic structures. Woo [9] introduced algorithm based approach to understand isomorphism of kinematic chains. Chang et al. [10] proposed the new technique to detect isomorphism of kinematic chains by using the concept of eigen value and eigen vector. Mruthyunjaya [11] proposed a new method of binary coding for structural synthesis of kinematic chains. Yadav et al. [12] used link distance, Kong et al. [13] used artificial neural network and Quist et al. [14] used loop method to detect the isomorphism. Most of these methods have their own short comings. Hence, in this paper an attempt has been made to compare the kinematic chain isomorphism identification results of adjacent matrices method (i.e. Eigen value and Eigen vector approach), least path matrices method, and fuzzy similarity index method.

II. THEORY

A. Procedure To Identify Isomorphism of Two Kinematic Chains Using Adjacent Matrices Method

1) Generate adjacent matrices for both the kinematic chains, say A and B.
2) Calculate eigen values and eigen vectors for both the adjacent matrices.
3) Compare the eigen values of adjacent matrices. If the corresponding eigen values are equal, proceed to next step, else the kinematic chains are non-isomorphic.
4) If the corresponding eigen vectors of both adjacent matrices obtained are equal then proceed to next step, else the kinematic chains are non-isomorphic.
5) Compute row transformation matrix 'T' based on matching eigen vector rows. If $TAT^{-1} = B$ then the kinematic chain is isomorphic.

Fig. 1 shows two inversions of 8 bar kinematic chain mechanisms (6-binary and 2-ternary). Adjacent Matrices Method was used to check the isomorphism of these two kinematic chains.

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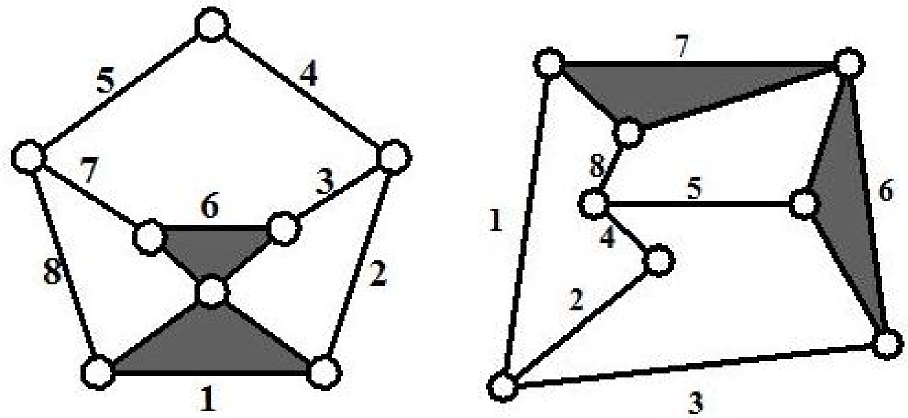


(a) (b)

Fig. 1 Eight link (2- ternary and 6- binary) kinematic chains

The adjacent matrices for the two chains is noted as A and B respectively as shown below:

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 1 & 0 & 1 \\ 1 & 0 & 1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 1 & 0 & 1 & 0 & 0 \\ 0 & 1 & 1 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 1 & 1 \\ 1 & 0 & 1 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 & 0 & 1 \\ 1 & 0 & 0 & 0 & 1 & 0 & 1 & 0 \end{bmatrix} \quad B = \begin{bmatrix} 0 & 1 & 1 & 0 & 0 & 0 & 1 & 0 \\ 1 & 0 & 1 & 1 & 0 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 & 1 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 & 0 & 1 & 0 & 1 \\ 0 & 0 & 1 & 0 & 1 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 & 0 & 1 & 0 & 1 \\ 0 & 0 & 0 & 1 & 1 & 0 & 1 & 0 \end{bmatrix}$$

Eigen values and eigen vectors were computed using MATLAB simulation tool and are tabulated in Table I, II and III. From Table I it is clear that the two adjacent matrices have the same eigen values. From Table II and III it is evident that even eigen values match with each other (1↔6, 2↔5, 3↔8, 4↔4, 5↔2, 6↔7, 7↔1, 8↔3).

TABLE I

EIGEN VALUES OF ADJACENT MATRICES A AND B

A	-2.4142	-1.7321	-1.0000	-1.0000	0.4142	1.0000	1.7321	3.0000
B	-2.4142	-1.7321	-1.0000	-1.0000	0.4142	1.0000	1.7321	3.0000

TABLE III

EIGEN VECTORS OF ADJACENT MATRIX A

0.5000	0.0000	-0.20000	0.2915	-0.5000	0.5000	0.0000	-0.3536
-0.3536	-0.2299	-0.2123	-0.5744	-0.3536	-0.0000	0.4440	-0.3536
0.3536	-0.2299	0.6123	-0.0087	0.3536	0.0000	0.4440	-0.3536
-0.0000	0.6280	-0.2000	0.2915	-0.0000	-0.5000	0.3251	-0.3536
-0.0000	-0.6280	-0.2000	0.2915	-0.0000	-0.5000	-0.3251	-0.3536
-0.5000	-0.0000	-0.2000	0.2915	0.5000	0.5000	-0.0000	-0.3536
0.3536	0.2299	-0.2123	-0.5744	0.3536	-0.0000	-0.4440	-0.3536
-0.3536	0.2299	0.6123	-0.0087	-0.3536	0.0000	-0.4440	-0.3536

TABLE IIIII
EIGEN VECTORS OF ADJACENT MATRIX B

0.3536	0.2299	-0.5935	0.1510	0.3536	-0.0000	-0.4440	0.3536
0.0000	-0.6280	0.2690	0.2294	-0.0000	-0.5000	-0.3251	0.3536
-0.3536	0.2299	0.0555	-0.6099	-0.3536	0.0000	-0.4440	0.3536
-0.0000	0.6280	0.2690	0.2294	-0.0000	-0.5000	0.3251	0.3536
-0.3536	-0.2299	-0.5935	0.1510	-0.3536	0.0000	0.4440	0.3536
0.5000	-0.0000	0.2690	0.2294	-0.5000	0.5000	0.0000	0.3536
-0.5000	-0.0000	0.2690	0.2294	0.5000	0.5000	0.0000	0.3536
0.3536	-0.2299	0.0555	-0.6099	0.3536	-0.0000	0.4440	0.3536

The row transformation matrix is obtained as

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

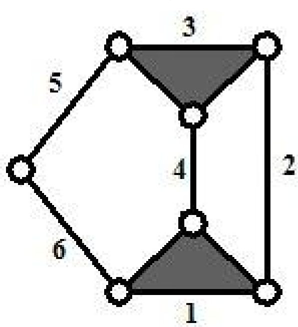
It was also observed that the product TAT^{-1} is equal to B, Hence the kinematic chains considered are isomorphic. The results obtained were compared with J.P. Cubillo et al. [6] and it was evident that the results were in good agreement with each other.

B. Procedure To Identify Isomorphism of Two Kinematic Chains Using Fuzzy Method

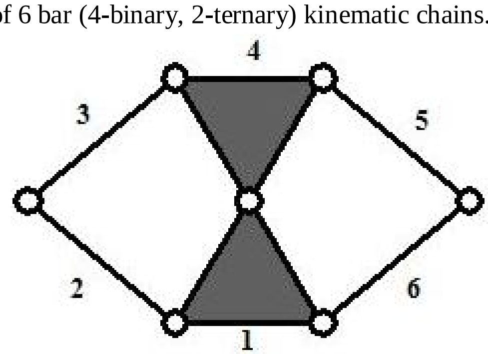
Wang et al. [10] proposed the formulation to identify the isomorphism between the kinematic chains. According to Wang, if the similarity index obtained from equation (1) is equal to 1 then the kinematic chains considered are isomorphic, where as if it is less than 1 then the kinematic chains are said to be non-isomorphic.

$$Sm(A,B) = \sum_{1}^{N} \frac{\min\left(\mu A(x)\mu B(y)\right)}{\max\left(\mu A(x)\mu B(y)\right)} \quad \ldots\ldots\ldots(1)$$

This method is explained by considering two inversions of 6 bar (4-binary, 2-ternary) kinematic chains.



(a)



(b)

Fig. 2 Six link (2- ternary and 4- binary) kinematic chains (a) Stephenson's mechanism (b) Watt's mechanism

Fuzzy numbers were computed for Stephenson's mechanism as shown below:

$$\mu A(1) = \frac{3+2+2+2}{6(6-1)} = \frac{9}{30} = 0.3\,,$$

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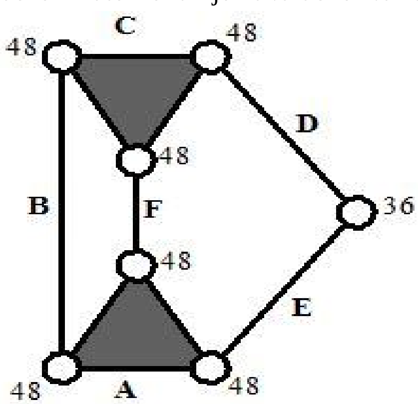
$$\mu A(2) = \frac{8}{30} = 0.26\,, \quad \mu A(3) = \frac{9}{30} = 0.3\,,$$
$$\mu A(4) = \frac{8}{30} = 0.26\,, \quad \mu A(5) = \frac{7}{30} = 0.23\,, \quad \mu A(6) = \frac{7}{30} = 0.23$$

Fuzzy numbers obtained above are arranged in descending order [0.3, 0.3, 0.26, 0.26, 0.23, 0.23]. Similarly the procedure is repeated for watt's chain shown in Fig. 2 (b), to obtain the fuzzy similarity index numbers as [0.3, 0.3, 0.23, 0.23, 0.23, 0.23].
Fuzzy similarity index was obtained by using equation 1, which is 0.96 in magnitude. The value obtained is less than one, hence the kinematic chains considered are non-isomorphic. The results obtained were compared with Kunal et al. [15] and the results were in line with each other.

C. Procedure To Identify Isomorphism of Two Kinematic Chains Using Least Path Method

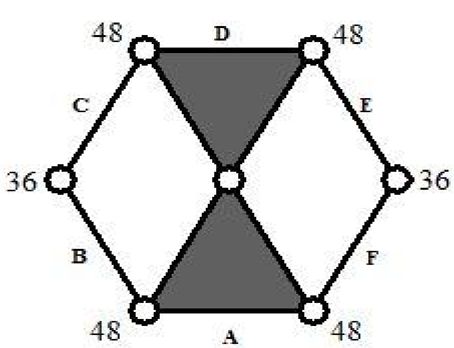
This method involves in detection of isomorphism and inversion by parametric approach. This method is illustrated using Stephenson's and Watt's chain mechanism. By using values on the basis of the parameter a least distance matrix [LDM] is formed. In these mechanisms, each node of quaternary link is assigned a node value "3/4" and for ternary link joint value "2/3" and for binary link joint value of "1/2" is assigned.
For simplicity of calculation to each joint a non fractional value is assigned on the basis of taking L.C.M. of joint values by which we can take same denominator for all joint value for various link connectivities.



LINK	A	B	C	D	E	F	K.L.V.
A	0	48	96	84	48	48	**324**
B	48	0	48	96	96	96	**384**
C	96	48	0	48	84	48	**324**
D	84	96	48	0	36	96	**360**
E	48	96	84	36	0	96	**360**
F	48	96	48	96	96	0	**384**
							2136

Fig. 3 Six bar Stephenson's chain with joint number

Thus at a node joining a ternary & binary, binary & binary links a node value will be assigned as 2/6 and 1/4 respectively. A 6X6 matrix will be formed for a six link Stephenson's chain shown in Fig. 3. Kinematic link value (KLV) for A, B, C, D, E & F are 324, 384, 324, 360, 360 and 384 respectively. Kinematic link string (KLS) for A, B, C, D, E & F are:-[0, 3(48), 84, 96] , [0, 2(48), 3(96)], [0, 3(48), 84, 96], [0, 36, 48, 84, 2(96)], [0, 36, 48, 84, 2(96)], [0, 2(48), 3(96)] respectively. From the above values it is clear that A and C will have the same inversions, link B and F will have same inversions, link D and E will have same inversions. Kinematic string value (KCS) is 2136,2[36,6(48),2(84),6(96)]. Further this method is applied to Watt's chain shown in Fig. 4.



LINK	A	B	C	D	E	F	K.L.V.
A	0	48	84	64	84	48	**328**
B	48	0	36	84	132	96	**396**
C	84	36	0	48	96	132	**396**
D	64	84	48	0	48	84	**328**
E	84	132	96	48	0	36	**396**
F	48	96	132	84	36	0	**396**
							2240

Fig. 4 Six bar Watt's chain with joint number

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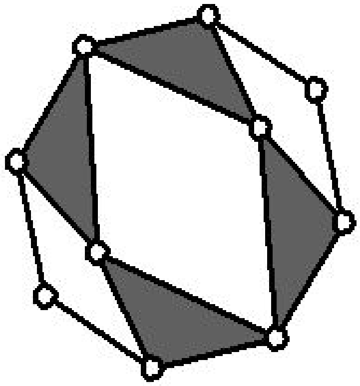
Kinematic link value (KLV) for A, B, C, D, E & F are 328, 396, 396, 328, 396, 396 respectively. Kinematic link string (KLS) for A, B, C, D, E & F are [0, 2(48), 64, 2(84)], [0, 36, 48, 84, 96, 132], [0, 36, 48, 84, 96, 132], [0, 2(48), 64, 2(84)], [0, 36, 48, 84, 96, 132] and [0, 36, 48, 84, 96, 132] respectively. The Kinematic chain string (KCS) is 204.2[2(36), 4(48), 64, 4(84), 2(96), 2(132)]. When both the KCS of two kinematic chains are compared it was found that they are non-isomorphic in nature. The results obtained were coincident with Syed et al. [16].

III.RESULTS AND DISCUSSION

Further the study was extended to understand and analyze all the three methods explained above by considering 19 different 8 link kinematics chains as shown in Fig. 5. Each of these kinematic chains were examined for possible isomorphism.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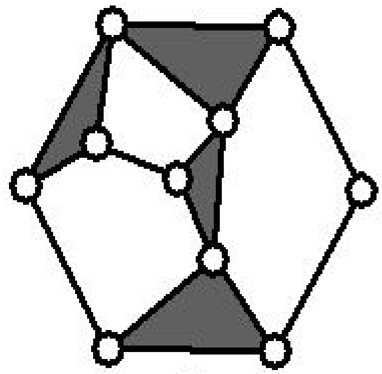
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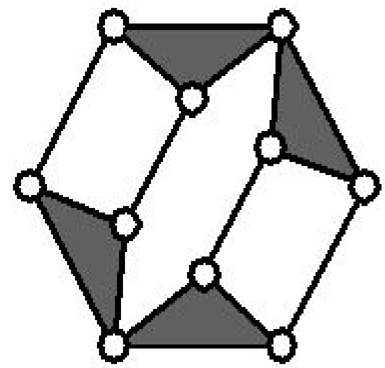
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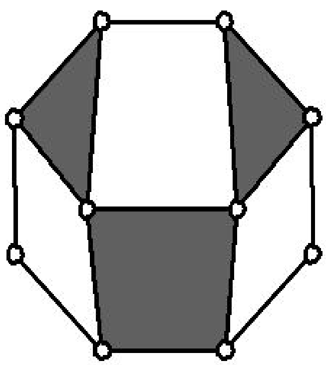
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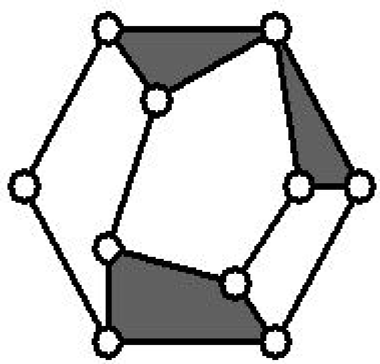
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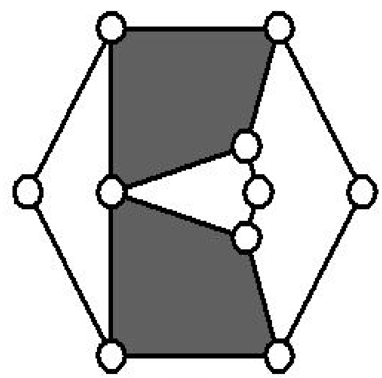
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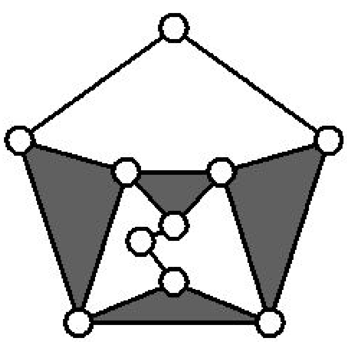
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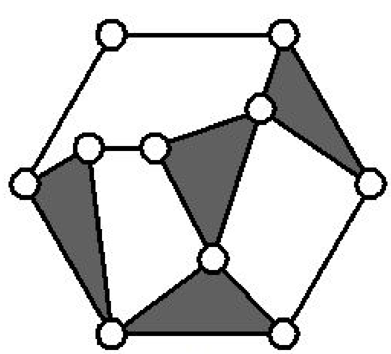
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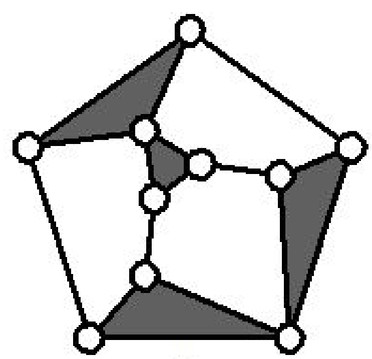
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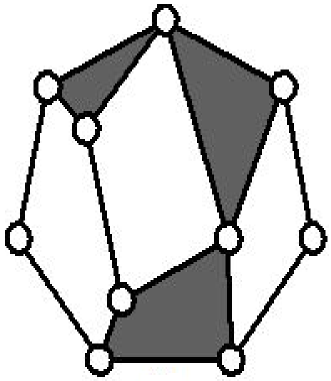
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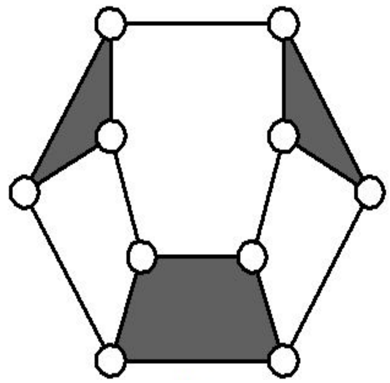
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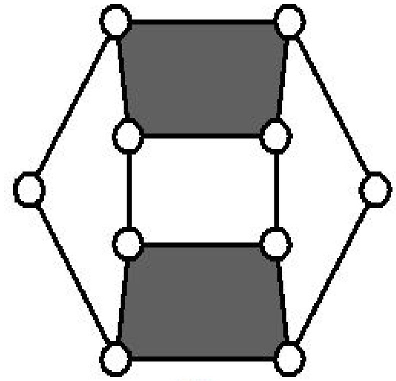
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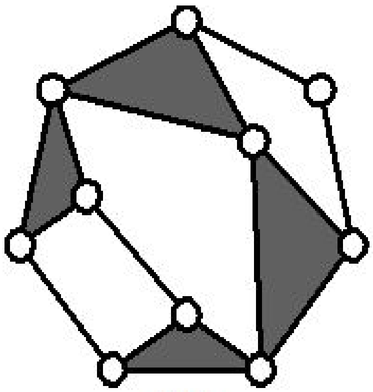
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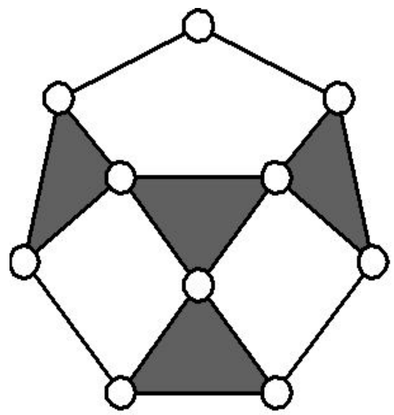
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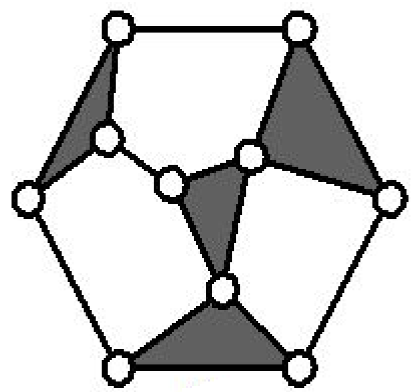
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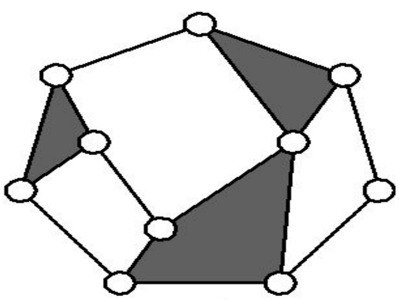
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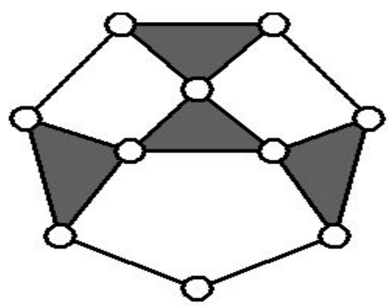
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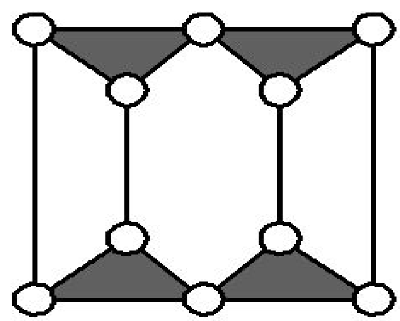
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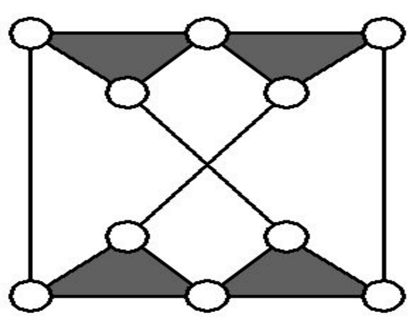
(s)

Fig. 5 Eight link (combination of binary, ternary and quaternary links) kinematic chains

From Table IV it is evident that the results obtained from all the three methods do not concur for the kinematic chains considered for the analysis. According to adjacent matrix method all the kinematic chains considered are non-isomorphic whereas according to least path matrix method kinematic chain pair c-r and i-s isomorphic mechanisms. According to fuzzy similarity index method c-r-i-s, are isomorphic and all other kinematic chains considered are non-isomorphic. It was also observed that the outputs of the adjacent matrix method depend on link numbers assigned and there is no specific method to do the same.

TABLE IV
COMPARATIVE ISOMORPHIC RESULTS OF 19 KINEMATIC CHAINS CONSIDERED

Methods	Isomorphism	Non-Isomorphism
Adjacent Matrix Method	Nil	All
Least Path Matrix Method	(c – r) and (i – s)	All other
Fuzzy Similarity Index Method	(c – r– i – s)	All other

IV. CONCLUSIONS

Comparative analysis of different methods of identifying isomorphic kinematic chain was carried out. Adjacent matrices method (i.e. Eigen value and Eigen vector approach), least path matrices method and fuzzy similarity index methods were chosen for the analysis. 19 inversions of 8 bar kinematic chain mechanisms were selected for the simulations. From the results it was evident that each of these methods have their short comings as they fail to agree in their outcomes.

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