

RESEARCH ARTICLE

DISTINCT MECHANISMS OF 10 LINKS KINEMATIC CHAINS OF GROUP A

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ABSTRACT

In this paper a new, easy, reliable, and efficient method to detect isomorphism and a catalogue of fixed link with its corresponding equivalent links in the distinct mechanisms of kinematic chains of Group-A, has been presented. It is helpful to the new researchers and designers to choose the best mechanism to perform the desired task at the conceptual stage of design. The proposed method is presented by comparing the structural invariants ‘sum of the absolute values of the characteristic polynomial coefficients’ (SCPC) and ‘maximum absolute value of the characteristic polynomial coefficient’ (MCPC) of (JJ) matrices. These invariants are used to detect isomorphism in the mechanism kinematic chain having simple joints. The method is explained with the help of examples of planar kinematic chain.

Key Words: Kinematic Chain, Fixed Link, Equivalent Link, SCPC, MCPC.

INTRODUCTION

Over the past several years much work has been reported in the literature on the structural synthesis of kinematic chains and mechanisms. Undetected isomorphism results in duplicate solutions and unnecessary effort. Therefore, the need for a reliable and efficient algebraic method for this purpose is necessary. Identifying isomorphism among kinematic chains using characteristic polynomials of adjacency matrices of corresponding kinematic chains are simple methods (Uicher and Raicu 1975), (Mruthyunjaya and Raghavan 1979), (Yan and Hall, 1982), (Raicu,1974), (Tuttle,1975). But the reliability of these methods was in questions as several counter examples were found by ((Mruthyunjaya, 1984), (Mruthyunjaya and Balasubramaniam, 1987). The test proposed by Mruthyunjaya (Mruthyunjaya, and Balasubramaniam 1987) is based on characteristic coefficients of the ‘Degree matrix’ of the graph of the kinematic chains.

The elements of the degree matrix were sum of the degree of vertices (degree or type of links) or unity in a link-link adjacency matrix. Later on, this test was also found unreliable. The representation polynomial is the determinant of the generalized adjacency matrix, called representation matrix of the kinematic chain. But the representation matrix requires the use of a large number of symbols, the calculation and comparison of the representation polynomials is not as easy as that of the characteristic coefficients of the adjacency matrix. The reliable procedures are proposed for the purpose by (Mohd,1998), (Rao,1989, 1997, 2000), (Srinath and Rao, 2006), Rao and Rao, 1993, (Rao, Pratap and Deshmukh, 2001), (Yadav, Pratap and Agrawal, 1996), (Yan and Hwang, 1991),

(Zhang and Lio 1999), (Hasan, 2007) and by several other researchers. Several other methods like (Hasan A., 2009, 2010, 2012, 2013), (Agrawal and Rao, 1987), (Ambeker and Agrawal,1987), (Gibson and Marsh,1989) are also in use.

The Joint-Joint (JJ) Matrix

This matrix is based upon the connectivity of the joints through the links and defined, as a square symmetric matrix of size $N \times N$, where n is the number of joints in a kinematic chain.

$$[JJ] = \left\{ \begin{matrix} L_{ij} \end{matrix} \right\}_{N \times N} \quad \text{-----} \quad (1)$$

Where

$$L_{ij} \left\{ \begin{matrix} = \text{Degree of link between } i^{\text{th}} \text{ and } j^{\text{th}} \text{ joints} \\ \text{those are directly connected} \\ = 0, \text{ if joint } i \text{ is not directly connected to joint } j \end{matrix} \right\}$$

Offcourse all the diagonal elements $L_{ii} = 0$

CHARACTERISTIC POLYNOMIAL OF (JJ) MATRIX

$D(\lambda)$ gives the characteristic polynomial of (JJ) matrix. The monic polynomial of degree n is given by equation (2).

$$|(JJ - \lambda I)| = \lambda^n + a_1 \lambda^{n-1} + a_2 \lambda^{n-2} + \text{-----} + a_{n-1} \lambda + a_n$$

(2)

Where; n = number of simple joints in kinematic chain and $1, a_1, a_2, a_{n-1}, a_n$ are the characteristic polynomial coefficients.

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The two important properties of the characteristic polynomials are

The sum of the absolute values of the characteristic polynomial coefficients (SCPC) is an invariant for a (JJ) matrix. i.e.

$$|1| + |a_1| + |a_2| + \dots + |a_{n-1}| + |a_n| = \text{invariant}$$

The maximum absolute value of the characteristic polynomial coefficient (MCPC) is another invariant for a (JJ) matrix.

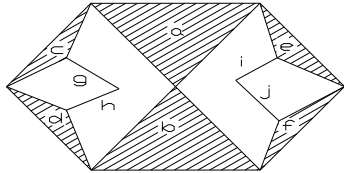
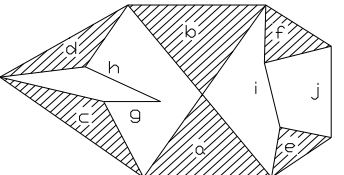
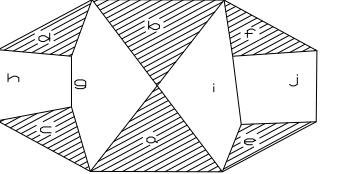
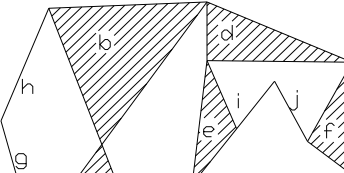
Structural Invariants (SCPC) and (MCPC)

The values of characteristic polynomial coefficients are invariants for a (JJ) matrix. To make these (JJ) matrix characteristic polynomial coefficients as a powerful single number characteristic index, new composite invariants have been proposed.

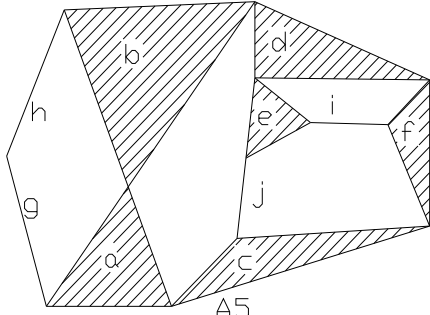
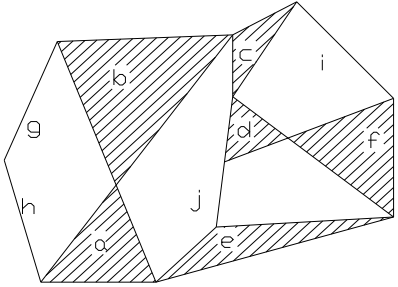
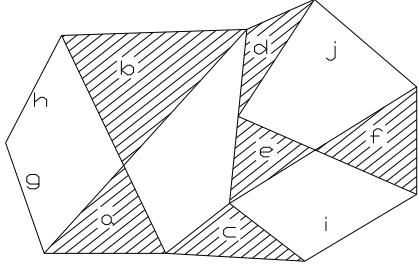
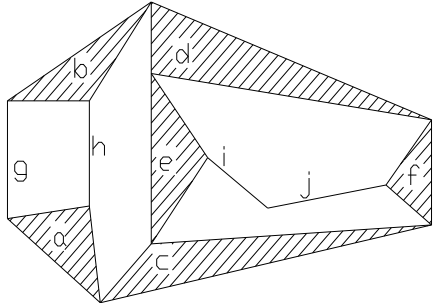
These invariants are ‘SCPC’ and ‘MCPC’. These invariants are unique for a (JJ) matrix and may be used as identification numbers to detect the isomorphism among simple jointed kinematic chains. The characteristic polynomial coefficients values are the characteristic invariants for the kinematic chains. Many investigators have reported co-spectral graph (non-isomorphic graph having same Eigen spectrum).

But these Eigen spectra (Eigen values or characteristic polynomial) have been determined from (0, 1) adjacency matrices. The proposed (JJ) matrix provides distinct set of characteristic polynomial coefficients of the kinematic chains having co-spectral graphs. Therefore, it is verified that the structural invariants ‘SCPC’ and ‘MCPC’ are capable of characterizing all kinematic chains and mechanisms uniquely. Hence, it is possible to detect isomorphism among all the given kinematic chains.

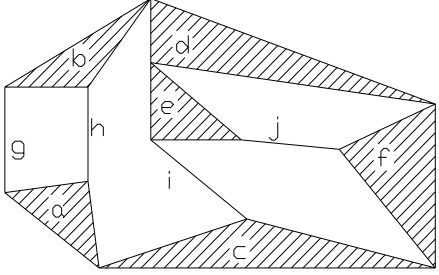
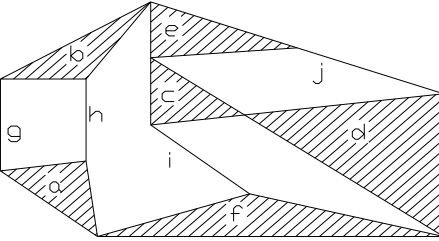
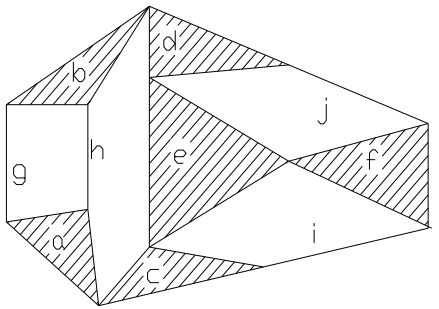
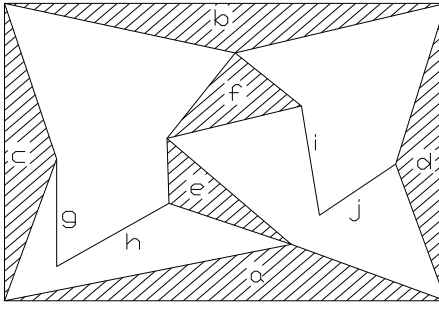
Table-1(A). Distinct mechanisms of 10 links, 13 Joints, 1F Kinematic Chains GROUP A

Kinematic Chain	$n_5 n_4 n_3 n_2$	F. L.	E. L.	D. M.
 <p>A1 SCPC(A1) = 4.9381e+007 MCPC(A1) = 1.6621e+007</p>	0064	a c g	b d, e, f h, i, j	3
 <p>A2 SCPC(A2) = 8.7835e+007 MCPC(A2) = 4.0385e+007</p>	0064	a c e g i	b d f h j	5
 <p>A3 SCPC(A3) = 2.6193e+008 MCPC(A3) = 1.1298e+008</p>	0064	a c g	b d, e, f h, i, j	3
 <p>A4 SCPC(A4) = 7.8600e+007 MCPC(A4) = 3.3592e+007</p>	0064	a c e g i	b d f h j	5

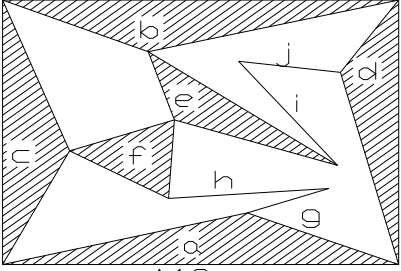
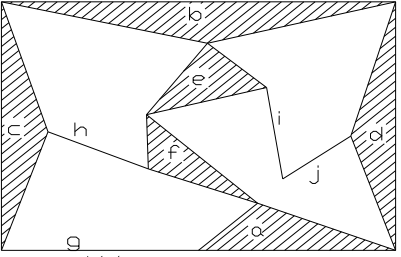
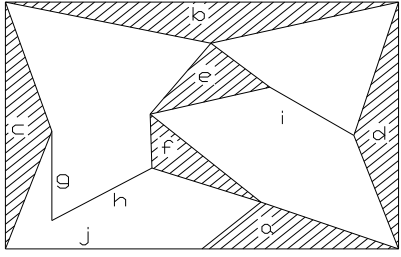
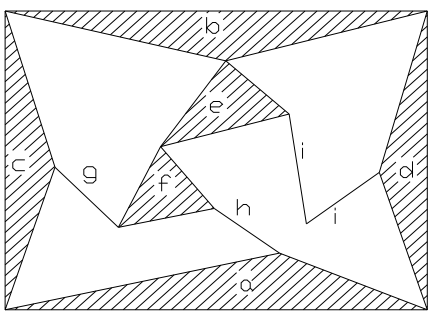
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Kinematic Chain	$n_5 n_4 n_3 n_2$	F. L.	E. L.	D. M.
 <p>A5</p> <p>SCPC(A5) = 6.5867e+007 MCPC(A5) = 3.1871e+007</p>	0064	a b c d e f g h i j	- - - - - - - - - -	10
 <p>A6</p> <p>SCPC(A6) = 6.1025e+007 MCPC(A6) = 2.1748e+007</p>	0064	a c d g i	b e f h j	5
 <p>A7</p> <p>SCPC(A7) = 5.0572e+007 MCPC(A7) = 2.0191e+007</p>	0064	a c e f g i	b d - - h j	6
 <p>A8</p> <p>SCPC(A8) = 8.5189e+007 MCPC(A8) = 3.9001e+007</p>	0064	a c e g i	b d f h j	5

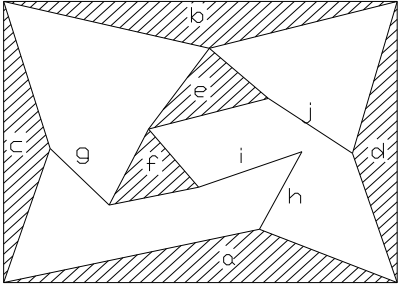
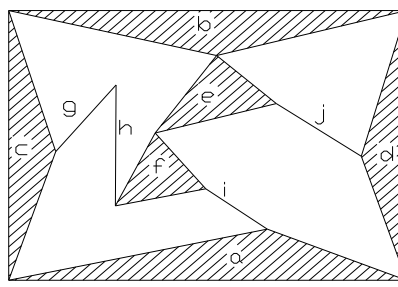
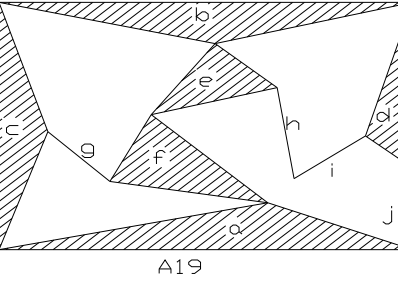
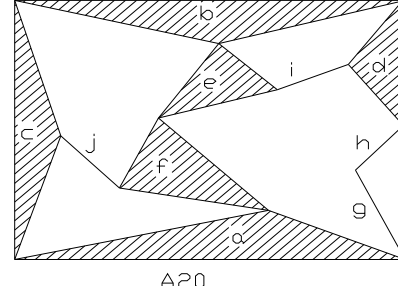
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Kinematic Chain	$n_5 n_4 n_3 n_2$	F. L.	E. L.	D. M.
 <p>A9 SCPC(A9) = 9.7147e+007 MCPC(A9) = 4.0322e+007</p>	0064	a b c d e f g i j	- - - - - h -	9
 <p>A10 SCPC(A10) = 9.1929e+007 MCPC(A10) = 34715628</p>	0064	a c d e g i	b - - f h j	6
 <p>A11 SCPC(A11) = 77678554 MCPC(A11) = 3.4465e+007</p>	0064	a c e f g i	b d - - h j	6
 <p>A12 SCPC(A12) = 1.4560e+008 MCPC(A12) = 6.0466e+007</p>	0064	a c e g h	b d f j i	5

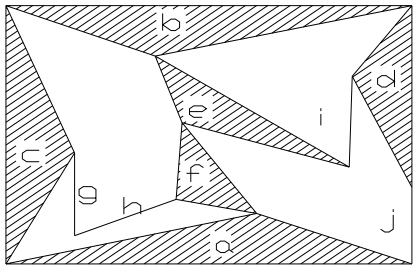
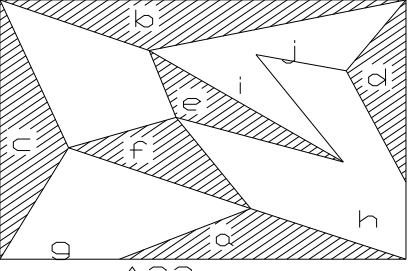
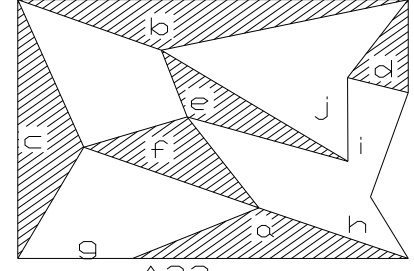
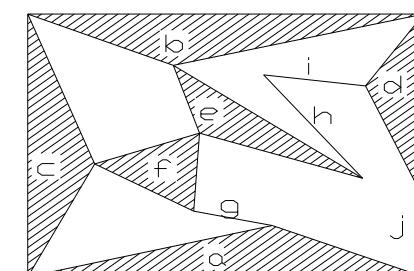
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Kinematic Chain	$n_5 n_4 n_3 n_2$	F. L.	E. L.	D. M.
 <p>A13</p> <p>SCPC(A13) = 9.4899e+007 MCPC(A13) = 3.7791e+007</p>	0064	a b g	d, e, f c h, i, j	3
 <p>A14</p> <p>SCPC(A14) = 2.0475e+008 MCPC(A14) = 8.9650e+007</p>	0064	a b c d g i	f - - e h j	6
 <p>A15</p> <p>SCPC(A15) = 1.1257e+008 MCPC(A15) = 4.5205e+007</p>	0064	a b c d e f g h i j	- - - - - - - - - -	10
 <p>A16</p> <p>SCPC(A16) = 1.6067e+008 MCPC(A16) = 7.1804e+007</p>	0064	a b c d e f g h i j	- - - - - - - - - -	10

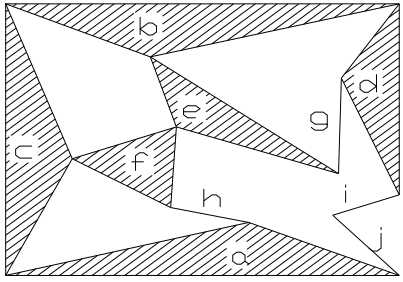
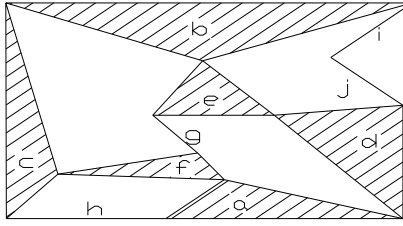
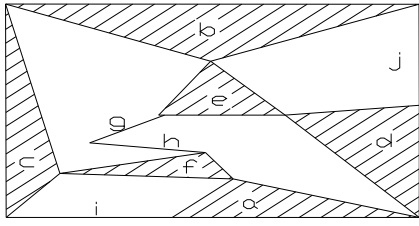
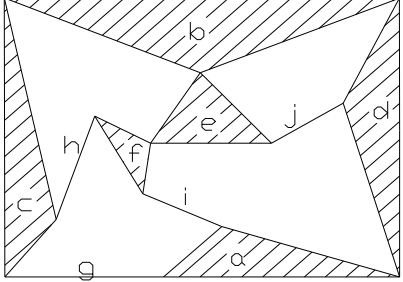
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Kinematic Chain	$n_5 n_4 n_3 n_2$	F. L.	E. L.	D. M.
 <p>A17</p> <p>SCPC(A17) = 8.7034e+007 MCPC(A17) = 3.8005e+007</p>	0064	a b c d e f g h i j	- - - - - - - - - -	10
 <p>A18</p> <p>SCPC(A18) = 9.8173e+007 MCPC(A18) = 4.1209e+007</p>	0064	a b c d e f g h i j	- - - - - - - - - -	10
 <p>A19</p> <p>SCPC(A19) = 1.4957e+008 MCPC(A19) = 6.5715e+007</p>	0064	a b c d e f g h i j	- - - - - - - - - -	10
 <p>A20</p> <p>SCPC(A20) = 5.5881e+007 MCPC(A20) = 3.3914e+007</p>	0064	a b c d e f g h i j	- - - - - - - - - -	10

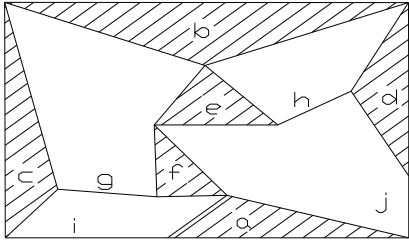
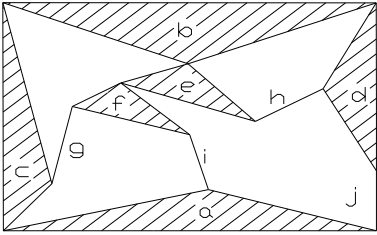
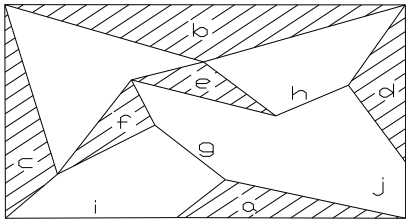
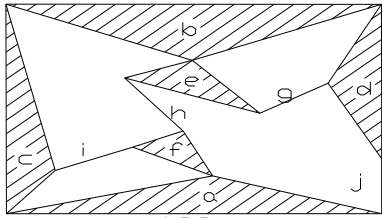
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Kinematic Chain	$n_5 n_4 n_3 n_2$	F. L.	E. L.	D. M.
 <p>A21</p> <p>SCPC(A21) = 1.2525e+008 MCPC(A21) = 5.3337e+007</p>	0064	a b c d e f g h i j	- - - - - - - - - -	10
 <p>A22</p> <p>SCPC(A22) = 1.0178e+008 MCPC(A22) = 4.0245e+007</p>	0064	a b c d e f g h i j	- - - - - - - - - -	10
 <p>A23</p> <p>SCPC(A23) = 5.3724e+007 MCPC(A23) = 2.4553e+007</p>	0064	a b c g h	d f e j i	5
 <p>A24</p> <p>SCPC(A24) = 1.1625e+008 MCPC(A24) = 4.9840e+007</p>	0064	a b c d e f g h i j	- - - - - - - - - -	10

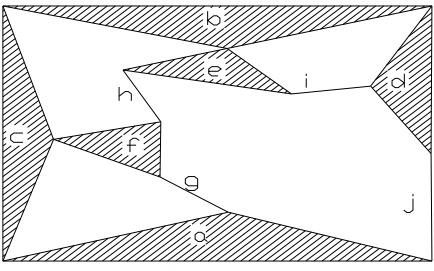
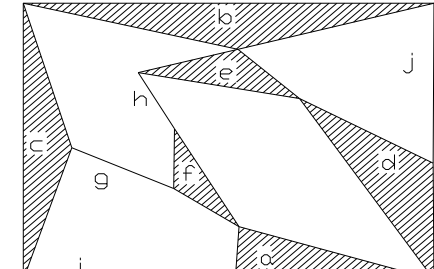
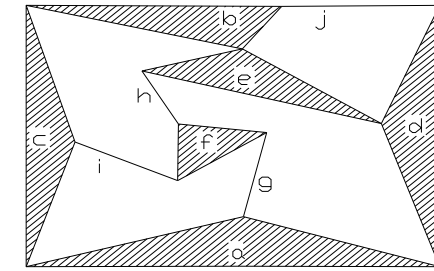
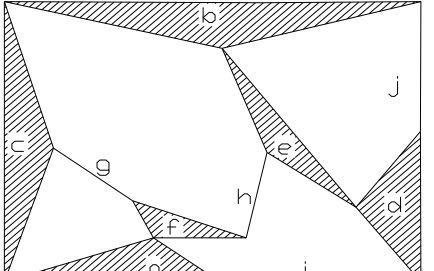
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Kinematic Chain	$n_5 n_4 n_3 n_2$	F. L.	E. L.	D. M.
 <p>A25 SCPC(A25) = 7.2612e+007 MCPC(A25) = 3.7352e+007</p>	0064	a b e g i	d c f h j	5
 <p>A26 SCPC(A26) = 1.3599e+008 MCPC(A26) = 5.4001e+007</p>	0064	a b e f g h i	c d - - - - j	7
 <p>A27 SCPC(A27) = 5.3355e+007 MCPC(A27) = 2.6584e+007</p>	0064	a e g i	b, c, d f h j	4
 <p>A28 SCPC(A28) = 1.4872e+008 MCPC(A28) = 4.7964e+007</p>	0064	a b c d g i j	f - - e h - -	7

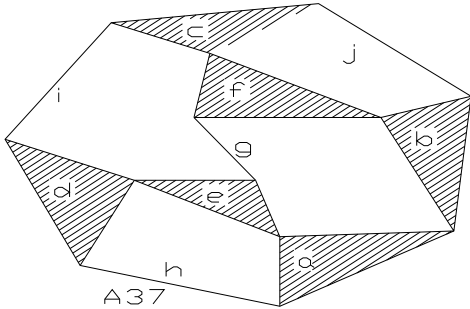
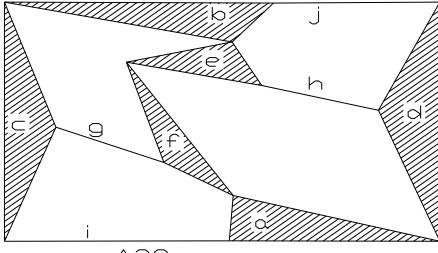
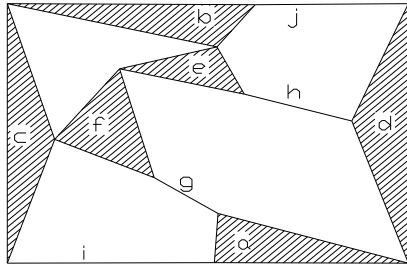
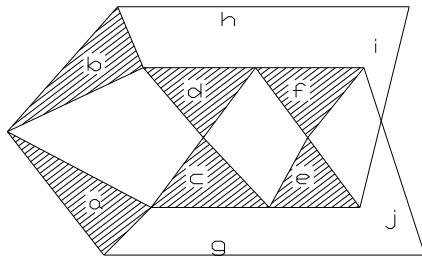
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Kinematic Chain	$n_5 n_4 n_3 n_2$	F. L.	E. L.	D. M.
 <p>A29</p> <p>SCPC(A29) = 1.5512e+008 MCPC(A29) = 5.2530e+007</p>	0064	a b c d e f g h i j	- - - - - - - - - -	10
 <p>A30</p> <p>SCPC(A30) = 2.0286e+008 MCPC(A30) = 8.6714e+007</p>	0064	a 2 c d e f g h i j	- - - - - - - - - -	10
 <p>A31</p> <p>SCPC(A31) = 1.4672e+008 MCPC(A31) = 5.9970e+007</p>	0064	a b c d e f g h i j	- - - - - - - - - -	10
 <p>A32</p> <p>SCPC(A32) = 1.4121e+008 MCPC(A32) = 5.5956e+007</p>	0064	a b c d e f g h i j	- - - - - - - - - -	10

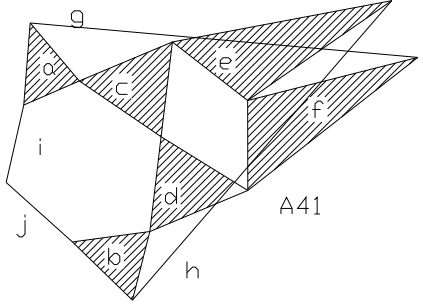
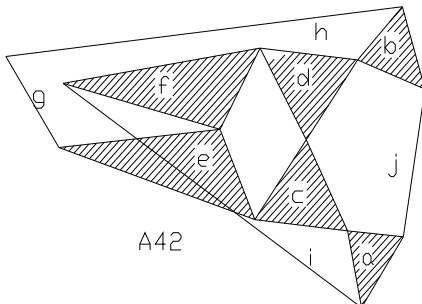
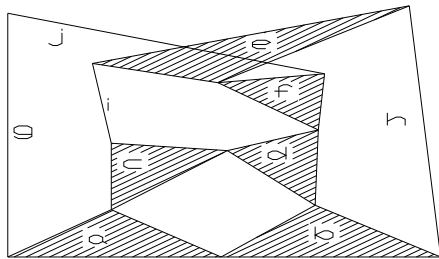
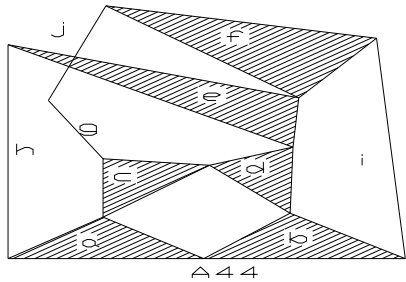
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Kinematic Chain	$n_5 n_4 n_3 n_2$	F. L.	E. L.	D. M.
 <p>A33</p> <p>SCPC(A33) = 2.0704e+008 MCPC(A33) = 8.6692e+007</p>	0064	<p>a b g h</p>	<p>d, e, f c i j</p>	4
 <p>A34</p> <p>SCPC(A34) = 1.6077e+008 MCPC(A34) = 6.0212e+007</p>	0064	<p>a b c d e f g h i j</p>	<p>- - - - - - - -</p>	10
 <p>A35</p> <p>SCPC(A35) = 1.8055e+008 MCPC(A35) = 5.8827e+007</p>	0064	<p>a b e f g h j</p>	<p>c d - - i -</p>	7
 <p>A36</p> <p>SCPC(A36) = 1.5079e+008 MCPC(A36) = 5.6923e+007</p>	0064	<p>a b d g h</p>	<p>e c f j i</p>	5

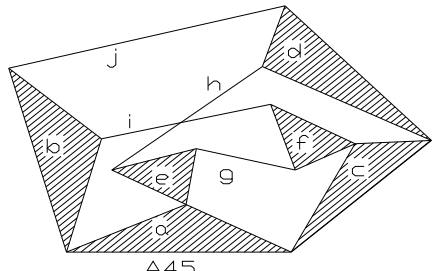
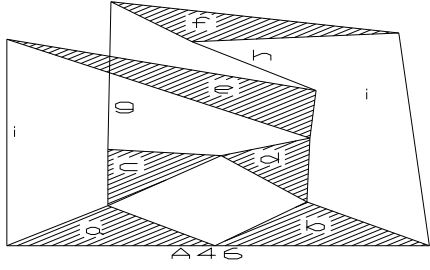
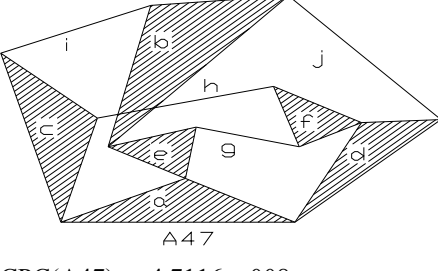
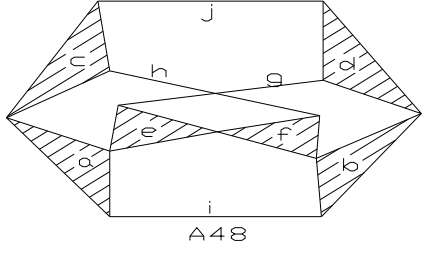
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Kinematic Chain	$n_5 n_4 n_3 n_2$	F. L.	E. L.	D. M.
 <p>A37 SCPC(A37) = 1.4389e+008 MCPC(A37) = 5.7080e+007</p>	0064	a c e g h i	b d f - j -	6
 <p>A38 SCPC(A38) = 2.3781e+008 MCPC(A38) = 9.6604e+007</p>	0064	l c e g i	b d f h j	5
 <p>A39 SCPC(A39) = 2.2153e+008 MCPC(A39) = 9.0699e+007</p>	0064	a b g	d c, e, f h, i, j	3
 <p>A40 SCPC(A40) = 1.0787e+008 MCPC(A40) = 4.8814e+007</p>	0064	a c e g	b d f h, i, j	4

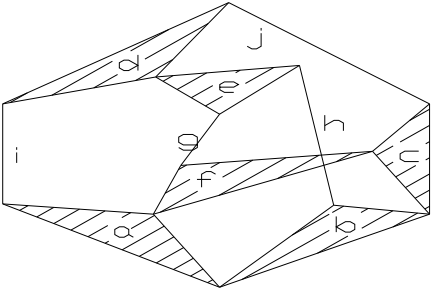
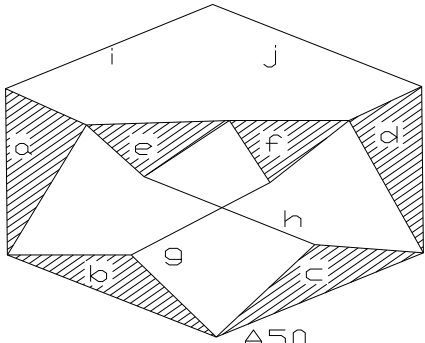
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Kinematic Chain	$n_5 n_4 n_3 n_2$	F. L.	E.L.	D. M.
 <p>A41</p> <p>SCPC(A41) = 2.0898e+008 MCPC(A41) = 8.2795e+007</p>	0064	<p>a c e g i</p>	<p>b d f h j</p>	5
 <p>A42</p> <p>SCPC(A42) = 1.8832e+008 MCPC(A42) = 7.9008e+007</p>	0064	<p>a b d g h</p>	<p>e c f j i</p>	5
 <p>A43</p> <p>SCPC(A43) = 2.1556e+008 MCPC(A43) = 9.3429e+007</p>	0064	<p>a b d e f g h j</p>	<p>- c - - - - i -</p>	8
 <p>A44</p> <p>SCPC(A44) = 1.7933e+008 MCPC(A44) = 7.8370e+007</p>	0064	<p>a b c d e f g h i j</p>	<p>- - - - - - - -</p>	10

Continued.....

Kinematic Chain	$n_5 n_4 n_3 n_2$	F. L.	E. L.	D. M.
 <p>A45</p> <p>SCPC(A45) = 1.5707e+008 MCPC(A45) = 6.1630e+007</p>	0064	<p>a b g</p>	<p>c d, e, f h, i, j</p>	3
 <p>A46</p> <p>SCPC(A46) = 4.2489e+008 MCPC(A46) = 1.8957e+008</p>	0064	<p>a b d e f g h i</p>	<p>- c - - - j - -</p>	8
 <p>A47</p> <p>SCPC(A47) = 4.7116e+008 MCPC(A47) = 2.1112e+008</p>	0064	<p>a b c d g h</p>	<p>- f - e j i</p>	6
 <p>A48</p> <p>SCPC(A48) = 4.1447e+008 MCPC(A48) = 1.8512e+008</p>	0064	<p>a c e g i j</p>	<p>b d f h - -</p>	6

Continued.....

Kinematic Chain	$n_5 n_4 n_3 n_2$	F. L.	E. L.	D. M.
 <p style="text-align: center;">A49</p> <p>SCPC(A49) = 4.0281e+008 MCPC(A49) = 1.8140e+008</p>	0064	a d g	b, c, f e h, i, j	3
 <p style="text-align: center;">A50</p> <p>SCPC(A50) = 1.9948e+008 MCPC(A50) = 8.4121e+007</p>	0064	a b d g i	- c, e, f - h j	5

Continued.....

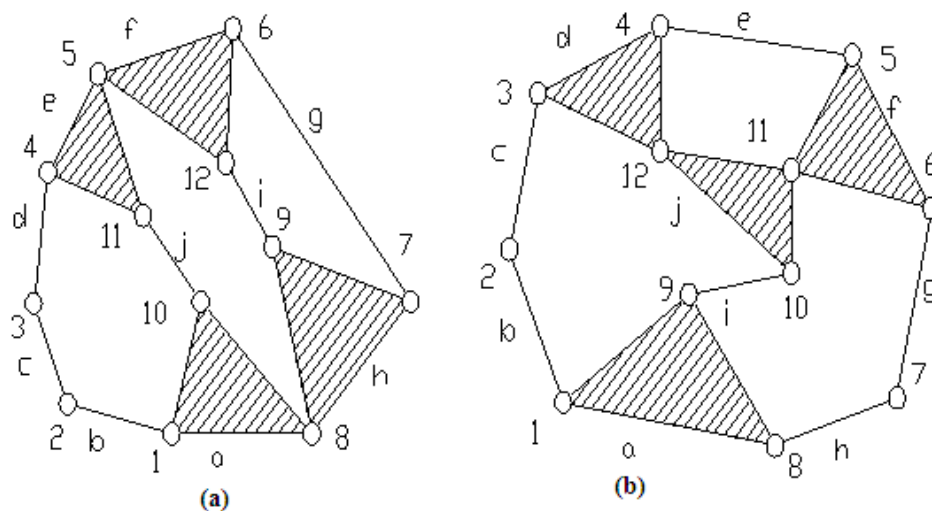


Fig 1: Ten bar KC with 3 dof

ISOMORPHISM OF KINEMATIC CHAINS

Theorem: Two similar square symmetric matrices have the same characteristic polynomials.

Proof:

Let the two kinematic chains are represented by the two similar matrices A and B such that $B = P^{-1}AP$, taking into account that the matrix λI commutes with the matrix P and $|P^{-1}| = |P|^{-1}$. Since the determinant of the product of two square matrices equals the product of their determinants, we have

$$\begin{aligned} |B - \lambda I| &= |P^{-1}AP - \lambda I| \\ &= |P^{-1}(A - \lambda I)P| \\ &= |P^{-1}| |A - \lambda I| |P| = |A - \lambda I| \end{aligned}$$

Hence, $D(\lambda)$ of 'A' matrix = $D(\lambda)$ of 'B' matrix.
 $D(\lambda)$ = characteristic polynomial of the matrix.

It means that if $D(\lambda)$ of two (JJ) matrices representing two kinematic chains is same, their structural invariants 'SCPC' and 'MCPC' will also be same and the two kinematic chains are isomorphic otherwise non-isomorphic chains.

EXAMPLE- 1

Considering two kinematic chains with 10 bars, 12 joints, three degree of freedom as shown in Fig 1.

The task is to examine whether these two chains are isomorphic. The structural invariants of these two chains are as follows:

For chain 2(a): (SCPC) = $8.3734e+006$, (MCPC) = $3.5938e+006$

For chain 2(b): (SCPC) = $7.0147e+006$, (MCPC) = $2.9393e+006$

Our method reports that chain 2(a) and 2(b) are non-isomorphic as the set of values of (SCPC) and (MCPC) are different for both the kinematic chains. Note that by using other method comments (Cubillo and Wan, Jinbao, 2005), the same conclusion is obtained.

RESULTS

The proposed invariants (SCPC) and (MCPC) are used as the identification number of the kinematic chains having simple joints. The identification numbers of all 1-dof kinematic chains up to 10-Links are with the author. These invariants are also able to detect isomorphism among the kinematic chains with multiple joints also. Fixed Links and Equivalent Links in Distinct Mechanisms of 10 Links, 13 Joints, Single degree of freedom Kinematic Chains GROUP A are listed in Table 1(A).

Conclusion

In this paper, a simple, efficient, and reliable method to identify isomorphism is proposed. By this method, the isomorphism of mechanisms kinematic chains can easily be identified.

It incorporates all features of the kinematic chains and as such, violation of the isomorphism test is rather difficult. The method has been found to be successful in distinguishing all known 16 kinematic chain of 8-links, 230 kinematic chain of 10-links having 1-F. The advantage is that they are very easy to compute using MATLAB software. It is not essential to determine both the structural invariants to compare two chains, only in case the (SCPC) is same then it is needed to determine (MCPC) for both kinematic chains. The (JJ) matrices can be written with very little effort, even by mere inspection of the chain. The proposed test is quite general in nature and can be used to detect isomorphism of not only planar kinematic chains of one degree of freedom, but also kinematic chains of multi degree of freedom. All the results of distinct mechanisms obtained from 8 links of 1 degree of freedom are listed in Table- 1(A).

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