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Identification Of Distinct Inversions In A Kinematic Chain Using Link-Joint-Loop Adjacency

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Abstract

Every machine needs a suitable mechanism to impart motion and transmit power. Hence, it becomes necessary to study the various aspects of a mechanism in terms of synthesis and structural analysis of kinematic chain. In past few decades, a lot of researchers had put their efforts in identifying distinct kinematic chain with a given degree of freedom, tested them for isomorphism and identified the distinct number of mechanisms (inversions) that can be obtained by fixing a link in a particular kinematic chain. All those methods are solely dependent on the study and analysis of two basic factors of any kinematic chain i.e links and joints. However, the presence of loops and its effect in driving a mechanism is somehow neglected. The complete analysis of the structure of a kinematic chain depends on the study of all the three factors i.e. links, joints and loops. This paper approaches with a new method based on matrix composition to identify the accurate number of distinct mechanisms which can be obtained in a particular kinematic chain. The method adopted is quite simple and reliable as it considers the presence of loop among the kinematic chain along with the links and the joints hence uses link-joint-loop adjacency.

Keywords: Kinematic chain, Distinct mechanism, Inversions, Adjacency matrix.

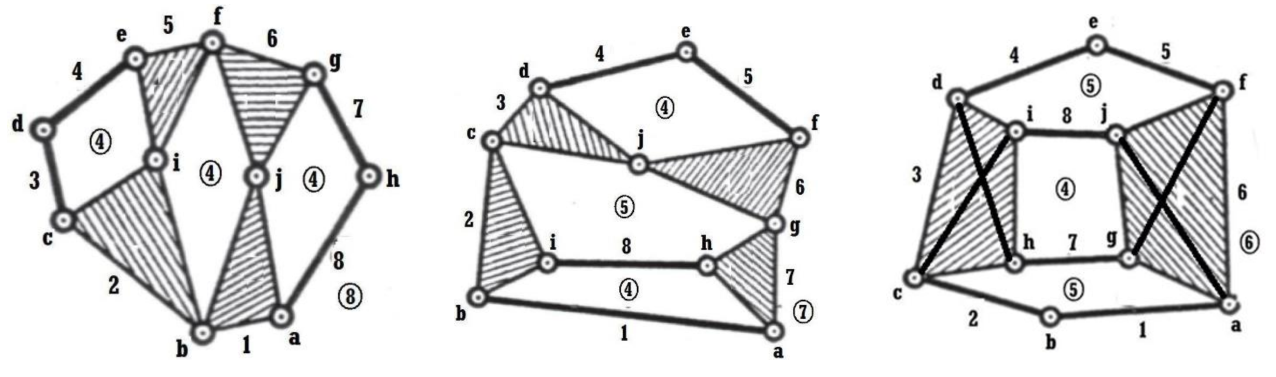
1. Introduction

In design of machine and machine elements, the analysis of the structure and the synthesis of various kinematic chains is a prime phenomenon and selection of a particular mechanism driving a definite motion plays a crucial part in designing of mechanisms. Hence, from past few decades, a lot of efforts had been made by various researchers for analyzing the various parameters governing the kinematic chains. In that context, identifying distinct inversions or mechanisms from a particular kinematic chain is very essential for which a lot of study and analysis had been done for evolving methods which should be simple, efficient and reliable. In the early 70's, it was firstly identified 219 distinct inversions from the available kinematic chains having nine links with two degree of freedom using graph theory (Manolescu, 1973). Later, a computerized methodology was proposed and 71 distinct inversions were identified for 8-links 1-dof, 254 inversions for 9-links 2-dof and 1834 inversions for 10-links 1-dof kinematic chains (Mruthyunjaya, 1984). MIN code method was also used and approach was given relevant to identifying the distinct number of inversions of kinematic chains (Ambekar et al., 1987). Thereafter, a method was proposed by drawing velocity diagrams thereby preparing a motion transfer point matrix to detect distinct inversions (Patel et al., 1988). Hamming number technique was used and a chain hamming string was formed to reveal the number of possible mechanisms out of a given chain (Rao et al., 1991). A links adjacent-chain table was originated which describes the relationships topologically between various links in the kinematic chains for successful detection of mechanisms (Chu Jin Kui et al., 1994). Later, an advanced variant was proposed called the arranged sequence of all the links in terms of modified total distance ranks and taken into account the types of joint as well as the degrees of links along with degrees of freedom of the kinematic chain to identify the distinct mechanisms (Yadav et al., 1996). A pseudo probability scheme was developed to distinctively represent the kinematic chain and the same method is adopted directly to detect distinct mechanisms of the kinematic chain (Sanyal et. al., 1997). Rao and his co-workers proposed information theory, fuzzy logic and loop based methods to detect various parameters of kinematic chains including detection of distinct mechanisms (Rao et. al., 2000). The concept of correlation was presented to discover isomorphism and reveals the kinematic attributes such as symmetry between the chains, parallelism, type of freedom, inversions, etc. (Srinath et. al., 2006). A method was presented for the detailing of kinematic chains without isomorphism and degraded chains for all screw systems and a new approach based on group theory techniques for enumeration of kinematic chain inversions (Simoni et al., 2009). Later, two new invariants was developed, called as first adjacency link value [FALV] and second adjacency link value [SALV], for each link, for the identification of distinct mechanisms in occurrence with a planar kinematic chain (Dargar et. al., 2009). A method was proposed where at different levels, the various connectivity of joints in a kinematic chain is used to identify the inversions as well as to detect the isomorphism (Bedi et al., 2010). The method was further improved and made it more effective by including the type of joint for detecting the isomorphism and to identify the distinct inversions by introducing the concept of motion transfer ability. Madan [17] used the invariant labeling of links for detection of inversions (Bedi et al., 2011). Later, a unique algorithm was proposed which uses adjacency matrices for enumerating the various possible distinct inversions from a given kinematic chain (Madan, 2014). [JJ] matrix was used to determine the number of mechanisms from a given kinematic chain having multiple joints (Rizvi et al., 2016). A least distance matrix (LDM) was developed thereby forming chain strings as well as link strings to detect isomorphism and inversions (Dewangan et al., 2019). Lastly, an algorithm was introduced for defining a new framework called ‘additive adjacency’ and also developed an unique table of computation called ‘remote adjacency influence table’ where the advancement of the adjacency calculations is controlled and is used to detect distinct inversions (Kames et al., 2021).

Many of the techniques and methods reported by past researchers are either indirect identification of distinct mechanism or would take sufficiently large computational time and are highly complex in nature. Further the methods depends only on any of the two parameters i.e link-link, link-joint or link-loop adjacency. Hence, an uniquely simple and highly reliable approach is proposed using all the three important parameters of any kinematic chain i.e. link, joint and loop, simultaneously, in the configuration of a link-joint-loop adjacency matrix, to identify the distinct inversions in a given available kinematic chain with multiple degree of freedom. The method is applied successfully to all the available kinematic chains with single and multiple degrees of freedom as per the literature and the results are validated through the results earlier reported.

2. Representation of Kinematic Chain

Consider three kinematic chains consisting of eight links with single degree of freedom having ten revolute joints as shown in Figure 1.



(a) (b) (c)

Figure 1: Kinematic chains with 8 links – 1 DOF

The notations for the links and joints are done in usual manner. The various loops occurring in the chain are identified according to the number of distinct links occurring in that loops. Thus it can be observed that Figure 1(a) has an outermost loop a-b-c-d-e-f-g-h-a having 8 links (four ternary & four binary links), three individual loops having 4 links i.e. a-h-g-j-a (two ternary & two binary links), b-j-f-i-b (four ternary links), c-i-e-d-c (two ternary & two binary links) and two sub-loops having 6 links i.e a-h-g-f-i-b-a (four ternary & two binary links) and b-j-f-e-d-c-b (four ternary & two binary links).

3. Link-Joint-Loop Adjacency Matrix

Now a three dimensions matrix has been constructed showing the correlation between the various links and the joints along with the loops. This will result in the string values of a particular link and finally we will get a link-joint-loop (LJL) value for a given kinematic chain. When a link is connected with another link at a joint, then its link-joint value is the summation of number of remaining joints that can be further connected to other links which is known as design parameter. When a ternary link connects with a binary link at a joint, then it has three remaining joints to be further connected to other links. Hence, its link-joint value for that joint is '3'. Similarly, when a ternary link connects with another ternary link at a joint, then it has four remaining joints to be further connected to other links giving a link-joint value of '4' for that joint. In Figure 1, link 1 is connected to three other links at joints a, j and b. Thus, the link-joint values of link 1 at joints 'a' is '3', at 'b' is '4' and at 'j' is also '4'. Now the link-joint values of other joints in relation with link 1 will be the shortest distance of other joints with the joints of link 1. Thus it can be observed that joint 'c' is at a shortest distance of '2' from link 1, 'd' is at '3', 'e' is at '3', 'f' is at '2', 'g' is at '2', 'h' is at '2' and 'i' is also at '2'. All these link- joint values are tabulated in the matrix and same procedure is adopted for all the other links of the kinematic chain. The summation of these values will give the string link-joint value of that particular link.

Now, link-loop value is assigned only to all the joints of a particular link in consideration and will be the summation of links in two loops containing that joint. For joints of other links, the link-loop value will be considered zero. The two loops which will constitute the link-loop value is identified by using 4 simple rules as follows:

Rule 1: If a kinematic chain is consisting of only binary and ternary links, then the link-loop value for an outer joint will be the summation of links of individual loop containing that joint and links of outermost loop of kinematic chain. In Figure 1(a), for link 1, outer joint 'a' is participating in individual loop a-h-g-j-a (4 links) as well as also in outermost loop a-b-c-d-e-f-g-h-a (8 links). Hence, link-loop value for 1-a will be '12'. Similarly, for 1-b, the link-loop value is again '12'.

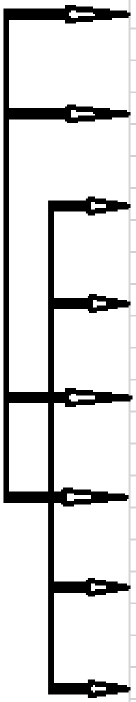
Rule 2: If a kinematic chain is consisting of only binary and ternary links, then the loop value for an intermediate joint will be the summation of links of both the adjacent individual loops containing that joint. In Figure 1(a), for link 1, intermediate joint 'j' is participating in individual loop a-h-g-j-a (4 links) as well as also in another adjacent individual loop b-j-f-i-b (4 links). Hence, link-loop value for 1-j will be '8'.

Rule 3: If a kinematic chain is consisting of only ternary and binary links such that at any part of the chain, two parallel binary links are connected to either two ternary links or to one ternary and another quaternary link thus constituting a 4-bar, then the link-loop values for outer joints are considered by the summation of links in individual loop and links in the next sub-loop for the whole kinematic chain. In Figure 1(b), links '1' and '8' are connected in parallel to two ternary links '2' and '7' thereby constituting a 4-bar. Link-loop value for 1-a will be summation of links in individual loop a-h-i-b-a (4 links) and links in next sub-loop a-g-j-c-b-a (5 links) as '9'. For intermediate joints, link-loop values are obtained by Rule 2.

Rule 4: If a kinematic chain is consisting of a quaternary or quinary or any other higher link along with ternary and binary links, then the link-loop values for outer joints are considered by the summation of links in individual loop and links in the next sub-loop for the whole kinematic chain. In Figure 1(c), the link-loop value for 1-a will be summation of links in individual loop a-g-h-c-b-a (5 links) and links in next sub-loop a-j-i-c-b-a (5 links) as '10'. For intermediate joints, link-loop values are obtained by Rule 2.

The above mentioned procedure will result in a three dimensional link-joint-loop adjacency matrix for a particular kinematic chain relating all the three basic parameters for structural analysis. Table 1 shows a link-joint-loop adjacency matrix developed for the chain given in Figure 1(a):

Table 1: Link-Joint-Loop Adjacency Matrix for Figure 1(a)



	a	b	c	d	e	f	g	h	i	j	Total
1	3	4	2	3	3	2	2	2	2	4	**27**
	12	12	0	0	0	0	0	0	0	8	**32**
2	2	4	3	2	2	2	3	3	4	2	**27**
	0	12	12	0	0	0	0	0	8	0	**32**
3	3	2	3	2	2	3	4	4	2	3	**28**
	0	0	12	12	0	0	0	0	0	0	**24**
4	4	3	2	2	3	2	3	4	2	3	**28**
	0	0	0	12	12	0	0	0	0	0	**24**
5	3	2	2	2	3	4	2	3	4	2	**27**
	0	0	0	0	12	12	0	0	8	0	**32**
6	2	2	3	3	2	4	3	2	2	4	**27**
	0	0	0	0	0	12	12	0	0	8	**32**
7	2	3	4	4	3	2	3	2	3	2	**28**
	0	0	0	0	0	0	12	12	0	0	**24**
8	3	2	3	4	4	3	2	2	3	2	**28**
	12	0	0	0	0	0	0	12	0	0	**24**

4. Detection of Distinct Inversions

The above mentioned procedure is applied for all the available chains with fixed degree of freedom and number of links. Now from above link-joint-loop adjacency matrix it can be observed that links 1, 2, 5 and 6 are giving the same Total String Value (TSV) of 27/32 and also each and every values of the strings matches with each other which indicates that any of these links will behave in same manner and will give same motion to the chain if the link is fixed. Hence, this will constitute a single inversion. Similarly, links 3, 4, 7 and 8 will provide distinct motion to the kinematic chain and constitute another inversion. This can be tabulated as:

Table 2: Identification and Schematic of Distinct Inversions for Fig. 1(a)

Distinct Links	Total String Value	Scheme	Inversion
1-2-5-6	27/32	1(4/12), 1(4/8), 1(3/12), 2(3/0), 5(2/0)	1
3-4-7-8	28/24	1(3/12), 1(2/12), 2(4/0), 3(3/0), 3(2/0)	1
Total Distinct Inversions			**2**

The method is applied and tested for all the identified distinct kinematic chains as per the references i.e 2 six-bar 1-dof chains, 16 eight bar 1-dof chains, 40 nine-bar 2-dof chains, 98 ten-bar 3-dof and 230 ten-bar 1-dof distinct kinematic chains. The total number of inversions obtained are fully agree with those given in the literature tabulated as:

Table 3: List of Distinct Inversions in Kinematic Chains

S. No.	Type of Kinematic Chains	Number of Distinct Chains	Total Distinct Inversions
1	6-Links, 1-DOF	2	**5**
2	8-Links, 1-DOF	16	**71**
3	9-Links, 2-DOF	40	**254**
4	10-Links, 3-DOF	98	**684**
5	10-Links, 1-DOF	230	**1834**

The results in the form of distinct mechanisms obtained in each of the distinct kinematic chain with 8-links 1-dof and with 9-links 2-dof is included in the appendix I and II.

5. Conclusion

Quantitative methods are always needed for identification of the number of distinct inversions detected from a particular kinematic chain with given degree of freedom and it must be reliable, efficient and less time consuming. Keeping in view, a unique method is proposed which incorporates the analysis of all the three basic parameters of a kinematic chain simultaneously i.e. link, joint and loop in a single link-joint-loop adjacency matrix which is fully capable of identifying distinct inversions of kinematic chain. The method is successfully applied to all the available kinematic chain reported in the literature with single as well as multiple degrees of freedom and the results matches with the earlier reported results.

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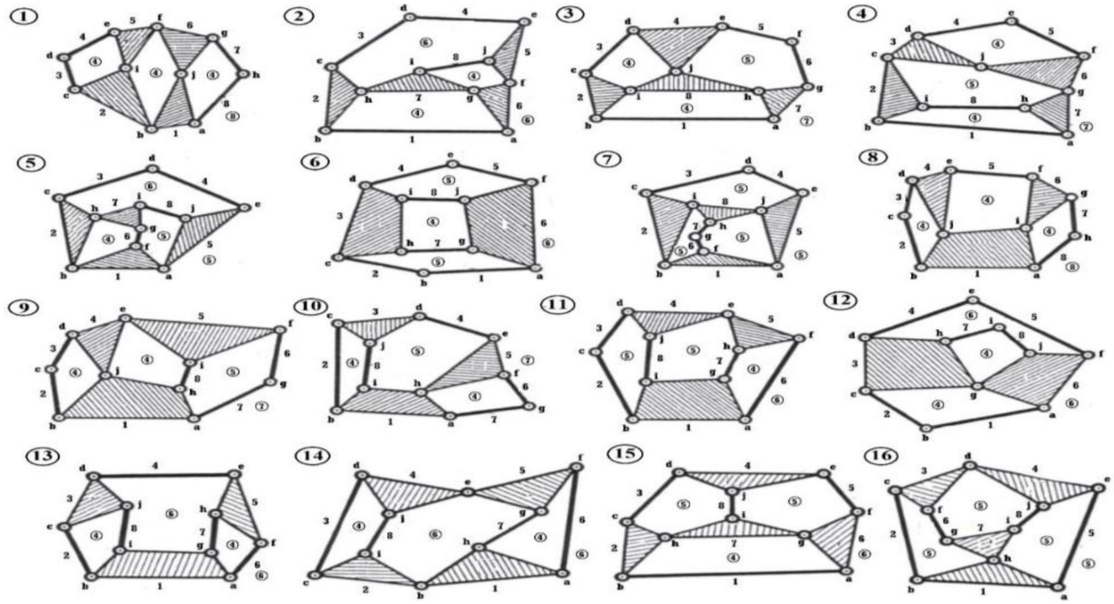
Appendix -I

Distinct Inversions for 8-Links 1-dof Kinematic Chains

Chain No.	Distinct Links	Inversions
1	(1,2,5,6) (3,4,7,8)	2
2	(1,8) (2,5) (3,4) (6,7)	4
3	(1,3) (2) (4,7) (5,6) (8)	5
4	(1,8) (2,7) (3,6) (4,5)	4
5	(1) (2) (3) (4) (5) (6) (7) (8)	8
6	(1,2,4,5) (3,6) (7,8)	3
7	(1,2,5,8) (3,4,6,7)	2
8	(1) (2,8) (3,7) (4,6) (5)	5
9	(1) (2) (3) (4) (5) (6) (7) (8)	8
10	(1) (2,8) (3) (4) (5) (6) (7)	7
11	(1) (2) (3) (4) (5) (6,7) (8)	7
12	(1,2,4,5,7,8) (3,6)	2
13	(1) (2,6,7,8) (3,5) (4)	4
14	(1,2,4,5) (3,6,7,8)	2
15	(1) (2,6) (3,5) (4) (7) (8)	6
16	(1,3,4,7) (2,5,6,8)	2
Total Inversions in 8-Links 1 DOF Chains		71



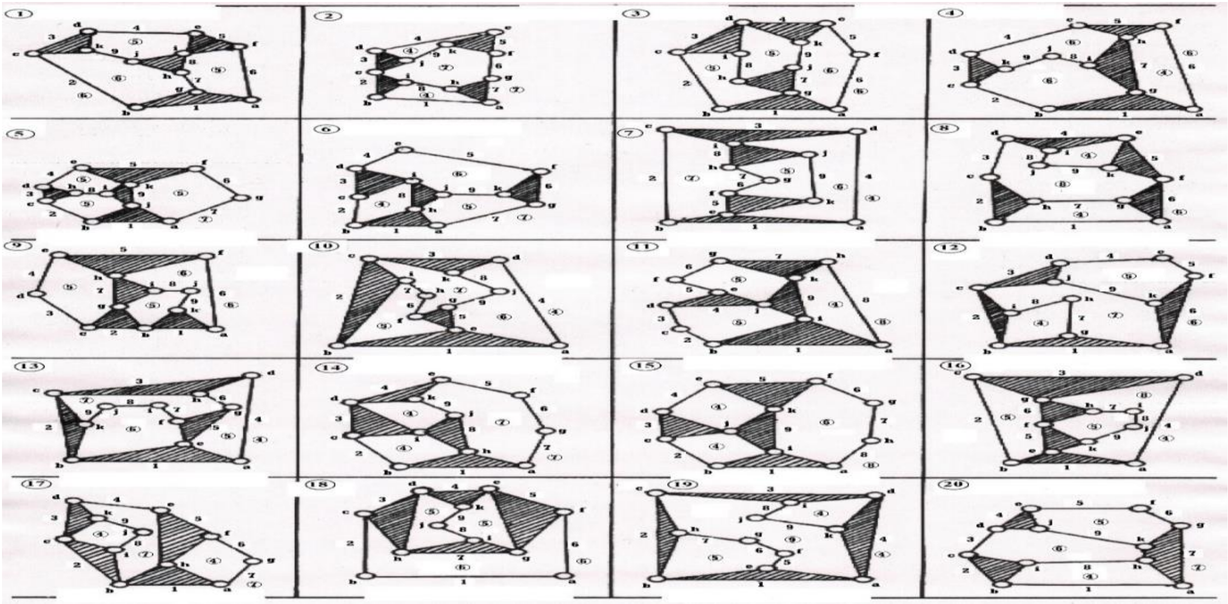
Appendix – II

Distinct Inversions for 9-Links 2-dof Kinematic Chains

Chain No.	Distinct Links	Inversions
1	(1,3) (2) (4,6,7,9) (5,8)	4
2	(1,4,8,9) (2,3) (5,7) (6)	4
3	(1,4) (2,9) (3,7) (5,6) (8)	5
4	(1,5) (2,4) (3) (6) (7) (8) (9)	7

Chain No.	Distinct Links	Inversions
21	(1,6,8,9) (2,5) (3,4) (7)	4
22	(1,7) (2) (3,9) (4,8) (5) (6)	6
23	(1,2) (3,7) (4,6) (5) (8,9)	5
24	(1,9) (2) (3) (4,6) (7) (8) (9)	7

5	**(1,5) (2,4) (3) (6,7) (8) (9)**	**6**
6	**(1) (2) (3) (4) (5) (6) (7) (8) (9)**	**9**
7	**(1,3) (2,4) (5,8) (6,7) (9)**	**5**
8	**(1,7) (2) (3) (4) (5) (6) (8) (9)**	**8**
9	**(1,5) (2,7) (3,8) (4,9) (6)**	**5**
10	**(1) (2) (3) (4) (5) (6) (7) (8) (9)**	**9**
11	**(1,7) (2,6) (3,5) (4) (8) (9)**	**6**
12	**(1,2) (3,6) (4,5) (7,8) (9)**	**5**
13	**(1) (2) (3) (4) (5) (6) (7) (8) (9)**	**9**
14	**(1,4) (2,9) (3,8) (5,7) (6)**	**5**
15	**(1,5) (2,4) (3) (6,8) (7) (9)**	**6**
16	**(1,3) (2,4) (5,6) (7,9) (8)**	**5**
17	**(1,2) (3,5) (4) (6,9) (7,8)**	**5**
18	**(1) (2,6) (3,5) (4,7) (8,9)**	**5**
19	**(1,2) (3,4) (5,7) (6) (8,9)**	**5**
20	**(1,8) (2) (3) (4) (5) (6) (7) (9)**	**8**
25	**(1,6) (2) (3) (4) (5) (7) (8) (9)**	**8**
26	**(1) (2) (3) (4) (5) (6) (7) (8) (9)**	**9**
27	**(1,9) (2) (3) (4) (5) (6) (7) (8)**	**8**
28	**(1) (2,7) (3) (4) (5) (6) (8) (9)**	**8**
29	**(1) (2,6) (3) (4) (5) (7) (8) (9)**	**8**
30	**(1) (2) (3) (4) (5) (6) (7) (8) (9)**	**9**
31	**(1,4) (2,3) (5) (6) (7,9) (8)**	**6**
32	**(1,6) (2,7) (3) (4) (5) (8) (9)**	**7**
33	**(1) (2,6) (3) (4) (5) (7,9) (8)**	**7**
34	**(1) (2) (3) (4) (5) (6) (7) (8) (9)**	**9**
35	**(1,7) (2,6) (3,5) (4) (8,9)**	**5**
36	**(1) (2) (3) (4) (5) (6) (7) (8) (9)**	**9**
37	**(1,2,6,7,8,9) (3,5) (4)**	**3**
38	**(1,3) (2,7) (4,6) (5) (8,9)**	**5**
39	**(1,2,8,9) (3,7) (4,6) (5)**	**4**
40	**(1) (2,8) (3,9) (4) (5,7) (6)**	**6**
Total Inversions in 9-Links 2 DOF Chains		**254**



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