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Analysis of kinematic characters using screw displacement method in case of manufacturing errors of a four-bar mechanism

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Abstract

The performance of any mechanism is affected by the manufacturing errors on the links and joints that were used in the manufacture of the mechanism. With the increase in the requirements of its performance, it is necessary to analyze the effect of manufacturing errors on kinematic accuracy. This analysis can help designers to verify whether the output performance of the mechanism is within the indicated limit or not.This paper describes a new method that can be used for the analysis of the kinematic accuracy of a four-bar mechanism, taking manufacturing errors of links and joints into consideration by using successive screw displacement method and its effectiveness.

Keywords: *Screw displacement method, Four-bar mechanism, Kinematic character, Link, Joint*

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Introduction

The kinematic character of a simple mechanism can be analyzed by graphical or vector methods, but a complex mechanism requires the screw displacement method and its transformation matrices.

The kinematic accuracy of a point on a given mechanism is influenced by the manufacturing errors that cause variation in the length of links and in the gap of joints. The analysis of kinematic accuracy of the mechanism is the process of determining the deviation of the nominal position of a given point on the mechanism produced by manufacturing errors. Only by the correct analysis, can we verify whether the output errors are within t he indicated limit or not, and accomplish an optimal method that makes the output errors be within the indicated limit.

In this paper, assuming that couplers of a planar mechanism are rigid bodies, we propo se a new method that can be used for the ana lysis of the kinematic accuracy of a four-bar mechanism, taking manufacturing errors of links and joints into consideration by using successive screw displacement method and prove its effectiveness.

1. Screw displacement method

Let us consider the successive screw displ acement method used in the study of the pos itional kinematics.

Motion of a rigid body can be regarded as a rotation about an axis and a translation alo ng some axis. Such a combination of rotatio n and translation is called screw displaceme nt. Fig 1 shows displacement of a point p o n a rigid body from its first position p_0 to n ext position p_1 by rotation of θ about a scr ew axis followed by a translation of t along the same axis. The rotation angle θ and tra nslational distance t are called screw param eters. The direction of the screw axis is deno ted by $s=[s_x, s_y, s_z]^t$ and the position vector of a point lying on the screw axis is represe nted by $s_0=[s_{0x}, s_{0y}, s_{0z}]^t$ with respect to a g lobal Cartesian coordinate system $oxyz$. The parameters s and s_0, together with the screw parameters (θ, t) are called as Rodrigues pa rameters that define the general displacemen t of a rigid body.

Displacement of point p can be represent ed in homogeneous transformation matrix us ing the Rodrigues parameters as following.

$$A=\begin{pmatrix} R(\theta) & p(t) \\ 0 & 1 \end{pmatrix} \qquad (1)$$

Where A is a 4×4 transformation matrix.

$R(\theta)$ is rotation matrix given by

$$R(\theta)=\begin{pmatrix} c\theta+s_x^2(1-c\theta) & s_y s_x(1-c\theta)-s_z s\theta & s_z s_x(1-c\theta)+s_y s\theta \\ s_y s_x(1-c\theta)+s_z s\theta & c\theta+s_y^2(1-c\theta) & s_y s_z(1-c\theta)-s_x s\theta \\ s_z s_x(1-c\theta)-s_y s\theta & s_y s_z(1-c\theta)+s_x s\theta & c\theta+s_z^2(1-c\theta) \end{pmatrix} \quad (2)$$

Where $c\theta=\cos\theta$ and $s\theta=\sin\theta$.

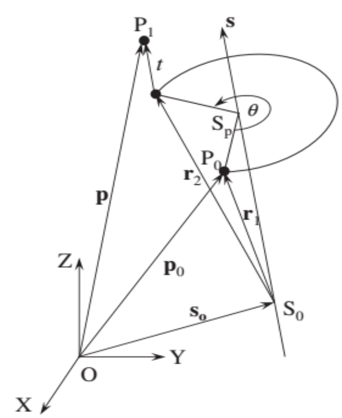


Fig 1. Screw displacement of a rigid body

The matrix $p(t)$ given below represents th e position of the point with respect to the ref erence coordinate $oxyz$

$$p(t)=ts+[I-R(\theta)]s_0 \quad (3)$$

where I is a 3×3 identity matrix and t is translation distance.

In an n-link serial manipulator, motion of a link relative to another link connected by a joint i is represented by a screw s_i and the associated transform matrix A_i is determine d as in Eq.(1) from the Rodrigues parameter s of the joint. The displacement from a refer ence position to a target position can be cons idered as a resultant of n successive screw di splacements. The total screw displacement c an be obtained by pre-multiplying the associ ated transformation matrices and the target p osition from the reference position can be ob tained as:

$$p = A_1 A_2 \ldots A_n p_0 \qquad (4)$$

2. Kinematic analysis of a planar four-bar mechanism using screw displacement method

In this section, linkages are assumed to be rigid and analysis is done on the kinematic characters using successive transformation matrices based on screw displacement metho d. We propose a system for incorporating m anufacturing errors on joint clearances and li nk lengths by virtual links and virtual joints.

3.1 Analysis without manufacturing errors

Let us apply the screw displacement meth od to a planar four-bar mechanism with link lengths r_1, r_2, r_3 and r_4 as shown in Fig. 2. It is to be noted that the angles are defined w ith reference to previous link in order to appl y screw displacement method. Table 1 gives relevant details of the mechanisms and the R odrigues parameters are given in Table 2.

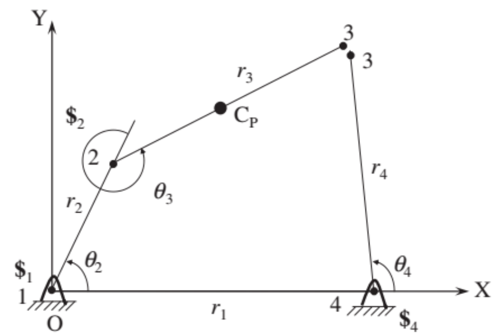


Fig 2. A planar four-bar mechanism

Table 1. Specifications considered for chose n four-bar mechanism

Link i	r_i (mm)	Δ_i (mm)	Joint j	r_j (mm)
1	50	± 0.1	1	$0.2(r_a)$
2	20	± 0.1	2	$0.2(r_b)$
3	50	± 0.1	3	$0.2(r_c)$
4	45	± 0.1	4	$0.2(r_d)$

Table 2. Rodrigues parameters for four-bar mechanism without manufacturing errors

screw	s_i	$s_{0,i}$	θ_i	t_i
First open chain				
1	(1,0,0)	(0,0,0)	θ_2	0
2	(1,0,0)	$(r_2,0,0)$	θ_3	0
Second open chain				
4	(1,0,0)	$(r_1,0,0)$	θ_4	0

Link-2 and link-4 are taken as input and output links respectively. Link-1 is fixed to the ground and link-3 is the coupler with coupler point C_p positioned at a specified distance from joint-2. For analysis purpose, the mechanism is considered to be made up of two open chains closed at joint-3. The first chain is made up of link-2 and link-3, and associated screws of joint-1 and joint-2 are shown in Fig.2. Link-1 and link-4 constitute the second open chain and associated screw is s_4. Considering the first open chain and taking Rodrigues parameters from Table 2, the position of end-point 3 of link-3 is determined by

$$^3p = A_1A_2\,^3p_0 = \begin{pmatrix} c\theta_2 & -s\theta_2 & 0 & 0 \\ s\theta_2 & c\theta_2 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}\begin{pmatrix} c\theta_3 & -s\theta_3 & 0 & r_2(1-c\theta_3) \\ s\theta_3 & c\theta_3 & 0 & -r_2 s\theta_3 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}\begin{pmatrix} r_2+r_3 \\ 0 \\ 0 \\ 1 \end{pmatrix} \quad (5)$$

For the second open chain, the appropriate Rodrigues parameters given in Table 2 are used and the position of end-point 3 of link-4 is obtained as

$$^3p = A_4\,^3p_0 = \begin{pmatrix} c\theta_4 & -s\theta_4 & 0 & r_1(1-c\theta_4) \\ s\theta_4 & c\theta_4 & 0 & -r_1 s\theta_4 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}\begin{pmatrix} r_1+r_4 \\ 0 \\ 0 \\ 1 \end{pmatrix} \quad (6)$$

Equating Eqs.(5) and (6), as the end point 3 of both open chains has to coincide to form a four-bar mechanism, the following relation is obtained.

$$\begin{pmatrix} r_1 + r_4 c\theta_4 \\ r_4 s\theta_4 \\ 0 \\ 1 \end{pmatrix} = \begin{pmatrix} r_2 c\theta_2 + r_3 c\theta_{23} \\ r_2 c\theta_2 + r_3 c\theta_{23} \\ 0 \\ 1 \end{pmatrix} \quad (7)$$

where $c\theta_{23} = \cos(\theta_2+\theta_3)$ and $s\theta_{23} = \sin(\theta_2+\theta_3)$. θ_{23} and θ_4 can be obtained as follows.

$$\theta_{23} = 2\tan^{-1}\left(\frac{-2L \pm \sqrt{(2L)^2 - 4(-K-M)(K+M)}}{2(-K-M)}\right)$$

$$\theta_4 = \tan^{-1}\left(\frac{r_2 s\theta_2 + r_3 s\theta_{23}}{-r_1 + r_2 c\theta_2 + r_3 c\theta_{23}}\right)$$

where $K = -r_1 + r_2 c\theta_2$, $L = r_2 s\theta_2$ and $M = \frac{r_4^2 - r_3^2 - (K^2 + L^2)}{2r_3}$.

Using the value of θ_{23}, the path traced by the coupler point C_P can be computed as

$$\left.\begin{aligned} P_x &= r_2\cos\theta_2 + C_p\cos\theta_{23} \\ p_y &= r_2\sin\theta_2 + C_p\sin\theta_{23} \end{aligned}\right\} \quad (8)$$

For typical dimensions of the links given in Table 1, nominal path traced by coupler point is shown in Fig.5.

3.2 Analysis considering manufacturing error

There are several errors in the planar mechanism. Two important errors are considered in this work. One is called a ‘joint-error’ and the other one is called a ‘link-error’.

3.2.1 Analysis with one joint error

Clearance between the hole and pin at a joint causes an error and this error is called a ‘joint-error’. Though maximum material conditions for hole and pin are critical for assembly purpose, clearance is the maximum when hole and pin are at their minimum material conditions. In other words, maximum hole and minimum pin size cause the larger cleara nce. As the pin can contact the hole at any point, maximum error of r_v will occur at the joint (Fig. 3(a)).

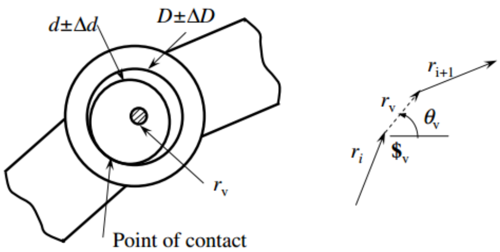


Fig. 3. Joint error and virtual link

a) Joint error, $D_{max} - d_{min}$ b) Virtual rotational link, r_v

In this work, it is represented by a virtual link of dimension r_v and its angular position is taken to vary from 0 to 360°, as the contact between the pin and hole can occur anywhere along the circle.

In terms of screw displacement method, a joint-error can be treated as a virtual link connected to an adjacent link by a virtual screw S_v .

In this section, variation in coupler point position is investigated with errors at one joint. Four-bar mechanism with one virtual link is shown in Fig. 4.

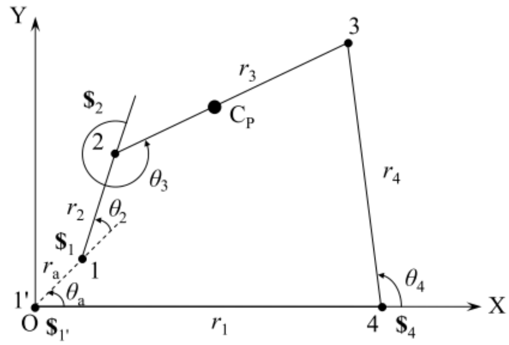


Fig. 4. Four-bar mechanism with errors at joint-1

Table 3. Rodrigues parameters for four-bar mechanism with errors at joint-1

Screw	s_i	$s_{0,i}$	θ_i	t_i
First open chain				
1'	(0,0,1)	(0,0,0)	θ_a	0
1	(0,0,1)	$(r_a,0,0)$	θ_2	0
2	(0,0,1)	$(r_a+r_2,0,0)$	θ_3	0
Second open chain				
4	(1,0,0)	$(r_1,0,0)$	θ_4	0

Screw $S_{1'}$ associated with joint-1′ is also shown. Input is given to link-2 and angle θ_2 is varied. The virtual link r_a is very small in comparison with active links and angle θ_a is varied from 0 to 360°, as the contact can oc cur along any point on the circle of the hole/pin for every θ_2.

Eq. (5) for the first open chain is modified to include the effect of virtual link.

$$ {}^{3}P = A_{1'}A_1A_2\,{}^{3}P_0 \qquad (9) $$

where the transformation matrix A1′ for virtual link r_a is given as

$$ A_{1'} = \begin{pmatrix} c\theta_a & -s\theta_a & 0 & 0 \\ s\theta_a & c\theta_a & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} $$

It should be noted that A1 and A2 get modified according to Rodrigues parameters given in Table 3.

$$ A_1 = \begin{pmatrix} c\theta_2 & -s\theta_2 & 0 & r_a(1-c\theta_2) \\ s\theta_2 & c\theta_2 & 0 & -r_a s\theta_2 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} $$

$$ A_2 = \begin{pmatrix} c\theta_3 & -s\theta_3 & 0 & (r_a+r_2)(1-c\theta_3) \\ s\theta_3 & c\theta_3 & 0 & -(r_a+r_2)s\theta_3 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \qquad (10) $$

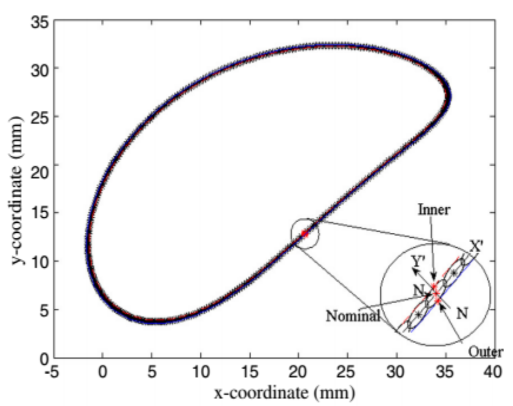
Taking ${}^{3}P_0$ as the following equation, the path traced by coupler point is determined by the procedure outlined in Section 3.1.

$$ {}^{3}P_0 = \begin{pmatrix} r_a + r_2 + r_3 \\ 0 \\ 0 \\ 1 \end{pmatrix} \qquad (11) $$

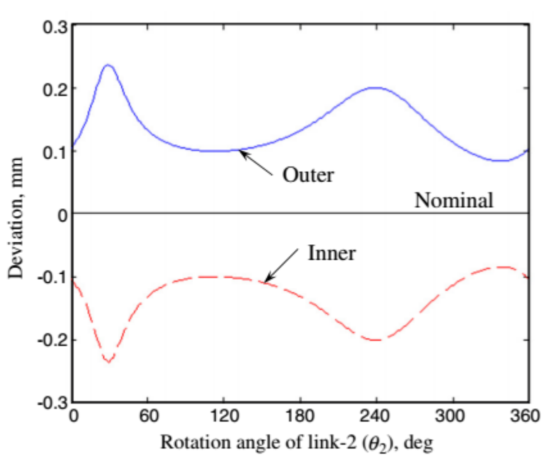
Fig. 5(a) shows nominal, outer and inner paths traced by the point C_p, when r_a is taken to be 0.2 mm. A closer look will reveal that the inner and outer paths are envelopes of cluster of points obtained for each incremental rotation of input link. For a given point on the nominal path, the corresponding points on the outer and inner paths can be different. Error plots can be easily drawn, taking the distances between this points. However, the shortest distance between a point on either the outer or inner path and a given point on the nominal path is required, as it uniquely represents the kinematic performance of the mechanism under consideration. In other words, foot of the perpendicular from a nominal point to the outer or inner path will give the shortest distance. A two-stage procedure is followed in the present work for getting the shortest distance. In the first stage, two neighbor points for a given nominal point are considered to establish X′ axis and a local coordinate system with Y′ axis perpendicular to X′ at the given point is established.

The cluster of points corresponding to a given θ_2 is transformed to local coordinate system X′–Y′ and maximum point in Y′ direction is determined. This maximum point is not always perpendicular from the given nominal point. This procedure is repeated for all the points on the nominal path. It may be seen that the maximum points actually form the outer/inner path. In the next stage, a second iteration is carried out to get the shortest distance. Two points that are nearest to Y′ axis but lying on the opposite side to each other are chosen and the shortest distance is computed by interpolation.

The normal deviations obtained from the nominal path are shown in Fig. 5(b). The inner path corresponds to a condition when the mechanism is assumed to be shrunk by forces acting on it. In other words, one can imagine an elastic band around the mechanism leading to a shrunk condition. Conversely outer path can be visualized as path traced by the coupler point when the mechanism is subjected to forces acting to open it up. If one can imagine an elastic bladder blown with air inside the mechanism, then the condition corresponds to an expanded position of the mechanism. Total bandwidth quantifies the effect of manufacturing errors.



a) Paths traced by coupler point



b) Variation in normal deviation with input angle

Fig. 5. Deviation from nominal path for error in joint-1

3.2.2 Analysis with one link-error

Another common error is in the center distance between two holes/pins in a link which is called ‘link-error’ in this work. This is designated as a bilateral error and the link can have a dimension, r ± Δ as shown in Fig. 6. This link-error can be treated as a virtual prismatic joint and represented by a screw S_{v}.

Fig. 7 shows four-bar mechanism with virtual prismatic joint representing error on link-2 and its associated screw S_{12}.

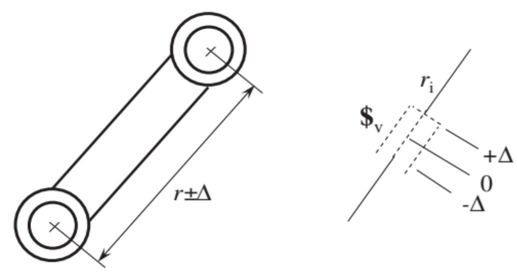


Fig. 6. Link error and virtual joint

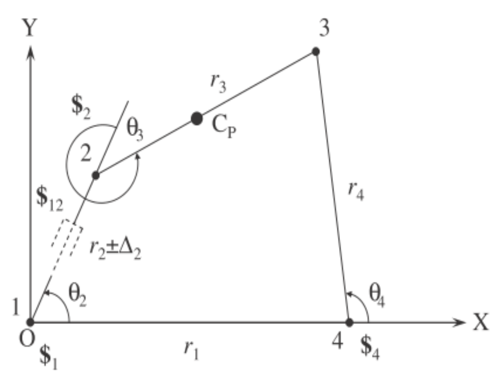


Fig. 7. Four-bar mechanism with error in link-2

Eq. (5) for the first open chain is modified to include the effect of virtual prismatic joint.

$$^{3}\mathrm{P} = \mathrm{A}_{1'}\mathrm{A}_{12}\mathrm{A}_{2}\,^{3}\mathrm{P}_{0} \qquad (12)$$

From Table 4, Rodrigues parameters are taken and the transformation matrices are obtained as follows.

Table 4. Rodrigues parameters for four-bar mechanism with error in link-2

Screw	s_i	$s_{0,i}$	θ_i	t_i
First open chain				
1	(0,0,1)	(0,0,0)	θ_2	0
	(1,0,0)	(0,0,0)	0	Δ_2
2	(0,0,1)	$(r_2,0,0)$	θ_3	0
Second open chain				
4	(1,0,0)	$(r_1,0,0)$	θ_4	0

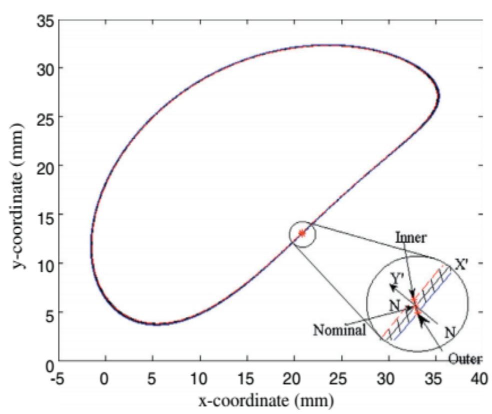
$$A_1 = \begin{pmatrix} c\theta_2 & -s\theta_2 & 0 & 0 \\ s\theta_2 & c\theta_2 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad A_{12} = \begin{pmatrix} 1 & 0 & 0 & \Delta_2 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$$\mathrm{A}_2 = \begin{pmatrix} c\theta_3 & -s\theta_3 & 0 & r_2(1-c\theta_3) \\ s\theta_3 & c\theta_3 & 0 & -r_2 s\theta_3 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \qquad (13)$$

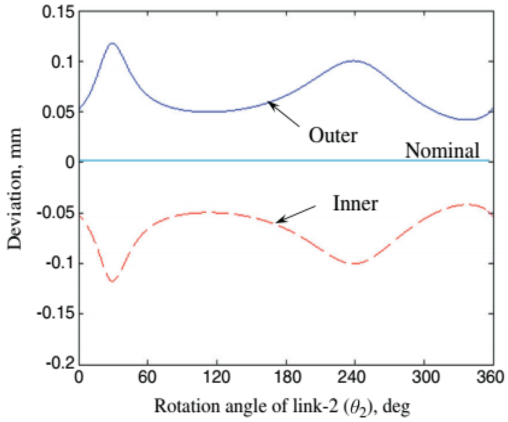
Taking $^{3}\mathrm{P}_0$ as Eq. (14) and following the procedure outlined in section 3.1, the coupler path can be traced for $\Delta_2 = \pm 0.1$ mm, taking Δ_2 to vary from -0.1 to $+0.1$.

$$^{3}p_0 = \begin{pmatrix} r_2 + r_3 \\ 0 \\ 0 \\ 1 \end{pmatrix} \qquad (14)$$

With variation in Δ_2, the coupler point traces an inclined path for every input angle θ_2 as shown in Fig. 8(a). Normal deviations are computed in the same way as outlined in Section 3.2.1 and shown in Fig. 8(b). Outer path corresponds to a condition when link-2 is at its maximum limit, while inner path corresponds to minimum limit condition.



a) Paths traced by coupler point



b) Variation in normal deviation with input angle

Fig. 8. Deviation from nominal path for error in link-2
($\Delta_2 = \pm 0.1\text{mm}$)

3.2.3 Analysis with both joint and link errors

Having illustrated the approach with two former examples, the combined effect of joint and link errors is analyzed in this section. The position of end point 3 in the first open chain is given as follows.

$$^{3}\mathrm{P} = \mathrm{A}_{1'}\mathrm{A}_{1}\mathrm{A}_{12}\mathrm{A}_{2}\,{}^{3}\mathrm{P}_{0} \quad (15)$$

In this case, variation in coupler point position is investigated with one joint-error taking higher and lower limits for link-2. The Rodrigues parameters are given in Table 5 and these parameters can be derived from a general case of four-bar mechanism having errors in all four joints and links given in the next section. The deviations from nominal path are shown in Fig. 9.

Table 5. Rodrigues parameters for four-bar mechanism with errors in joint-1 and length of link-2

Screw	s_i	$s_{0,i}$	θ_i	t_i
First open chain				
$1'$	(0,0,1)	(0,0,0)	θ_a	0
1	(0,0,1)	$(r_a,0,0)$	θ_2	0
12	(1,0,0)	(0,0,0)	0	Δ_2
2	(0,0,1)	$(r_a+r_2,0,0)$	θ_3	0
4	(1,0,0)	$(r_1,0,0)$	θ_4	0
Second open chain				
4	(1,0,0)	$(r_1,0,0)$	θ_4	0

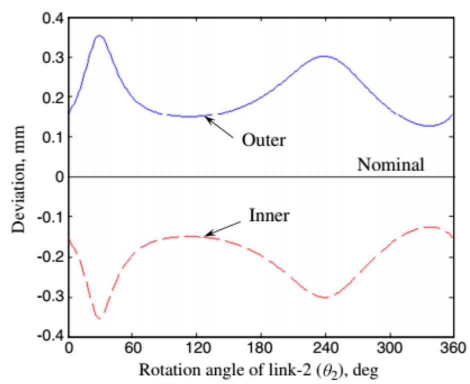


Fig. 9. Normal deviation plot for a four-bar mechanism with errors in joint-1 and link-2
($r_a = 0.2\text{mm}$, $\Delta_2 = \pm 0.1\text{mm}$)

3.2.4 Analysis with all joint and link errors

Computation of coupler point position becomes complex when errors are considered in all the four links and four joints as shown in Fig. 10(a). During preliminary analysis, it is found that virtual links represented by r_a at joint-1′ and r_b at joint-2′ behave in such a way that an equivalent virtual link of $(r_a + r_b)$ at joint-1 can replace r_b entirely. In the same way, an equivalent link of $(r_c + r_d)$ can be taken at joint-4 to replace the virtual link r_c at joint-3. Accordingly the Rodrigues parameters for the individual screws at joint-1 and joint-4 are given in Table 6. However, all link-errors cannot be taken to be only positive or negative and all combinations of higher and lower limits of link lengths have to be considered.

Table 6. Rodrigues parameters for four-bar mechanism with errors in all four joints and links

Screw	s_i	$s_{0,i}$	θ_i	t_i
First open chain				
$1'$	(0,0,1)	(0,0,0)	θ_a	0
1	(0,0,1)	$(r_a,0,0)$	θ_2	0
12	(1,0,0)	(0,0,0)	0	Δ_2
$2'$	(0,0,1)	$(r_a + r_2, 0,0)$	θ_b	0
2	(0,0,1)	$(r_a + r_2 + r_b, 0,0)$	θ_3	0
23	(1,0,0)	(0,0,0)	0	Δ_3
Second open chain				
14	(1,0,0)	(0,0,0)	0	Δ_1
$4'$	(0,0,1)	$(r_1,0,0)$	θ_d	0
4	(0,0,1)	$(r_1 + r_d, 0,0)$	θ_4	0
34	(1,0,0)	(0,0,0)	0	Δ_4
$3'$	(0,0,1)	$(r_1 + r_d + r_4, 0,0)$	θ_c	0

For the first open chain, the position of end point 3 is given as Eq.(16).

$$ {}^3\mathrm{P} = \mathrm{A}_{1'}\mathrm{A}_1\mathrm{A}_{12}\mathrm{A}_2\mathrm{A}_{23}\,{}^3\mathrm{P}_0 \qquad (16)$$

where

$$ {}^3p_0 = \begin{pmatrix} r_a + r_b + r_2 + r_3 \\ 0 \\ 0 \\ 1 \end{pmatrix} $$

The associated transformation matrices are as follows.

$$ A_{1'} = \begin{pmatrix} c\theta_a & -s\theta_a & 0 & 0 \\ s\theta_a & c\theta_a & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}, $$

$$ A_1 = \begin{pmatrix} c\theta_2 & -s\theta_2 & 0 & (r_a + r_b)(1 - c\theta_2) \\ s\theta_2 & c\theta_2 & 0 & -(r_a + r_b)s\theta_2 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}, $$

$$A_{12} = \begin{pmatrix} 1 & 0 & 0 & \Delta_2 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix},$$

$$A_2 = \begin{pmatrix} c\theta_3 & -s\theta_3 & 0 & (r_a + r_b + r_2)(1 - c\theta_3) \\ s\theta_3 & c\theta_3 & 0 & -(r_a + r_b + r_2)s\theta_3 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix},$$

$$A_{23} = \begin{pmatrix} 1 & 0 & 0 & \Delta_3 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \qquad (17)$$

Position of end point 3 for the second open chain is given as Eq. (18).

$$^{3}\mathrm{P} = \mathrm{A}_{14}\mathrm{A}_{4'}\mathrm{A}_{4}\mathrm{A}_{34}{}^{3}\mathrm{P}_0 \qquad (18)$$

where

$$^{3}p_0 = \begin{pmatrix} r_1 + r_c + r_d + r_4 \\ 0 \\ 0 \\ 1 \end{pmatrix} \qquad (19)$$

Associated matrices are given as follows.

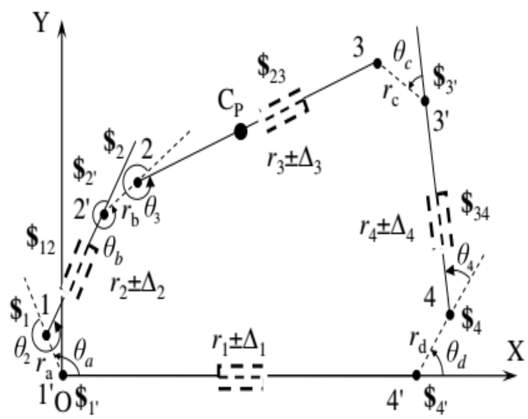
$$A_{14} = \begin{pmatrix} 1 & 0 & 0 & \Delta_1 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix},$$

$$A_{4'} = \begin{pmatrix} c\theta_d & -s\theta_d & 0 & r_1(1 - c\theta_d) \\ s\theta_d & c\theta_d & 0 & -r_1 s\theta_d \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix},$$

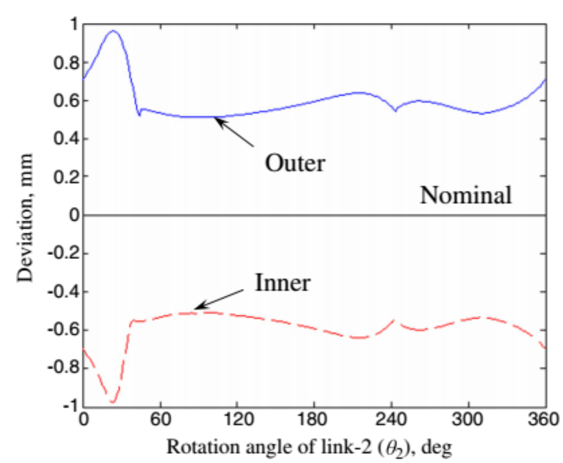
$$A_4 = \begin{pmatrix} c\theta_4 & -s\theta_4 & 0 & (r_1 + r_c + r_d)(1 - c\theta_4) \\ s\theta_4 & c\theta_4 & 0 & -(r_1 + r_c + r_d)s\theta_4 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix},$$

$$A_{34} = \begin{pmatrix} 1 & 0 & 0 & \Delta_4 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \qquad (20)$$

With different combinations of higher and lower limits of link lengths, extreme paths will form outer and inner paths. The deviations of outer and inner paths from nominal path are plotted in Fig. 10(b). A suitable portion of the traced path can be selected depending on a given application.



a)



b)Fig. 10. Four-bar mechanism with errors in all four joints and links

Conclusion

In this paper has been proposed a new method that is to analyze the kinematic characters of a planar mechanism using screw displacement and we have introduced it into four-bar mechanism. During the analysis, we have taken variations in the gap of joints and in the length of links into consideration and proved that the position of point of the coupler can be affected by the errors.

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