Overview of Kinematics Design of Multi Section Planar Continuum Robot

[1]S. R. Chandramouli, [2]Dr. G Krishna Mohana Rao

[1]*Dy. General Manager, ACE Designers Limited,*
Peenya Industrial Area, Bangalore 560058

[2]*Associate Professor of Mech. Engg., JNTU College of Engineering,*
Kukatpally, Hyderabad – 500085

Abstract

The limitations with regard to manoeuvrability of robots built using rigid links & joints lead to the concept development of hyper redundant continuum robots. In order to enhance the flexibility, redundancy will built by adding additional sections. These multi section robots bend continuously along their length. This calls for challenging kinematics design. In this paper author focusses on understanding and development of multi section continuum robot arm kinematics. Initial breadboards that are developed to understand the mechanism is also briefly described.

Keywords: Kinematics, hyper redundant robot, multi section, continuum robot

1. Introduction

Industrial robots are already in use for automating tasks such as welding, painting, loading – unloading of jobs to the machinery etc. that has rigid links & joints.Kinematics design of the traditional robots has been well established by various methods. Popularly Geometric & DH methods are used to develop kinematic equations and further for controlling the robots. As we all know these robots are made of rigid links and joints. Due to the increase in application side of robots, especially in critical segments such as defence, nuclear & medical, called for demanding need of flexibility of robots. Flexibility can be brought in either by increasing number of rigid links and joints or by making the link itself flexible. These futuristic multi section robots are termed as Continuum style robot.As understood briefly, continuum style robot arm does not contain rigid links and joints. These can be considered to be made of multiple sections.

Denavit&Hartenberg technique has been adopted here also to develop robot arm kinematicsas in the case of robots with rigid links and joints[1].

2. Description

Single section continuum robot armsare similarto biological tentacles & trunks. This allows better manoeuvrability & reachability in a task demanding environment.
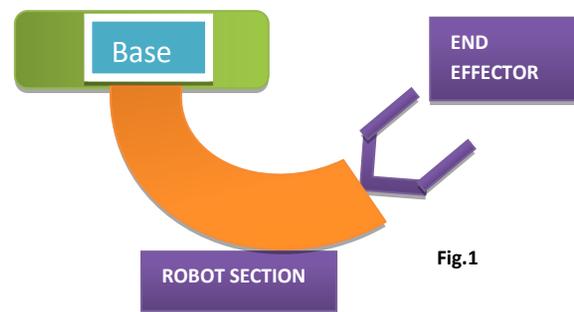
Fig.1

Let us understand the single section construction, to begin with.Constant curvature has often been viewed as desirable characteristic in continuum robots due to the simplification it enables in kinematic modeling. It is considered to be of curved nature as shown in Fig.1, physically conceptualised as multiple segments in each section, say 4. Each section has 2 degrees of

freedomfor spatial construction and 1 degree of freedom forplanar construction. Though not limited, the scope of this paper describes planar robot configuration.

3. Geometrical Representation of Single Section
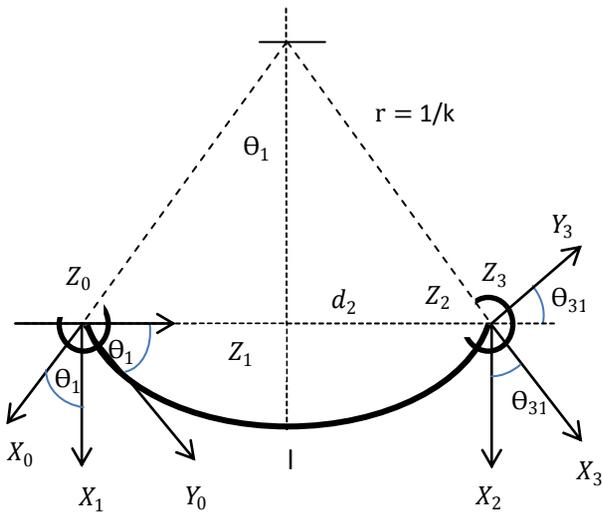
Fig.2

Section curvature, fixing co-ordinate frame and arc parameters are as shown in Fig.2 where Radius of curvature = r = 1/k and Arc length = l.

4. DH Representation

Forward kinematics of a planar curve [4] with constant curvature 'k' and arc length 'l' can be established by 3 coupled movements (transformations).

1. Rotation by an angle, $\Theta 1$
2. Translation by position vector X, d2
3. Another rotation by an angle, $\Theta 3$

Based on the DH rules, DH table is obtained which is as shown in Fig.3.

Joint i	Θ_i	d_i	a_i	α_i
1	Θ_1	0	0	-90
2	0	d_2	0	90
3	Θ_3	0	0	0

Fig.3

5. Kinematics of Single Section

Single section robot arm kinematics [3] is described and derived based on above DH table and standard transformation matrix.

$$T_{i-1}^{i} = T(z_{i-1}, d_i) R(z_{i-1}, \theta_i) T(x_i, a_i) R(x_i, \alpha_i)$$

$$\begin{bmatrix} Cos\theta_i & -Cos\alpha_i Sin\theta_i & Sin\alpha_i Sin\theta_i & a_i Cos\theta_i \\ Sin\theta_i & Cos\alpha_i Cos\theta_i & -Sin\alpha_i Cos\theta_i & a_i Sin\theta_i \\ 0 & Sin\alpha_i & Cos\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$^{0}T_i = {}^{0}A_1 * {}^{1}A_2 \dots \dots {}^{i-1}A_i$$

From the geometry,

$\Theta 1 = \Theta 3 = \Theta$; $2\Theta = kl$

Considering the above said 3 transformations and after substituting & simplification, homogeneous transformation matrix for the section is obtained as,

$$^{0}T_3 = \begin{bmatrix} Coskl & -Sinkl & 0 & \frac{1}{k}\{Coskl - 1\} \\ Sinkl & Coskl & 0 & \frac{1}{k}\{Sinkl\} \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

......Eqn. (1)

6. Kinematics of Multi Section Continuum Robot

Based on the single section transformation matrix as described above, let us look at derivation of 3 sections robot transformation matrix.
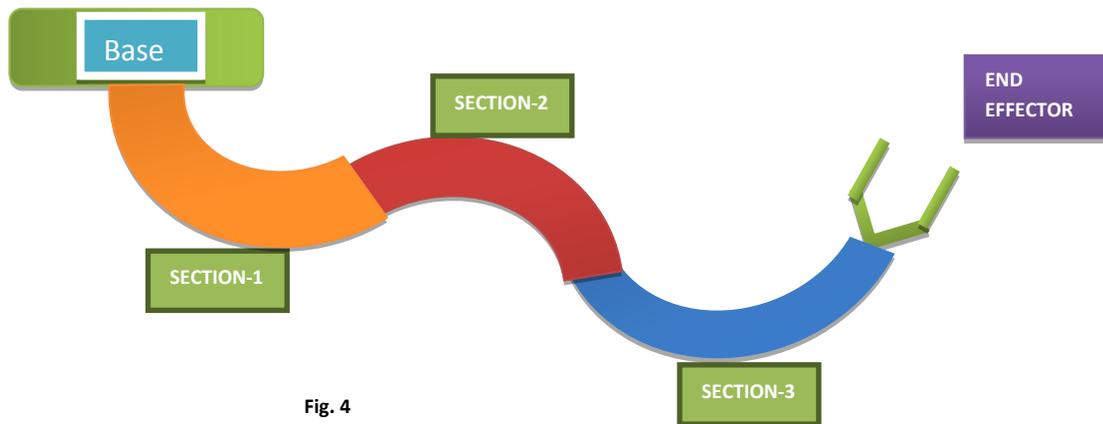
Fig. 4

Physical structure is conceptualised & constructed from a finite number of actuated sections (3 sections) with segments, as shown in Fig.4. Compared to kinematics of a conventional robot manipulator use of joint angles & link lengths does not supply enough data for describing manipulator shape. In order to arrive at the shape, hyper redundant robot can be constructed based on sections with segments.

Robot sections that are conceptualised are of constant curvature and are considered to have finite number of curved links [2]. Above shown three-section hyper redundant robot is actuated individually to bend over their length in order to obtain the required end effector position.

Using repetitive structure of the DH table, the transformation matrix for the forward kinematics is the product of three matrices of the form of Eqn. (1). Hence for 3 section robot one requires 9 transformations.

Therefore,

$$^{0}[T]_9 = {}^{0}[T]_3 * {}^{3}[T]_6 * {}^{6}[T]_9$$

7. Deriving 3 SectionHomogeneous Transformation Matrix

Let us define Section parameters as,

k1 and l1 are curvature & length of Section-1;

k2 and l2 are curvature & length of Section-2;

k3 and l3 are curvature & length of Section-3;

SECTION-1 TRANSFORMATION MATRIX:

$$^{0}T_3 = \begin{bmatrix} Cosk_1l_1 & -Sink_1l_1 & 0 & \frac{1}{k_1}\{Cosk_1l_1 - 1\} \\ Sink_1l_1 & Cosk_1l_1 & 0 & \frac{1}{k_1}\{Sink_1l_1\} \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Let $Cosk_1l_1 = C_1$; $Sink_1l_1 = S_1$

Substituting,

we get transformation matrix forSection-1.

Similarly transformation matrix for other two sections is obtained.

SECTION-2 TRANSFORMATION MATRIX:

$$
{}^{3}T_{6} = \begin{bmatrix} C_2 & -S_2 & 0 & \frac{1}{k_2}\{C_2 - 1\} \\ S_2 & C_2 & 0 & \frac{1}{k_2}\{S_2\} \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

SECTION-3 TRANSFORMATION MATRIX:

$$
{}^{6}T_{9} = \begin{bmatrix} C_3 & -S_3 & 0 & \frac{1}{k_3}\{C_3 - 1\} \\ S_3 & C_3 & 0 & \frac{1}{k_3}\{S_3\} \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

Hence, the transformation matrix from frame-0 to frame-9 can be computed by multiplying the matrices serially to get,

$$
{}^{0}T_{9} = \begin{bmatrix} C_{123} & -S_{123} & 0 & E_{14} \\ S_{123} & C_{123} & 0 & E_{24} \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

Where,

$$Cos(k_1 l_1 + k_2 l_2 + k_3 l_3) = C_{123}$$
$$Sin(k_1 l_1 + k_2 l_2 + k_3 l_3) = S_{123}$$

and

$$Cos(k_1 l_1 + k_2 l_{23}) = C_{12}$$

$$Sin(k_1 l_1 + k_2 l_2) = S_{12}$$

8. Deriving Kinematics Equations from Transformation Matrix

Thus forward kinematics equations are arrived by comparing with the standard form:

$$
T = \begin{bmatrix} n_x & s_x & a_x & p_x \\ n_y & s_y & a_y & p_y \\ n_z & s_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

Where, position of the end effector is given by

$$p_x = E_{14}$$

$$p_y = E_{24}$$

$$p_z = \mathbf{O} \text{ [for planar configuration]}$$

That implies,

$$E_{14} = \frac{C_{123} - C_{12}}{k_3} + \frac{C_{12} - C_1}{k_2} + \frac{C_1 - 1}{k_1}$$

And

$$E_{24} = \frac{S_{123} - S_{12}}{k_3} + \frac{S_{12} - S_1}{k_2} + \frac{S_1}{k_1}$$

Thus completes the derivation of forward kinematics of a three-section planar continuum robot which can be extended to any number of sections.

9. Breadboard Development

Though the initial experiments have been conducted elsewhere in the world, it is pretty nascent in India for industrial application. Authors have initiated toexperiment, understand & build the constant

curvature concept envisaged above by way of building simple breadboards with cable / tendon arrangement [3].

Fig. 5   **Fig. 6**

Fig.5&6 shows the breadboard with single section planar robot model with 4 segments. One pair of cable controls one DOF of the section.Actuation has been verified using hand controlled cable movement, which intern confirms that the cable with guide is suitable to build the required mechanism.
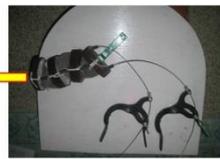
Fig. 7   **Fig. 8**

Fig.7&8 shows improvised version of breadboard built using foam and springs between the segments for smoother curvature control. Fig.7 shows the verticalposition of the end point of the robot. Cables are actuated to achieve the robot end point movement from vertical position to horizontal position (rotation by 90 degrees clockwise), as shown in Fig.8.

Thus, working concept with cable actuation has been verified for a planar configuration.This verifies that end point position can be controlled by varying the arc length 'l' obtained through actuating the cables.

10.   Conclusion

It is evident that present day world can use robots for non-industrial applications also. Especially rapid research in this area is being carried out across the globe. In this paper, authors limit to development of methodology and approach to derive planar kinematics of a hyper redundant robot with multiple sections.

Experiments are being conducted to understand and verify the ground mechanism for building continuum style robot. However,authors are carrying out further research and development on spatial configuration and for its real time implementation as well. These robots are envisaged to work in environments where flexibility is needed.

In future, theses robots find application in the field of assembly robotics, medical robotics, nuclear robotics &defence robotics etc.

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