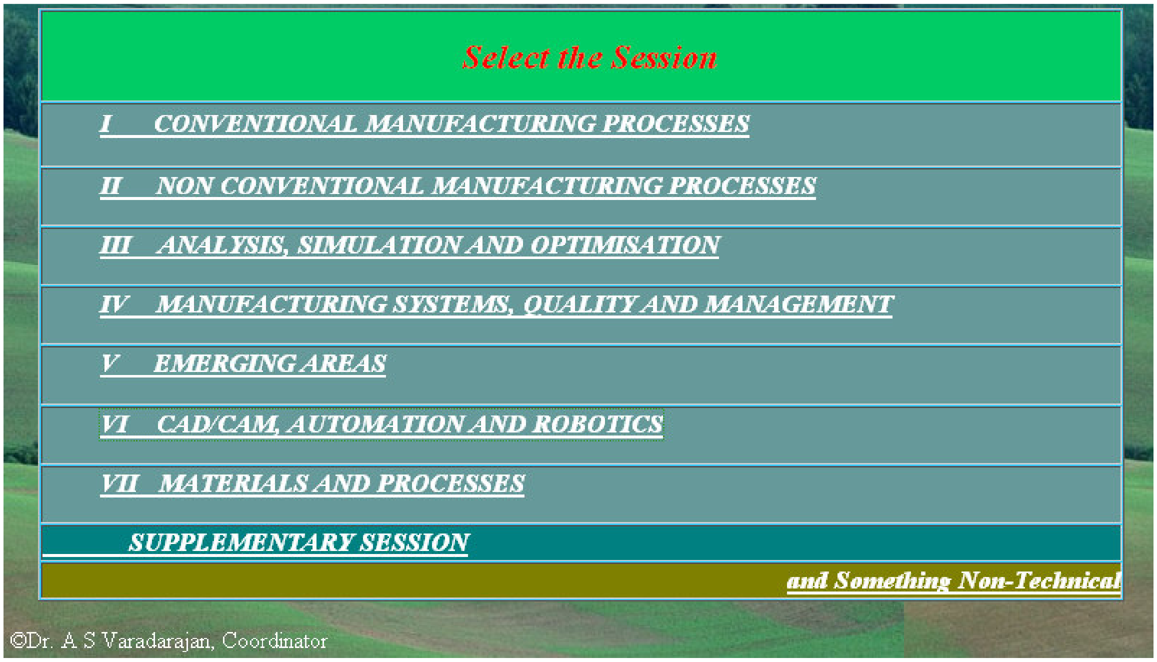

Statistics Regarding Participation.......................

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1	Tamil Nadu	20	46
2	Andra Pradesh	14	12
3	Karnataka	12	17
4	Maharashtra	5	16
5	Punjab	3	3
6	Bihar	3	4
7	Bengal	2	2
8	Gujarath	1	2
9	Kerala	7	23
10	Utter Pradesh	1	1
	Total	68	126

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KINEMATIC MODEL OF A FLEXIBLE LINK USING LOCAL CURVATURES AS THE DEFORMATION COORDINATES

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INTRODUCTION

The kinematics of flexible beam is a fundamental part in modeling flexible manipulators and has raised great interest in the past twenty years [1]. To describe link deformation, most of researches took the link 's deflections as the deformation coordinates [2, 3]. This approach has the advantages of intuitive modeling procedure since it is coupled with the use of natural coordinates. However, the problem arises when the real-time simulation and control are performed since it is difficult to detect the link deflection using conventional measurement systems.

Rather than link deflections, the local curvatures can be used as the deformation coordinates [4]. The link deformation in this approach is described in terms of local curvatures and related to a floating frame attached to the flexible link. This approach yields a small number of equations and is more effective or real-time simulation and control purposes since it is easily interfaced with on-line strain measurements [5].

In this paper, a kinematic model of a flexible beam is developed using local curvatures as the deformation coordinates. Initially, the local frames are defined. Then, the orientation and position variations of the local frame are considered. At the end, the endpoint position and orientation are given in terms of local curvatures.

FLEXIBLE-LINK KINEMATICS

The kinematic model of a manipulator implies finding the relationships between the various reference-frames attached to the manipulator. These relationships are completely specified by the rotation matrix (or vector) and position vector. The kinematic model of a flexible link is constructed similarly to the robotic manipulator. To describe position and orientation of the flexible link, the flexible link is divided into *n*sections. Each section has the same length Δs in its neutral axis. A local frame is assigned to each section and represents the position and orientation of the section. The origin of the local frame is located at the left point of the neutral axis of the section with its x-axis tangent to the neutral axis. All the local frames have the same orientation when the link undergoes no deformation. In order to represent the endpoint, two frames are assigned to the last section, one has its origin at the left point of neutral axis and another has its origin at right point of the neutral axis.

Fig.1 shows the flexible beam with the four reference frames that are of interest. Specially, the relation between the base frame $\{C_0\}$ and the endpoint frame $\{C_n\}$ is to be derived. The following assumptions are made to build the model:

a). The link is considered as an Euler-Bernoulli beam, implying that the beam sections stay in plane and perpendicular to the neutral axis.
b). The deformations are kept within the elastic limit of the beam material and there is no permanent deformation.
c). The neutral axis is non-extensible. Hence, the longitudinal deformation is ignored.
d). The link has a circular cross-section so no wrapping occurs.

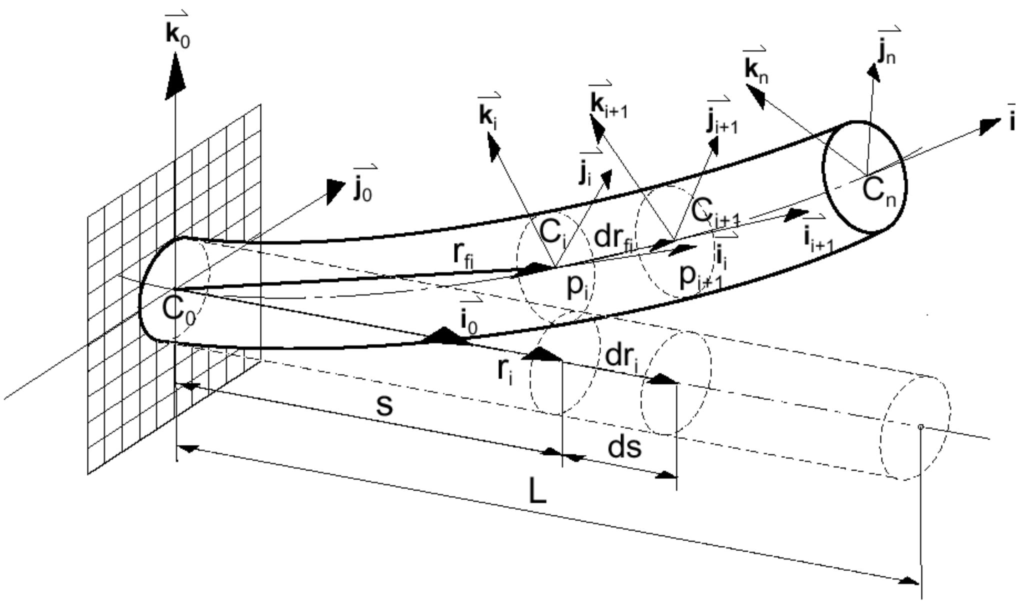

Fig. 1 Flexible Link and Its Frames

To derive the model, the orientation variations of the frames $\{C_i\}$ are first considered. It is assumed that the time is fixed and is considered only the variation about space variable. Realizing that as $n \to \infty$, the arc length $\Delta s \to ds$, the orientation variations of the frame $\{C_i\}$ can be expressed as

$$^{i}\delta\theta = \frac{^{i}\partial\theta}{\partial s} ds = {}^{i}kds \qquad \ldots(1)$$

where the leading superscript i indicates that the quantity is defined in frame $\{C_i\}$ and ^{i}k represents the local curvature vector and is defined by

$$ {}^{i}k = \lim_{s\to 0}\frac{\Delta\theta}{\Delta s} \Leftrightarrow \begin{bmatrix} {}^{i}k_x \\ {}^{i}k_y \\ {}^{i}k_z \end{bmatrix} = \begin{bmatrix} \frac{{}^{i}\partial\theta_x}{\partial s} \\ \frac{{}^{i}\partial\theta_y}{\partial s} \\ \frac{{}^{i}\partial\theta_z}{\partial s} \end{bmatrix} \qquad \ldots(2) $$

Equation (i) gives the orientation variation defined in frame $\{C_i\}$. In many cases, there is a need to express the orientation in the base frame $\{C_0\}$. This can be obtained through the mapping of the frame $\{C_i\}$ to the frame $\{C_0\}$ and the orientation variation in frame $\{C_0\}$ is given by

$$ {}^{\theta}\delta\theta = {}^{0}_{i}R\,{}^{i}k\,ds \qquad \ldots(3) $$

where ${}^{0}_{i}R$ represents the rotation matrix of the frame $\{C_i\}$ relative to base frame $\{C_0\}$.

The same kind of relation exists between the rotation matrix ${}^{0}_{i}R$ and ${}^{i}k$as between the rotation matrix and angular velocity vector. This relation leads to the differential equation [3]:

$$ \frac{d\,{}^{0}_{i}R}{ds} = {}^{0}_{i}R\,{}^{i}\tilde{k} \qquad \ldots(4) $$

The tilde symbol in ${}^{i}\tilde{k}$ indicates that ${}^{i}\tilde{k}$ is the skew symmetric matrix formed with the elements of ${}^{i}k$.

The rotation matrix can now be found by solving the differential of equation (4). Piedboeuf [3] has proposed a simple approach to solve this differential equation by separating the rotation matrix into different order terms. Now, the result presented by Piedboeuf is directly used. To simplify notation, the following definitions are used:

$$ \nu = \int_0^s\int_0^\xi {}^{i}k_z\, d\eta\, d\xi \omega = -\int_0^s\int_0^\xi {}^{i}k_y\, d\eta\, d\xi \alpha = \int_0^s {}^{i}k_x\, d\xi \qquad \ldots(5) $$

The rotation matrix from frame $\{C_i\}$ to $\{C_0\}$ is

$$ {}_0^iR = \begin{bmatrix} 1-\frac{1}{2}\left(\nu'^2+\varpi'^2\right) & -\nu' - \int_0^s \alpha'\omega' d\xi & -\omega' + \int_0^s \alpha'\nu' d\xi \\ \nu' - \int_0^s \alpha\ \omega'' d\xi & 1-\frac{1}{2}\left(\nu'^2+\alpha^2\right) & -\alpha\ - \int_0^s \nu'\omega'' d\xi \\ \omega' + \int_0^s \alpha\ \nu'' d\xi & \alpha\ - \int_0^s \nu''\omega' d\xi & 1-\frac{1}{2}\left(\omega'^2+\alpha^2\right) \end{bmatrix} \qquad \ldots(6) $$

The rotation angles $\{C_i\}$ relative to the base of the link can now be determined by integrating equation (3) and the resulting rotation vector is expressed as

$$ \theta = \begin{bmatrix} \theta_x \\ \theta_y \\ \theta_z \end{bmatrix} = \begin{bmatrix} \alpha - \int_0^s \omega'\nu'' d\xi + \int_0^s \nu'\omega'' d\xi \\ -\omega' + \int_0^s \nu'\alpha' d\xi - \int_0^s \alpha\nu'' d\xi \\ \nu' - \int_0^s \alpha\omega'' d\xi + \int_0^s \omega'\alpha' d\xi \end{bmatrix} \qquad \ldots(7) $$

To obtain the position vector relative to the base of the link, the position variation in Fig.1 is considered :

$$ {}^0\delta r_{fi} = {}_0^iR\, {}^i dr_{fi} = {}_i^0R \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} \qquad \ldots(8) $$

Using the above equation and substituting the rotation matrix given in equation (6), the endpoint position vector is obtained by integration of the variation ${}^0\delta r_{fi}$

$$ r = \begin{bmatrix} r_x \\ r_y \\ r_z \end{bmatrix} = \begin{bmatrix} s - \frac{1}{2}\int_0^s \left(v'^2 + w'^2\right) d\xi \\ v - \int_0^s \int_0^\xi w''\alpha d\eta d\xi \\ w + \int_0^s \int_0^\xi v''\alpha d\eta d\xi \end{bmatrix} \qquad \ldots(9) $$

where s is the arc length if the neutral axis from frame $\{C_i\}$to frame $\{C_0\}$

Equation (7) and (9) give the orientation and position of the frame $\{C_i\}$. The orientation and position of the endpoint of the flexible link can be obtained by simply replacing the s with L, the length of the flexible link in equation (7) and (9) respectively.

CONCLUSION

The kinematic model of a flexible link has been developed using the local curvatures as the deformation coordinates. This model is more suitable for the real-time simulations since the local curvatures can be obtained using the on-line strain measurements. As long as the curvatures are detected the endpoint position and orientation can be easily determined using the forward kinematics, which is similar to the rigid manipulator.

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