Research on Kinematics Simulation of Continuum Robot Based on ADAMS

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Abstract. As a prevalent biological inspired robot, continuum robots has good bending performance and excellent flexibility. In this paper, a continuum robot is designed, then the kinematic model is established to analyze the motion characteristics of the robot. Secondly, the simulation model of the continuum robot is conducted in ADAMS to verify the feasibility of the established kinematic model and to simulate its bending ability. At the same time, it also showed that ADAMS software had value in building a flexible body model.

1. Introduction
Continuum robot has received the widespread attention. It uses the "bionic" design concept to mimic the "invertebrate" flexible design of animals’ structure, and there aren’t any rigid joints or rigid links. Compared with the rigid robot, the continuum robot has excellent flexibility and good bending performance. It can regulate its shape flexibly according to the obstacles and working condition. Then make it owes strong adaptability to unstructured and limited environment[1]. So continuum robots have a wide application prospect. Walker designed a continuum robot based on the elephant nose and achieved certain load capacity[2]. Simaan developed a continuum robot for throat surgery, which can be applied to medical treatment[3].

However, continuum robot still has unsolved problems, ranging from material selection, structural design, mechanical analysis, control and perception. The development process of continuum robot based on the virtual prototype technology can reduce the cost greatly[4]. Automatic Dynamic Analysis of Mechanical Systems (ADAMS) is one of the famous virtual prototype analysis softwares. In this paper, it is used to test the designed continuum robot’s motion characteristics.

2. Structural design of continuum robot
The structure of designed continuum robot is shown in figure 1. It consists of a main skeleton, four drive lines (secondary skeleton), and some disks. The material of the skeleton is the NiTi alloy, and that of the disk is lightweight aluminum to make the robot lighter. There are five small holes in each disk. The central main hole makes the disk fix to the main skeleton. The sub-holes around the main hole that are distributed at 90 degrees to each other. The diameter of the main skeleton is 1 mm, the diameter of the driving line is 0.6 mm, the diameter of the disk is 12 mm, and the diameter of the hole corresponds to the diameter of the flexible body that passes through. When the drive lines are driven, the corresponding drive lines produce displacement and the robot can be driven to achieve continuum bending motion.
Figure 1. Illustration and the geometric model of the continuum robot [5]

3. Kinematic analysis of continuum robot

Geometric analysis [5] is used for kinematic analysis of the continuum robot. The flexible body is considered as a smooth continuum arc with the same curvature, and its axial deformation is ignored [5]. The single-segment’s geometric model is given as in figure 2.

Let the center point of the base disk be the origin of the base coordinate frame \( \{ O_0 \} \), let the center point of the end disk be the origin of the terminal coordinate frame \( \{ O_1 \} \). The coordinate frames are shown as in figure 1. The bending angle is represented by \( \theta \), the rotation angle is represented by \( \phi \), and the radius of the minor skeleton dividing circle are represented by \( r \). \( \{ O_1 \} \) can be seen as the result of translation and rotation transformation by \( \{ O_0 \} \).

A homogeneous transformation matrix expressed as equation (1) is used to represent the coordinate transformation matrix.

\[
R = \begin{bmatrix}
    n_x & o_x & a_x & p_x \\
    n_y & o_y & a_y & p_y \\
    n_z & o_z & a_z & p_z \\
    0 & 0 & 0 & 1
\end{bmatrix}
\]

(1)

where \( n = [n_x, n_y, n_z]^T \), \( o = [o_x, o_y, o_z]^T \), \( a = [a_x, a_y, a_z]^T \) is the attitude matrix.

\( p = [p_x, p_y, p_z]^T \) is the positional matrix.

Use the geometric method, the homogeneous transformation matrix can be obtained as:

\[
R^0_1 = \text{Trans} \left[ \frac{l}{\theta} c \varphi (1 - c \theta), \frac{l}{\theta} \varphi (1 - c \theta), \frac{l}{\theta} s \theta \right] \cdot \text{Rot}(z, \varphi) \cdot \text{Rot}(y, \theta) \cdot \text{Rot}(z, -\varphi)
\]

\[
= \begin{bmatrix}
    c^2 \varphi \theta + s^2 \varphi & c \varphi s \varphi \theta - c \varphi s \varphi & c \varphi s \theta & \frac{l}{\theta} c \varphi (1 - c \theta) \\
    c \varphi s \varphi \theta - c \varphi s \varphi & s^2 \varphi \theta + c^2 \varphi & c \varphi s \theta & \frac{l}{\theta} s \varphi (1 - c \theta) \\
    - c \varphi s \theta & - s \varphi s \theta & c \theta & \frac{l}{\theta} s \theta \\
    0 & 0 & 0 & 1
\end{bmatrix}
\]

(2)

From the established forward kinematic model equation (2), the pose matrix of the end coordinate frame relative to the base coordinate frame can be obtained as follows:

\[
p_x = \frac{l}{\theta} \cos \varphi (1 - \cos \theta), \quad p_y = \frac{l}{\theta} \sin \varphi (1 - \cos \theta) \quad a_z = \cos \theta
\]

(3)

According to equation (3), the bending angle and rotation angle can be obtained as:
The change of drive length can be expressed as \( \Delta l = l_l - l_i \), where \( l_l \) is the initial length of the drive line, \( l_i \) is the length of instantaneous moment in the movement, \( \Delta l_i \) is the elongation of the drive line. The transformation relationship between the drive variation and the angle can be obtained as:

\[
\Delta_l_1 = -\Delta l_3 = r\theta \cos \phi, \quad \Delta l_2 = -\Delta l_4 = r\theta \sin \phi
\]  

Then the inverse solution is:

\[
\begin{aligned}
\varphi &= \arctan(\Delta l_2 / \Delta l_1) \\
\theta &= \sqrt{\Delta l_1^2 + \Delta l_2^2} / r
\end{aligned}
\]  

From equation (1), the vector expression of the end position corresponding to bending angle and rotation angle can be obtained as:

\[
p = [p_x, p_y, p_z]^T = F(x)
\]

where \( x = [\theta, \varphi]^T \). Simultaneously, differentiating equation (7) about \( \theta \) and \( \varphi \) respectively yields the speed matrix equation, which can be given as:

\[
\dot{p} = \begin{bmatrix}
\frac{\partial p_x}{\partial \theta} & \frac{\partial p_x}{\partial \varphi} \\
\frac{\partial p_y}{\partial \theta} & \frac{\partial p_y}{\partial \varphi} \\
\frac{\partial p_z}{\partial \theta} & \frac{\partial p_z}{\partial \varphi}
\end{bmatrix} = J(x) \dot{x}
\]  

4. Kinematic analysis of continuum robot

This paper use the method of establishing a rigid body first and then establishing a flexible body. Taking the reference point on the established rigid body as the end point for establishing the flexible body, the operation of moving the flexible body can be avoided. In order to modify the model in the design easily, parametric modeling is used when building the model, which can shorten the design time and improve the efficiency of the design work.

4.1. Disk Parametric Modeling Process

4.1.1. Create variables. Drop down the "Create" option in the menu bar and click on the "Design Variable". The key to parameterize disk model is to parameterize appropriate point. The coordinates of the points are expressed as design variables, the distance between the center of each hole and the center of the disk is denoted by the design variable RA_1. The value of the radius of the disk is represented by \((1+RA_1)\), and the thickness of the disk is represented by the design variable RA_2. Set the standard value for RA_1 to 5, the standard value of RA_2 is 0.5.

4.1.2. Parametric modeling disks. Select the cylinder model in the "Object" option in the toolbar. When certain length and cross-sectional radius are required, enter the design variable in the space corresponding to the length and radius. Check the “√” symbol before the space to indicate that the input value will be applied. Next, set up four parameterized geometric points on the disk, and their coordinates are represented by \((RA_1, 0, 0)\), \((0, RA_1, 0)\), \((-RA_1, 0, 0)\), \((0, -RA_1, 0)\).
4.1.3. Create circular disk holes. It is necessary to create holes on the four parameterized geometric points and the center of the disk. Select the "Drill" icon in the "Features" area in the "Object" option. Set the radius of holes to 0.05cm and the depth to (RA_2). When using the mouse to select the center point it can cause deviations, right-click on the hole, in the menu that appears, select “Modify”. In the empty column that sets the center of the hole, specify the center of the hole as point POINT_1 in the form of (LOC_RELATIVE_TO({0,0,0}, POINT_1)). The hole center is designated point POINT_1.

4.2. Establishing A Flexible Body

4.2.1. Add material settings. Drop down the "Create" option in the menu bar and click on the "New Material", in the dialog that appears, set the relevant information for the material like Young's modulus, Poisson's ratio and density.

4.2.2. Build a flexible body. The stretch method is used to create a liner flexible body with two known points as the endpoints. First, the disk is set up, then the point on the disk can be directly used as the endpoint to create a flexible body. By setting the center line, the stretching path in the global coordinate system is defined, and the radius of the cross section is set according to the diameter of the hole. The unit size will affect the accuracy of the flexible body and the calculation speed during simulation. When the unit setting is larger, the solver will calculate faster, but the accuracy of the simulated flexible body will decrease. When setting the attachment points, take the two Marker points created in defining center line as outer joins. Clicking the OK button then the flexible body will be successfully created.

4.3. Adding System Constraints

There are some constraint among each components. The constraint determines the connection relationship, the relationship between physics and mechanics, the degree of freedom among objects, and the way two objects move relative to each other. In ADAMS, different connects are used to express different constraint relationships. First set fixed constraints, click "Connect" in the menu bar, and select the "fixed" icon in the connectors bar of the toolbar that appears. Use the fixed to fix the main skeleton flexible body and the disks at two ends, and select the parameterized geometry point as the outer joints of the fixed. Use the fixed to connect the top of the drive line with the disk, and the drive lines at both sides of the rotary disk are connected together by fixed into a whole.

4.4. Adding Drivers

The drive is to constrain the two components to allow them to move according to a certain law. Observe the movement of the robot in a plane with a rotation angle of 45 degrees. It is necessary to first establish a translation between the bottom end of the flexible body and the ground, and then add the motion to the translation, then the bending motion of the robot is achieved by setting the parameters of the motion. To make the rotation angle achieve 45 degrees, the four motion functions should be set to the same value, two of the signs are positive, while others are negative.

4.5. Adding Contact

The drive line comes into contact with the inner wall of the disk hole during bending deformation, accompanied by the deformation of the part and the change of the contact force. Therefore, establishing the model in ADAMS requires a contact between the hole and the flexible body of the drive line. And the flexible body needs to contact with the rigid body by adding a dummy part. Otherwise, an error will occur. In this case, the dummy part is constructed by adding a cylinder and setting its mass and inertia matrix to zero. Use fixed to fix the dummy part on the flexible body, in the simulation, the flexible body will contact the rigid disk through the dummy part, therefore, it’s necessary to add contact between dummy parts and the disk. Click the "Contact" icon in the "force" area of the toolbar, in the dialog that appears, select the dummy part and the disk as the I Solid and J
Solid to complete the setting of contact. The larger the bending angle to be achieved, the more dummy parts need to be added, and add more dummy parts, the simulation will be more accurate.

5. Kinematic analysis of continuum robot

5.1. Model Simulation
Because there is gravity in the actual application, it’s necessary to add a gravity environment in the simulation. After the model is set up, use the model checking tool to check for errors such as redundant constraints. If there is no error, click the "Run Interactive Simulation" icon under the simulation area to start simulate. Select the representative moment to display the simulation process as follows:

Figure 2. Pose diagram of the single robot

After the simulation is completed, enter the post-processing module to process the data. Select the data source by setting the source and object, then choose the characteristic in the characteristic bar which includes the point's running trajectory, velocity, acceleration, angular velocity, angular acceleration, and other information.

5.2. Analysis of Simulation Results
Because the end coordinate system of the kinematics equation is based on the end disk of the continuum robot, the center of mass of the end disk is used as the analysis object to analyze the motion position, velocity, acceleration and angular velocity. The simulation results are as follows:

Figure 3. The position curve of the end disk’s centroid in the Z direction (in ADAMS and MATLAB)

Figure 3 shows the position of the centroid of the end disk in the Z direction. In order to verify the feasibility of the kinematics equation proposed in section II, the position of the kinematics equation in the Z direction was simulated in MATLAB, compared with the figure of Z position in ADAMS, it can be seen that the movements of the two figures tend to be the same, although there are errors, the trends
are generally the same, so the kinematic law established in section III is basically correct. However, it should also be noted that as the bending angle increases, the error between the two also gradually increases. The reason for this phenomenon is that the derivation of kinematics is based on ideal conditions. In order to reduce the error, more realistic conditions must be taken into account in the formula to further improve it.

![Figure 4](image)

**Figure 4.** The velocity and acceleration curve of the end disk’s centroid

Figure 4 are the velocity and acceleration changes of the centroid of the end disk. It can be seen from the figure that the continuum robot has a certain transition time from the initial state to a more stable running state. After that, it can basically achieve uniform speed operation. When the speed fluctuates greatly appears at 1.5 s, analyze the length of dummy part in the model, it should be the fluctuation caused by the dummy part when it runs at the junction with the hole. The speed in the steady running state is basically consistent with the speed calculated by the formula, which shows that the kinematic relationship established in section II is basically correct, and also illustrates the feasibility of using ADAMS software to build a flexible body model, this software is of great help in the study of flexible study.

6. Conclusion
The model of continuum robots was established in the virtual prototype software ADAMS, rigid and flexible components were established during the process, the connection relationship was implemented with constraints such as connectors and contacts. The model was simulated and the motion of the continuum robot was observed. Finally, image analysis is performed on the motion characteristics data obtained from the simulation, and compared with the images obtained based on the derived kinematics equations, the correctness and rationality of the deduced kinematics model could be verified. At the same time, it also showed that ADAMS software had value in building a flexible body model.

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