Kinematics analysis of pneumatic soft manipulator

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Abstract. A software mechanical grabbing device is designed to deal with space debris. The robotic arm is composed of unit segments of modular design, and the kinematic model of the unit segments of the mechanical arm is established by simplifying it into a cantilever beam model. The relationship among the driving space, joint space, and operation space of the unit section is analyzed, and its kinematics equations are established.

1. Introduction
Space debris is a useless artificial object orbiting the Earth, in which space debris with a diameter between 1 and 10 cm in the near-earth orbit accounts for 90% of the total amount. Their existence has brought great hidden dangers to the aerospace industry. Researchers have proposed to use soft space robots to capture space debris in response to this problem. A soft manipulator is a structure designed based on bionic theory, simulating animal tissues and organs' movement, such as the expansion, bending, and torsion of Octopus feet[1]. The soft manipulator is composed of elastic materials driven by pneumatic, wire traction, SMA, or electrochemical reaction [2] to make the manipulator continuously bend, extend or twist, to make the end effector reach the required position. However, the soft manipulator does not have rigid links and joints, so it is impossible to extract the useful joint parameters to establish the kinematic model. Some researchers solve the kinematics equation based on the idea of constant curvature equation [3-5]. Nevertheless, the amount of calculation is generally large. Some researchers [6-7] In the continuous pneumatic manipulator study, the kinematic equation of continuous manipulator is derived by mathematical calculation through analyzing the relationship between structural curvature and bending moment; this paper designs a pneumatically driven space debris capture mechanism and the kinematics model of the manipulator in the mechanism is established.

2. Software arm structure
The space debris capture device has a complete drive and actuator structure, as shown in Figure 1, designed to capture debris with a diameter of 1 cm-10 cm. The whole structure is installed outside the spacecraft through the base. After the spacecraft is orbited to the target space debris orbit during operation, the gas source device inputs gas to the mechanical arm to drive the robotic arm to approach the target so that the mechanical capture hand reaches the target position. Then under the control of the solenoid valve, the air supply inputs a certain amount of gas into the manipulator to drive the manipulator to capture the target.
The pneumatic flexible manipulator arm comprises three-unit segments of modular design. Unit sections are screwed together in series. The air circuit is tied to the mechanical arm's outer wall and is connected to the gas tank by a solenoid valve. The arm is in a straight line when it is not driven, whereas bending or torsion occurs when gone, as shown in Figure 2. The data representation in the figure is shown in Table 1. Each unit section contains three air chambers with a uniform distribution of 120 degrees. As shown in Figure 3, the unit section is structured by connecting the air pumps controlled by solenoid valves at the base. The outer arm is evenly wound with a filament web to restrain the radial expansion of the peninsula, the inner arm contains a core chamber to increase the stiffness of the unit joints and transmit a certain amount of support force to the end actuator. The mechanical arm contains a core cavity used to increase the unit joints' stiffness to transfer a certain amount of support force to the end actuator.

| Table 1. mechanical arm unit parameters. |
|------------------------------------------|
| project | parameter |
| Diameter of mechanical arm joint | D |
3. Kinematic Analysis of Software Robot Arm

The flexible pneumatic manipulator does not have rigid joints and links, so the kinematic equation cannot be solved directly by the D-H method. Firstly, the manipulator is simplified as a cantilever beam model to solve the mapping between the driving force and deformation, which reduces the complexity of calculation and modeling. Then, the mapping between deformation and end position and attitude is obtained by coordinate transformation [9]. The two maps are combined into a kinematic model of the mechanical arm.

3.1 mapping between driving space and joint space

Under the action of driving air pressure, the flexible unit section bends. The air pressure in the three cavities in the manipulator section is uniformly distributed: \( P_1, P_2, \) and \( P_3 \). As shown in Figure 4, the arrows' density in the figure indicates the air pressure size. The mechanical arm is deformed when the air pressure in the three chambers is different. The deformed arm is simplified as a cantilever beam model, and the resultant air pressure is uniform load \( F \) distributed along the axis. \( \theta \) is the end bending angle, and \( \phi \) is the torsion angle, as shown in Figure 5.

![Figure 4 Section Pressure Diagram](image1)

![Figure 5 Simplified Force Diagram of Unit Section](image2)

According to formula (1) (2), the bending angle of the end of the manipulator unit is calculated as \( \theta \). Where \( EI \) is the overall stiffness, \( A_1, A_2, A_3 \) are the air chamber's cross-sectional area.

\[
F = \left( A_1 P_1 + A_2 P_2 + A_3 P_3 \right) A_{d1}
\]

\[
\theta = \frac{F h^2 H^2}{EI} - \frac{F h^3}{6EI}
\]

\( \phi' \) is the torsion angle of the unit fiber line. The sum of the rotation of the fiber wire around its axis is torsion angle \( \varphi' \). \( \varphi' \) is derived from Formula (3) ~ (6) \( M, GI, \) are the torque and stiffness on the unit fiber line.

\[
\phi' = \frac{M}{GI}
\]
Establish a single-section robotic arm coordinate system $X_Y_Z_1O_1$ with the robotic arm's initial end as the starting coordinate system and the end of the robotic arm as the end coordinate system, as shown in Figure 6. The mapping $T$ at both ends is obtained by coordinate transformation, as shown in Equation 7, Where $c$ is $\cos$, $s$ is $\sin$, $l$ is the pneumatic manipulator's length.

$$
T = \begin{bmatrix}
c^2\phi c\theta + s^2\theta & c\phi s\phi c\theta - c\phi s\phi & c\phi s\theta & \frac{l}{\theta}c\phi(1-c\theta) \\
c\phi s\phi c\theta - c\phi s\phi & c^2\phi c\theta + c^2\phi & s\phi s\theta & \frac{l}{\theta}s\phi(1-c\theta) \\
-c\phi s\theta & -s\phi s\theta & c\theta & \frac{l}{\theta}s\theta \\
0 & 0 & 0 & 1
\end{bmatrix}
$$

The equation of inverse kinematics is used to model the coordinates of the end pose, and the transformation matrix can be obtained from equations (3) ~ (6) and (7). Only the position and pose coordinates of the end are considered, and the corresponding coordinate method is used to express the manipulator element, as shown in equation (8). Among them, it is taken from the first in the kinematic equation, as shown in equation (9).
\[ \phi = \arctan\left(\frac{P_y}{P_z}\right) \quad (11) \]

4. Conclusion
A pneumatic space debris capture mechanism was designed based on the bionics principle; because it is challenging to solve the pneumatic manipulator's kinematics directly; this paper simplifies the manipulator's unit section as a cantilever structure and establishes the element node's kinematics equation.

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