Design and Kinematics Analysis for a Cable-driven Underwater Snake Arm Robot

Fufeng Xue¹, Yu Fan² and Zhimin Fan¹*

¹College of Electromechanical Engineering, Qingdao University of Science & Technology, Qingdao, Shandong Province, 266061, China;
²FAW Jiefang Qingdao Automobile Co., Ltd. Qingdao, Shandong Province, 266043, China

*Corresponding author’s e-mail: zmfan@163.com

Abstract. Aiming at the problem that underwater manipulators are mostly rigid structures and cannot meet the requirements of flexible operations, this paper designs and studies a cable-driven underwater snake arm robot. The snake arm is composed of multiple rigid links connected in series, and the joint rotation is realized by controlling the change of the length of the driving cable, which can effectively solve the problem that the traditional underwater manipulator has poor flexibility and cannot work in a narrow space. In this paper, the 3-D model of the cable-driven underwater snake arm is carried out, the mapping relations among driving space, joint space and operation space are analyzed.

1. Introduction

With the application of underwater robot in detection, salvage, pipeline repair and other fields, higher requirements are put forward for the precise operation of underwater manipulator. Traditional underwater manipulator mostly adopts discrete joint and rigid link structure, which cannot meet the requirements of flexible operation due to its own structure [1]. At the same time, due to the existence of specific factors such as water pressure, corrosion, current, tide and surge [2], especially in the deep sea environment, with high pressure and low temperature, an underwater manipulator with high flexibility and large load is urgently needed to adapt to the complex underwater operation environment.

In recent years, the research of hyper-redundant manipulator is the frontier in the field of robotics and. The hyper-redundant manipulators have received attention of the numerous scholars and put into application. Snake arm robots have been applied in such fields as nuclear power plant maintenance [3], pipe detection [4], minimally invasive surgery [5,6], and aircraft complex narrow cavity assembly [7,8]. According to its structure, the hyper-redundant robot can be grossly classified into two types: discrete manipulator with a large number of rigid links [9] and soft-bodied robot with continuum backbones [10]. And the kinematics modeling concepts for soft-bodied robot is based on constant curvature assumption [11]. So, the discrete manipulators are superior to the soft-bodied manipulators in motion accuracy and load capacity [12]. The kinematics and dynamics of the soft-bodied manipulators are modeled and analyzed by using the idea of constant curvature assumption, but it is difficult to get an accurate model[13], and the mechanical properties of elastic materials will be affected in the underwater environment, so the soft-bodied manipulator is not suitable for deep sea operation. The snake arm manipulator is driven by the cable, there is no hydraulic cylinder or driving
motor at the joint of the manipulator, and drive system is installed in the drive base, so the whole snake arm manipulator does not need to be sealed, so the serpentine manipulator driven by cable is suitable for working in the deep water environment.

In this paper, a kind of underwater snake arm robot is designed, which is based on the cross universal joint-the driving motor-synchronous belt-driving cable. Based on the designed cable driven manipulator, the kinematic model of the cable driven snake arm is established, the mapping relationship among the driving space, joint space and operation space is analyzed.

2. Design of the snake arm robot
The snake arm robot consists of a cable-driven snake arm mechanism, an actuation system, an end-effector and a feed-in mechanism, as shown in Figure 1. The snake arm with 10 sections has a length of 1500 mm and a diameter of 60 mm, and each section has two rotational joints. The end-effector can install many kinds of detection and execution equipment according to the specific task requirements, such as grippers, image perception module. The actuation system is usually mounted on the base of the robot and driven by cables, the advantages of this form are that it can guarantee the good load capacity of the snake arm robot and avoid the explosion of electrical and electronic control devices when the manipulator is working exposed to dangerous, confined conditions. The base of the snake arm robot is fixed to the feed-in mechanism and it can provide a linear advancement accurately, which greatly expanding the working space of the snake arm robot.

According to the working environment and strength requirements of underwater snake arm, joint disk, joint cylinder and universal joint are made of 6061 aluminum alloy. The snake arm is modular in design and consists of 10 repeated joint sections. Each joint section includes two joint discs and joint cylinder, and the joint sections are connected by an improved cross-axis universal joint. The assembly model of single joint section is shown in Figure 2. The disk has two ear plates, and 40 through-line holes with a diameter of 3mm are opened on the joint disk for the drive cable to locate. The joint cylinder and the side wall of the joint disk are provided with four uniformly threaded holes to complete the connection between the joint cylinder and the joint disk. The four end faces of the cross shaft are provided with threaded holes to complete the connection between the two joint segments.

![Figure 1. Structure of the snake arm robot.](image1)

![Figure 2. Schematic of a section of the snake arm.](image2)

3. Kinematics analysis of the snake arm robot
Each section of the snake arm is driven by 4 alloy wires with a diameter of 2mm [14]. Therefore, Kinematic analysis should not only consider the mapping relationship between joint variables and terminal pose, but also consider the cable length variables. The mapping relationship of the drive space, joint space and operation space, is shown in Figure 3.

![Figure 3. Kinematics relation between three spaces.](image3)
3.1. Mapping from the drive space to the joint space

Single-joint rotation is shown in Figure 4. The two dotted lines shows the state of the joint without rotation, and the two solid lines represents the state of the cable after rotation of the joint. $L_0$ represents the distance from the center of the universal joint to the joint disk, $L'$ is the length of the cable after the joint has rotated, $r$ represents the distance between the cable and the axis of the joint, and $\theta$ is the joint variable. According to the geometric relationship of single joint shown in Figure 4, the following relations can be obtained:

\[
a = r \tan \theta \\
b = \frac{r}{\cos \theta} \\
c = (a + L_0) \sin \theta \\
d = (a + L_0) \cos \theta \\
e = b - c \\
m = r - e = r - \frac{r}{\cos \theta} + (r \tan \theta + L_0) \sin \theta \\
k = L_0 + d = L_0 + (r \tan \theta + L_0) \cos \theta
\]

According to Equations (1)-(7), the cable length after rotation can be expressed as follows:

\[
L' = \sqrt{m^2 + k^2}
\]

The change of cable length can be obtained as follows:

\[
\Delta L = L' - 2L_0 = \sqrt{m^2 + k^2} - 2L_0
\]

The mapping relation between drive space and operation space be expressed as Equation (10):

\[
\Delta L = \begin{cases} 
0, & \theta = 0^\circ \\
\sqrt{m^2 + k^2} - 2L_0, & -30^\circ < \theta < 30^\circ
\end{cases}
\]

Figure 4. Single joint rotation.

3.2. Mapping from the joint space to operation space

In this paper, the underwater snake arm robot is characterized by a number of discrete joints and rigid links, which is a typical super-redundant robot. The D-H modeling method can be used to establish the kinematics model of the underwater snake arm mapping form the joint space to operation space. The
D-H coordinate system of the underwater snake arm is shown in Figure 5, and the corresponding D-H parameter table is shown in Table 1. The transformation matrix from joint N +1 to joint N is:

\[
^nT_{n+1} = A_{n+1} = \text{Rot}(z, \theta_{n+1}) \times \text{Tran}(0,0,d_{n+1}) \times \text{Tran}(a_{n+1},0,0) \times \text{Rot}(x, \alpha_{n+1})
\]

\[
= \begin{bmatrix}
    c\theta_{n+1} & -s\theta_{n+1}c\alpha_{n+1} & s\theta_{n+1}s\alpha_{n+1} & a_{n+1}c\theta_{n+1} \\
    s\theta_{n+1}c\alpha_{n+1} & c\theta_{n+1}c\alpha_{n+1} & -c\theta_{n+1}s\alpha_{n+1} & a_{n+1}s\theta_{n+1} \\
    0 & s\alpha_{n+1} & c\alpha_{n+1} & d_{n+1} \\
    0 & 0 & 0 & 1
\end{bmatrix}
\]

(11)

c\theta_{i+1} is shorthand for \(\cos \theta_{i+1}\), \(s\theta_{i+1}\) is shorthand for \(\sin \theta_{i+1}\), \(s\alpha_{i+1}\) is shorthand for \(\sin \alpha_{i+1}\), \(c\alpha_{i+1}\) is shorthand for \(\cos \alpha_{i+1}\).

The snake arm robot consist of \(n\) sections has \(2n+1\) degrees of freedom, and the joint variables are \(\mathbf{q} = [d_1, \theta_2, \theta_3, \ldots, \theta_{2n}, \theta_{2n+1}]^T\), the homogeneous transformation of the \(k\)-th section \(S_k\) can be expressed as follows:

\[
T_{S_k} = \prod_{i=0}^{2k+1} T_{i+1}
\]

(12)

Figure 5. Kinematic parameters and DH frames of the snake arm robot.

| k   | i  | α   | a   | \(\theta\) | d   |
|-----|----|-----|-----|------------|-----|
| S_0 | 1  | 0   | 0   | 0          | \(d_1\)|
| S_1 | 2  | -90 | 0   | \(\theta_2\)| 0   |
| S_2 | 3  | 90  | \(L_1\)| \(\theta_3\) | 0   |
| S_3 | 4  | -90 | 0   | \(\theta_4\)| 0   |
| ... | ...|     |     |            |     |
| S_k | 2k | -90 | 0   | \(\theta_{2k}\)| 0   |
| ... | ...|     |     |            |     |
| S_n | 2n | -90 | 0   | \(\theta_{2n}\)| 0   |
|     | 2n+1| 90  | \(L_n\)| \(\theta_{2n+1}\)| 0    |
3.3. Workspace of a serpentine manipulator

The working space of the snake arm is the space position that the end-effector can reach in the three-dimensional space, which is the primary standard to evaluate the working performance of the snake arm. In this paper, the Monte Carlo method is used to solve the working space of the snake arm.

1. The random function is used to generate the pseudo random number of each joint variable of the snake arm.

2. The obtained joint variables are substituted into the forward kinematics of the joint space to the operation space of the snake arm robot, and the three-dimensional space position of the end-effector is calculated.

3. Matlab is used to visualize the three-dimensional space of the end-effector of the snake arm robot, that is, to obtain the working space of the snake arm robot.

Using Monte Carlo method to solve the working space of the snake arm in Matlab to get the working space of the snake arm robot, as shown in Figure 6.

![Figure 6. The workspace for end-effector.](image)

Monte Carlo method is used to obtain the random point diagram of the snake arm in the three-dimensional space, which has a certain error with the actual working space of the snake arm robot, which is a problem of the algorithm itself. The working interval obtained by the simulation can only be an infinite approximation of the real working area, and its accuracy depends on the number of selected random points. It can be seen from the Figure 6 that the snake arm can reach almost all the space positions in the maximum working range, which proves that the snake arm robot has good flexibility.

4. Conclusion

1. In this paper, a kind of underwater snake arm robot driven by driving motor-synchronous belt-cable is proposed. By using one driving motor to control two cables at the same time, the cable jumping caused by traditional cable driving mode is effectively avoided. It has numerous degrees of freedom, so it is more flexible than the traditional hydraulically driven underwater manipulator in specific underwater environment.

2. The structure and connection relations between the joints of the snake arm are given and the mapping relationship between the joint space and the drive space is studied.

3. The mapping of joint space to task space of underwater snake arm is analyzed, and it lays a good theoretical foundation for the practical application of the project in the next step.

Acknowledgments

The authors gratefully acknowledge the support by Key Research and Development Program of Shandong Province of China (Grant No. 2019GGX104088)

Reference

[1] Zhao S, Yuh J. (1994) Experimental Study on Advanced Underwater Robot Control. IEEE Transactions on Robotics, 21: 695-703.
[2] Ma S, Hirose S, Yoshinada H. (1994) Development of a hyper-redundant multijoint manipulator for maintenance of nuclear reactors. Advanced robot, 9: 281-300.

[3] Buckingham R O, Graham A C. (2010) Dexterous manipulators for nuclear inspection and maintenance case study. In: Proceedings of the International conference on Applied Robotics for the Power Industry. Montreal. pp.1-6.

[4] Tang L, Zhu LM, Zhu XY, Gu GY. (2020) Confined space path following for cable-driven snake robots with prediction lookup and interpolation algorithms. Science China Technological sciences, 63: 255-264.

[5] Cianchetti M, Ranzani T, Gerboni G, et al. (2014) Soft robotics technologies to address shortcomings in today’s minimally invasive surgery: the stiff-flop approach[J]. Soft Robotics, 1(2): 122-131.

[6] Kai X and Simaan N. (2010) Intrinsic wrench estimation and its performance index for multisegment continuum robots[J]. IEEE Transactions on Robotics, 26(3): 555–561.

[7] Gao Q J, Wang WJ, et al. (2013) Study of bionic structure and kinematics of robot for aircraft fuel tank inspection. Acta Aeronautica et Astronautica Sinica, 34:1748-1756.

[8] Xin D, Axinte D, Plamer D, et al. (2017) Development of a slender continuum robotic system for on-wing inspection/repair of gas turbine engines. Robotics and computer-integrated manufacturing, 44: 218-229.

[9] Kai X and Simaan N. (2010) Intrinsic wrench estimation and its performance index for multisegment continuum robots. IEEE Transactions on Robotics, 26: 555–561.

[10] Ota T, Degani A, Schwartzman D, et al. (2009) A highly articulated robotic surgical system for minimally invasive surgery. The Annals of Thoracic Surgery, 87: 1253-1256.

[11] Li Z, Wu L, Ren HL. (2017) Kinematic comparison of surgical tendon-driven manipulators and concentric tube manipulators. Mechanism and Machine Theory, 107:148-165.

[12] Cao Y J, Shang J Z, Liang K S, et al. (2014) Review of soft-bodied robots picking. Journal of Mechanical Engineering, 48: 25-33.

[13] Yan J H, Shi P P, Zhang X B, et al. (2018) Review of biomimetic mechanism, actuation, modeling and control in soft manipulators. Journal of mechanical engineering, 54:1-14.

[14] Ota T, Degani A, Schwartzman D, et al. (2009) A highly articulated robotic surgical system for minimally invasive surgery. The Annals of Thoracic Surgery, 87: 1253-1256.