Design and Development of Multi-arm Cooperative Rescue Robot Actuator Based on Variant Scissor Mechanism

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Abstract. Search and rescue has become a key technology to be solved, but it is difficult for most rescue robots to implement safe and effective rescue for survivors. Based on two degree of freedom five bar variant scissor mechanism, this paper proposes a design scheme of combined bionic multi-arm cooperative rescue robot actuator. The actuator was designed to imitate elephant trunk, octopus and armadillo and the working track of rescue manipulator is designed by the cross section of human body. The kinematics of the actuator is analyzed based on the vector method, and the positive position solution and Jacobian matrix are obtained. The optimal design parameters of the actuator are determined, and the experimental prototype of the rescue robot actuator is developed, which lays the foundation for the development of the new rescue robot.

Keywords: Rescue robot · Variant scissor mechanism · Kinematics analysis

1 Introduction

Global accidents and natural disasters occur frequently, which seriously threaten human security and social stability. In order to save the lives of the survivors, it is so important to reach and rescue the survivors within 48 h after the disaster. At present, the rescue robot technology is developing rapidly, and various innovative researches are applied to the end-effector of the rescue robots, aiming at providing assistance and safety to the survivors in emergency.

The end-effector is similar to "robot's hand" and is used to grasp objects. In the rescue, these machines can replace human beings into complex and dangerous areas, and rescue the injured person. In the United States "911" terrorist attack disaster relief, the successful application of rescue robots [1–4] has triggered a research boom of rescue robots in universities, companies and research institutions around the world. In fact, the

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research of rescue robots mainly includes chassis walking part and the end-effector part. In order to make the robot move better in complex terrain, researchers have successfully developed various chassis walking mechanisms, such as wheeled type [5, 6], tracked type [7, 8] and legged type [9, 10]. However, how to rescue the injured person safely and effectively, that is, the research of the end-effector, has become a major challenge at present.

Most of the existing and available end-effector in the market are not safe, which puts forward higher requirements for the power supply and control system. The new rescue robot BEAR [11] developed by Vecna Robotics is mainly used for the rescue and transportation of the wounded after disaster. The upper limb is equipped with two arm actuators, which are driven by hydraulic devices. The actuator has the advantages of high power and large bearing capacity. The robot RoVA [12] developed by Hstar Technologies is designed to meet the needs of nursing service, with powerful arms and many intelligent sensors. South Korea's national defense development agency has developed a human rescue robot HURCULES [13], which is equipped with an electric end-effector. Ahalya Ravendran [14] of Thammasat University in Thailand has designed and developed a mobile robot with gripper and driller. At present, scholars from various countries have studied the end-effector of rescue robots accordingly, but there are still some problem: for example, they are noisier, more difficult to maintain, and have poor ring closure, etc.

At present, it is difficult for most rescue robots to implement safe and effective rescue for survivors. In order to significantly improve the safety and overall carrying capacity of rescue robots, this paper designs a safe and effective rescue robot end-effector based on variant scissor mechanism that is applicable to the survivors, so as to achieve the purpose of rescue for survivors.

2 Design of Robot Actuator

Nature has been the source of various scientific and technological principles and major inventions. In recent years, more and more scientific researchers focus on biology and propose many bionic robots. In the design process of rescue manipulator, we found some unique biological forms. In the ocean, the octopus arm can move flexibly, and its arms cooperate with each other to grasp objects better (Fig. 1).

The elephant trunk is soft and nimble, enabling flexible grasping of large loads, and the armadillo hard-shell is retractable and foldable, reducing the space constraints on some other sports. Based on the combined bionics principle, the overall design scheme imitates the shape characteristics of octopus multi-arm cooperation, and the design of the rescue robot arm is inspired by the elephant trunk and armadillo, as shown in Fig. 1.

Imitation octopus multi-arm collaborative rescue actuator design effectively reduces the weight of the human body apportioned to each rescue robot arm, improving the overall load-bearing capacity of the actuator while reducing the local force on the human body, improving contact safety and comfortable. At the same time, the combination of octopus and elephant trunk can simulate the cooperative transportation of multiple elephant trunks, which can realize large carrying capacity. The elephant trunk shape and its gripping movement can enable to hold the human body safely and stably, and the folding form of armadillo can increase the operating space of the actuator.

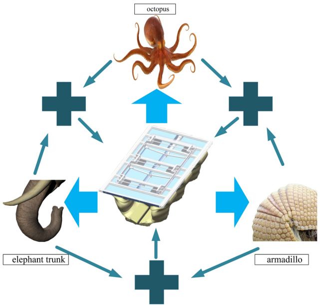

Fig. 1. Combined bionic design inspiration

So this paper proposes a design scheme of multi-arm cooperative rescue robot actuator, which is composed of three pairs of rescue manipulator, as shown in Fig. 2.

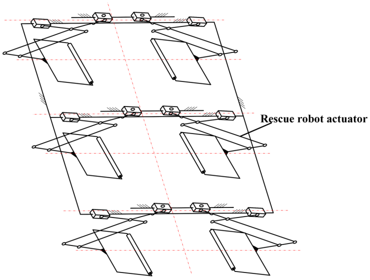

Fig. 2. Overall design of rescue robot actuator

By combining the above three organisms in a biomimetic manner, this paper designs the rescue end-effector. As an important part of the rescue robot actuator, the structure of the rescue manipulator framework directly determines the performance of the rescue robot actuator.

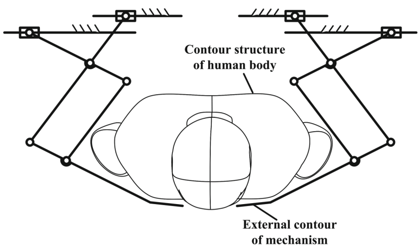

Fig. 3. Schematic diagram of operation range of rescue robot actuator

In order to design a reasonable manipulator framework mechanism, the first consideration is that it must meet the operational requirements, followed by the need to have a certain load-bearing capacity and a small space scale, and finally, safety and reliability, processing economy and other factors must be regarded. This paper designs a rescue robotic arm skeleton mechanism scheme based on two degree of freedom five bar variant scissor mechanism, and its overall structure and operation range are shown in Fig. 3. The scheme can meet the action requirements of rescue operation and bear the load of the whole human body and has good stiffness, large working space, convenient driving. At the same time, it has good telescoping and folding characteristics of the scissor-fork mechanism, the unfolding state can meet the large-scale range of operation when working, and the folding state can save space when not working, which is convenient for transportation. The design of less degrees of freedom makes the drive setting and its control easy to realize, and the work is stable and reliable.

The skeleton mechanism of rescue manipulator has multiple revolute and prismatic pairs. In the drive selection, priority should be given to setting the drive on the prismatic pair connected with the frame, which can effectively reduce the motion inertia of the mechanism and improve the flexible response performance of the mechanism. Due to the limitation of the mechanism layout space, it is difficult to set the drive motor and reducer at the revolute pair, so the prismatic pair connected with the frame are selected as the drive joints.

3 Kinematics Analysis of the Actuator

3.1 Establish the Kinematic Model

The executive mechanism of rescue robot is composed of several pairs of rescue manipulators, and the kinematic performance of the rescue manipulator is determined by the internal rigid skeleton. According to the skeleton configuration of the two degree of freedom variant scissor rescue executive mechanism, the kinematic model of the skeleton mechanism is established. First, a global coordinate system $O - XY$ is established, as shown in Fig. 4. The origin O is located on the axis of the first branch prismatic pair, the axis X coincides with the axis of the first branch, and the coordinate system $O_1 - XY$ of the first branch coincides with the global coordinate system. A branch coordinate system $O_2 - XY$ is established on the second branch. The second branch of the axis X moves the axis of the secondary axis coincides, and is parallel to the global coordinate system axis X. The distance between the two axis is e, and the axis Y coincides with the axis Y of the global coordinate system.

Therefore, the transformation matrix from the first branch coordinate system $O_1 - XY$ to the global coordinate system $O - XY$ is a 3×3 unit matrix. The transformation matrix ${}^oT_2$ from the second branch coordinate system $O_2 - XY$ to the global coordinate system $O - XY$ is determined by the structural parameters e of the mechanism, namely:

$$ {}^oT_2 = \begin{bmatrix} {}^oR_2 & {}^ot_2 \\ 0 & 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & e \\ 0 & 0 & 1 \end{bmatrix} \tag{1} $$

Where ${}^oT_2$ denotes the transformation matrix from coordinate system $O_2 - XY$ to coordinate system $O - XY$. ${}^oR_2$ is the direction transformation matrix from coordinate system $O_2 - XY$ to coordinate system $O - XY$. ${}^{o}t_2$ is the position transformation matrix from coordinate system $O_2 - XY$ to coordinate system $O - XY$. e is the distance between the axis X of the coordinate system $O_2 - XY$ and the axis X of the coordinate system $O - XY$.

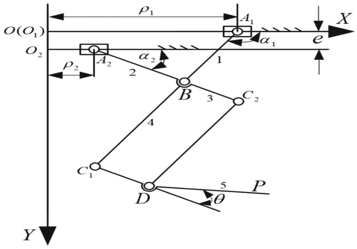

Fig. 4. Framework coordinate system of rescue manipulator

Through the transformation matrix, the point coordinates in the second branch coordinate system can be transformed into the global coordinate system, that is, there is $\left[x_o, y_o, 1\right]^{\mathrm{T}} = {}^{o}T_2\left[x_2, y_2, 1\right]^{\mathrm{T}}$. According to the relationship between the connecting rods in Fig. 3, ρ_1 and ρ_2 are the input variable of the prismatic pair in the first branch and the second branch respectively, and the length of the passive connecting rod in the first branch is l_1,the length of the passive link in the second branch is l_2, and other structural parameters are $l_3 = 100$ mm, $l_4 = 200$ mm, $l_5 = 250$ mm, $\theta = \frac{\pi}{9}$, respectively. Point P is the operating point at the end of the manipulator. As can be seen from Fig. 4, there is the following vector relationship:

$$\begin{gathered} \begin{bmatrix} x_B \\ y_B \end{bmatrix} = \begin{bmatrix} \rho_1 \\ 0 \end{bmatrix} + \begin{bmatrix} l_1 \cos\alpha_1 \\ l_1 \sin\alpha_2 \end{bmatrix} \\ \begin{bmatrix} x_B \\ y_B \end{bmatrix} = \begin{bmatrix} 0 \\ e \end{bmatrix} - \begin{bmatrix} \rho_2 \\ 0 \end{bmatrix} + \begin{bmatrix} l_2 \cos\alpha_2 \\ l_2 \sin\alpha_2 \end{bmatrix} \end{gathered} \tag{2}$$

Where x_B denotes the abscissa of point B in the coordinate system $O - XY$. y_B is the ordinate of point B in the coordinate system $O - XY$. ρ_1 is the input displacement of the slider A_1, l_1 is the length of 1st rod, α_1 is the angle between 1st rod and the axis X positive direction of the coordinate system $O - XY$. ρ_2 is the input displacement of the slider A_2, l_2 is the length of 2nd rod, α_2 is the angle between 2nd rod and the axis X positive direction of the coordinate system $O - XY$.

The algebraic equations are as follows:

$$\begin{cases} \rho_1 - \rho_2 + l_1 \cos\alpha_1 - l_2 \cos\alpha_2 = 0 \\ l_1 \sin\alpha_1 - l_2 \sin\alpha_2 - e = 0 \end{cases} \tag{3}$$

3.2 Positive Solution of Position

According to the geometric position of the mechanism, the coordinate of the manipulator end operation point P rod can be obtained:

$$\begin{bmatrix} x_P \\ y_P \end{bmatrix} = \begin{bmatrix} \rho_1 + (l_1 + l_4)\cos\alpha_1 + l_3\cos\alpha_2 + l_5\cos(\alpha_2 - \theta) \\ (l_1 + l_4)\sin\alpha_1 + l_3\sin\alpha_2 + l_5\sin(\alpha_2 - \theta) \end{bmatrix} \tag{4}$$

Where x_P is the abscissa of point P in the coordinate system $O - XY$. y_P is the ordinate of point P in the coordinate system $O - XY$. θ is the angle between 3rd rod and 5th rod. l_5 is the length of 5th rod.

In order to get the mapping relationship between the position of the manipulator end operation point P and the position of the input terminals ρ_1 and ρ_2, the sum of independent variables α_1 and α_2 in the middle should be eliminated. Then rewrite Eq. (3) as:

$$\begin{cases} l_2\cos\alpha_2 = \rho_1 - \rho_2 + l_1\cos\alpha_1 \\ l_2\sin\alpha_2 = l_1\sin\alpha_1 - e \end{cases} \tag{5}$$

The expression of α_1 can be obtained by square elimination of α_2 on both sides of the equation:

$$A\sin\alpha_1 + B\cos\alpha_1 + C = 0 \tag{6}$$

Where: $A = -2el_1$ $B = 2(\rho_1 - \rho_2)l_1$ $C = (\rho_1 - \rho_2)^2 + e^2 + l_1^2 - l_2^2$.

Let $x = \tan(\alpha_1/2)$, then $\sin\alpha_1 = 2x/1 + x^2$ $\cos\alpha_1 = 1 - x^2/1 + x^2$, substitute formula (6), the equation about α_1 can be transformed into quadratic equation about x:

$$(B - C)x^2 - 2Ax - (B + C) = 0 \tag{7}$$

The solution is $\alpha_1 = 2\arctan\frac{A\pm\sqrt{A^2+B^2-C^2}}{B-C}$, according to the arrangement of connecting rod, the "+" sign is taken here.

In the same way, $\alpha_2 = 2\arctan\frac{D\pm\sqrt{D^2+E^2-F^2}}{E-F}$, according to the arrangement of connecting rod, we can get the "-" sign here.

Where: $D = 2el_2,\ E = -2(\rho_1 - \rho_2)l_2,\ F = (\rho_1 - \rho_2)^2 + e^2 + l_2^2 - l_1^2$.

By substituting equations α_1 and α_2 into Eq. (4), the forward position solution of the rescue manipulator can be obtained:

$$\begin{bmatrix} x_P \\ y_P \end{bmatrix} = \begin{bmatrix} \rho_1 + f \\ g \end{bmatrix}$$
$$\begin{cases} f = f(\rho_1 - \rho_2) \\ g = g(\rho_1 - \rho_2) \end{cases} \tag{8}$$

It can be seen from Eq. (8) that the ordinate of the end P of the manipulator is only related to the difference $\rho_1 - \rho_2$ of the two input parameters, and has nothing to do with the specific value of a single input variable. The function with abscissa $\rho_1 - \rho_2$ is the sum of one of the inputs.

3.3 Velocity Analysis

The first derivative of time can be obtained by formula (5):

$$\begin{cases} -l_3 \sin\alpha_2\omega_2 = v_1 - v_2 - l_2 \sin\alpha_1\omega_1 \\ l_2 \cos\alpha_2\omega_2 = l_2 \cos\alpha_1\omega_1 \end{cases} \tag{9}$$

Where v_1 is the input speed of slider A_1, v_2 is the input speed of slider A_2. ω_1 is the angular speed of 1st rod. ω_2 is the angular speed of 2nd rod, the solution is as follows:

$$\begin{cases} \omega_1 = \dfrac{(v_1 - v_2)\cos\alpha_2}{l_1 \sin(\alpha_1 - \alpha_2)} \\ \omega_2 = \dfrac{(v_1 - v_2)\cos\alpha_1}{l_2 \sin(\alpha_1 - \alpha_2)} \end{cases} \tag{10}$$

The first derivative of time can be obtained by formula (4):

$$\begin{bmatrix} v_{P_x} \\ v_{P_y} \end{bmatrix} = \begin{bmatrix} \dot{x}_P \\ \dot{y}_P \end{bmatrix} = \begin{bmatrix} v_1 - (l_1 + l_4)\sin\alpha_1\omega_1 - l_3 \sin\alpha_2\omega_2 - l_5 \sin(\alpha_2 - \theta)\omega_2 \\ (l_1 + l_4)\cos\alpha_1\omega_1 + l_3 \cos\alpha_2\omega_2 + l_5 \cos(\alpha_2 - \theta)\omega_2 \end{bmatrix} \tag{11}$$

Where v_{P_x} is the component of point P velocity in axis X direction and v_{P_y} is the component of point P velocity in axis Y direction. It can be further expressed as

$$\begin{cases} \alpha_1 = 2\arctan\frac{A + \sqrt{A^2 + B^2 - C^2}}{B - C} \\ \alpha_2 = 2\arctan\frac{D - \sqrt{D^2 + E^2 - F^2}}{E - F} \end{cases} \tag{12}$$

Where: $\begin{matrix} A = -2el_1, B = 2(\rho_1 - \rho_2)l_1, C = (\rho_1 - \rho_2)^2 + e^2 + l_1^2 - l_2^2, D = 2el_2 \\ E = -2(\rho_1 - \rho_2)l_2, F = (\rho_1 - \rho_2)^2 + e^2 + l_2^2 - l_1^2 \end{matrix}.$

By substituting Eq. (10) into Eq. (11), we can get

$$\begin{gathered} \begin{bmatrix} v_{P_x} \\ v_{P_y} \end{bmatrix} = \begin{bmatrix} v_1 + u \\ w \end{bmatrix} \\ \begin{cases} u = u(v_1 - v_2) \\ w = w(v_1 - v_2) \end{cases} \end{gathered} \tag{13}$$

It can be seen from Eq. (13) that the velocity in Y direction at the end P of the manipulator is only related to the difference between the two input parameters, and has nothing to do with the specific value of a single input variable.

By calculating the first derivative of Eq. (8), we can get

$$\begin{gathered} \begin{bmatrix} \dot{x}_P \\ \dot{y}_P \end{bmatrix} = \begin{bmatrix} \dot{\rho}_1 + \dot{f} \\ \dot{g} \end{bmatrix} \\ \begin{cases} \dot{f} = \dfrac{df}{d(\rho_1 - \rho_2)}(\dot{\rho}_1 - \dot{\rho}_2) \\ \dot{g} = \dfrac{dg}{d(\rho_1 - \rho_2)}(\dot{\rho}_1 - \dot{\rho}_2) \end{cases} \end{gathered} \tag{14}$$

Therefore, the Jacobian matrix of rescue manipulator can be obtained

$$J = \begin{bmatrix} 1 + \frac{df}{d(\rho_1 - \rho_2)} & -\frac{df}{d(\rho_1 - \rho_2)} \\ \frac{dg}{d(\rho_1 - \rho_2)} & -\frac{dg}{d(\rho_1 - \rho_2)} \end{bmatrix} \quad (15)$$

3.4 Trajectory Simulation

The established kinematics model of rescue manipulator is analyzed, and the relevant conclusions of position solution and velocity solution are obtained. Based on ADAMS software, the simulation platform of rescue robot actuator is established. The variables of minimum mean square error of l_1, l_2 and e are analyzed respectively, and three groups of optimal solutions are obtained. Then the motion simulation of the three groups of solutions is carried out, and the trajectory simulation results are obtained and compared with the theoretical analysis results.

The 3D model of rescue manipulator is established in SolidWorks software. The 3D model is imported into Adams, and then the constraint conditions and motion pairs are set, as shown in Fig. 5.

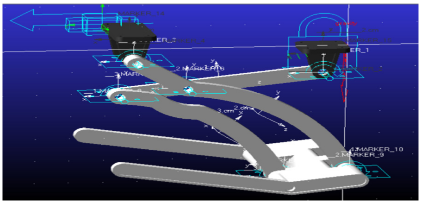

Fig. 5. ADAMS simulation model

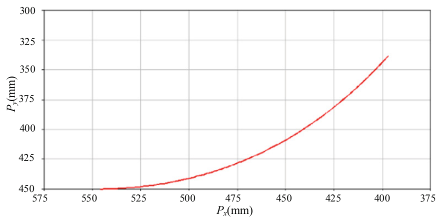

Fig. 6. Trajectory diagram of rescue manipulator end

In the ADAMS software, three groups of rescue manipulator arm end point operation trajectory diagram are shown in Fig. 6. Compared with the simulation results in the Fig. 6, the simulation results are basically consistent with the theoretical results, which verifies the correctness of the theoretical analysis, and its trajectory is basically the same as that of human body contour.

4 Prototype Development

Based on the theoretical design and kinematics analysis, this paper developes the experimental prototype of the multi-arm cooperative rescue robot's end-effector. The prototype scheme of rescue robot actuator is shown in Fig. 7.

This scheme mainly includes three parts: frame, rescue manipulator and drive transmission mechanism. Among them, rescue manipulators have three groups and include rigid framework and flexible safety cushion, and each group contains two mirror manipulator frameworks. In the development of experimental prototype, on the premise of

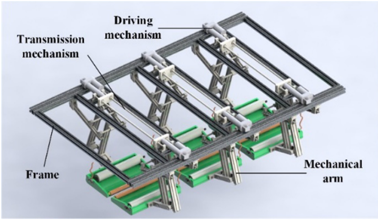

Fig. 7. Prototype drawing of rescue actuator

meeting the requirements of mechanism principle verification and experiment, the manufacturing process feasibility, assembly feasibility, cost economy and other factors should be fully considered. After comprehensive consideration of experimental requirements and research resources, the principle of prototype development with standard parts as the main part and non-standard parts as the auxiliary part is formulated. Based on this principle, the prototype is designed and manufactured.

Fig. 8. Rescue actuator

The rescue robot arm multi-link skeleton is made of aluminum profiles and aluminum alloy connectors spliced together, with good rigidity and standard profiles for easy connection. As a direct contact part with human body, the end drag reduction mechanism chooses a 3D printing shell made of high-strength nylon material and an active rotating conveyor belt to give consideration to the bearing capacity and experimental safety, which can reduce the resistance in the process of contact between the rescue robot actuator and human body and effectively avoid the secondary injury of the actuator to the rescued human body. The outer flexible coating is made of soft rubber material with moderate hardness based on 3D printing. It is wrapped outside the rigid framework and inflated in the cavity. It separates the human body from the rigid rescue manipulator framework and stabilizes the position of the human body. In the process of flexible contact with the human body, the pressure on the human body is evenly distributed, which effectively improves the safety of human-computer interaction. The prototype of the developed rescue actuator is shown in Fig. 8.

5 Conclusion

In the rescue process, in order to achieve low friction to hold and support the human body, the paper designs a multi-arm cooperative rescue robot actuator based on the combined bionic principle, which can safely and effectively carry the injured people. The position of the actuator and the relationship between the end velocity and the input velocity are obtained based on vector method. Finally, the design and manufacture of the experimental prototype of the rescue robot actuator are completed, and the basic action of encircling rescue is realized through motion control. The design theory of the robot provides a reference for the research and development of new rescue robot.

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