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The Design and Analysis of UPR-UPU-UR Vector Propulsion Mechanism

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***Abstract* - In recent years, many countries have gradually turned their development judgments to marine development, put forward the goal of building a powerful marine development country, underwater robots have become the hotspot of current development. The propulsion mechanism of underwater vehicle is the key technology that restricts the development of robot. In order to meet the needs of high efficiency propulsion of underwater vehicle, the model of UPR-UPU-UR vector propulsion mechanism is designed. According to the principle of parallel mechanism, Calculating the degree of freedom of the mechanism. Then the inverse solution of position is derived from the position relation. The position workspace simulation of the mechanism is carried out, and the simulation results are compared with the theoretical analysis results, which proves the correctness of the design and theoretical derivation. The parallel mechanism can achieve multiple directions attitude rotations, which provides a reliable theoretical basis for underwater vehicle.**

***Index Terms* - UPR-UPU-UR, Inverse position solution, Workspace simulation.**

I. Introduction

The ocean area accounts for 71% of the world's area and about 97% of the total water on the earth. So far, only 5% of the seafloor has been explored by human being, and 95% of the seafloor of the sea is a mysterious world have never explored [1]. The ocean contains huge resources and energy, many countries have gradually turned their development eyes to marine development, put forward the goal of building a powerful marine development country. Underwater robots have become the hotspot of present developments [2].

The maneuverability and agility of underwater vehicle become an important technical index. In addition to obtaining strong pushing force, the robot also needs to adjust the navigation attitude according to the needs of the task. The vector propulsion of parallel mechanism can overcome the shortcomings of single propeller driving direction single and undirected [3], and the problem of large navigation resistance when multiple propellers advance at low speed under water is solved [4]. Vector propulsion mechanism is not only involved in propeller rotation to provide forward propulsion power. but also involved a change in the position of the propeller to adjust the movement of the propulsion direction, perfectly combines the advantages of single propeller and multiple propellers [5], and greatly improves the position ability of the robot sailing at low speed under water. The parallel mechanism can simplifies the navigation propulsion structure of the robot, reduces the space occupied by the robot equipment, reduces the weight of the robot and improves the underwater maneuverability and maneuverability of the robot[6,7].

In order to meet the needs of high efficiency vector propulsion of underwater vehicle, the model of UPR-UPU-UR vector propulsion mechanism is designed with high position accuracy and less interference. According to the principle of parallel mechanism, the degree of freedom of mechanism is analyzed. Then the inverse solution of position is derived from the position relation. Finally, the simulation model of UPR-UPU-UR vector propulsion mechanism is established. The simulation results are compared with the theoretical analysis results to verify the effectiveness of vector propulsive mechanism [8].

II. Design and Analysis

Structural design

By using the vector propulsion technology of parallel mechanism and combining the advantages of single propeller and multiple propellers perfectly, the propulsion direction motion of underwater vehicle is adjusted by the change of attitude and azimuth of propeller, which greatly improves the position ability of underwater vehicle at low speed. In the process of advancing, the underwater vehicle can perfectly simplified the navigation propulsion structure and improves the maneuverability and maneuverability. In order to realize the deflection of the propeller spindle in a certain range in order to achieve the whole deflection of the underwater vehicle, it is necessary to complete the rotations in two directions, the propulsion mechanism has two rotational degrees of freedom.

Described in this article the vector propulsion mechanism said UPR-UPU-UR, through three movement branched chain will be connected to the fixed platform, the first branch chain is named UPR branch, which consists of a U pair, a mobile pair P and a rotating pair R. The second branch chain is named UPU branch, which consists of a mobile pair P and two U pairs. The spindle branch chain is named UR branch, which consists of a U pair and a rotating pair R.

Establishment of coordinate system

Through the P pair drive of the two branches, the mechanism can change the length of the branch chain, the moving platform can readjust the attitude and deflection. The three branches of the vector propulsion mechanism are analyzed respectively. In order to facilitate the representation, the coordinate systems are established on the fixed platform and the moving platform as shown in Fig.1, which are recorded as O-XYZ and o-xyz. The U sub-center O at the lower end of the spindle branch chain, the U sub-center point D_1 at the lower end of the first branch chain and the U sub-center point D_2 at the lower end of the second branch chain are all connected to the fixed platform. Similarly, the center point o of the R pair at the upper end of the spindle branch chain, the center point d_1 of the R pair at the upper end of the first branch chain and the center point d_2 of the U pair at the upper end of the second branch chain are all connected to the moving platform, The R pair in the spindle branch chain is perpendicular to the moving platform. The positive direction of X axis is from O point to D_1 point, and the positive direction of Y axis is from O point to D_2 point. The positive direction of Z axis is perpendicular to X axis and Y axis, which meets the right-handed rule. Similarly, the positive direction of the x axis is from the o point to the D_1 point, and the positive direction of the y axis is from the o point to the D_2 point. The positive direction of the z axis is perpendicular to the x axis and the y axis, which also meets the right-handed rule. The Z axis coincides with the z axis in the positive direction. The positive direction of Z axis and z axis coincides with each other. The distance both marking OD_1 and OD_2 are A. The distance both marking od_1 and od_2 are a. The distance to mark Oo is e.

Calculation of degrees of freedom

Based on the coordinate relationship, at the initial position of the O-XYZ in the reference coordinate system, the direction vector of each motion pair will be represented as S_{ij} (i=1, 2, 3; j=1, 2, 3, 4, 5), and the coordinates of the center point of each motion pair will be represented as r_{ij} (i=1, 2, 3; j=1, 2, 3, 4, 5).

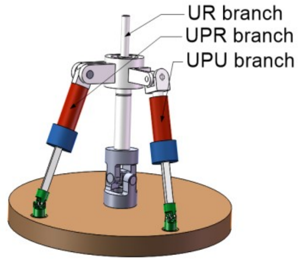


Fig. 1 Mechanism Structure.

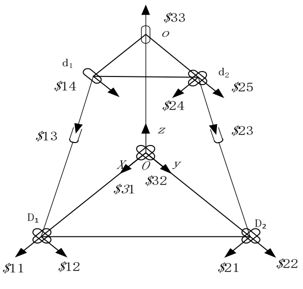


Fig. 2 Kinematic spiral distribution map of mechanism

The branch chain UPR: The kinematic spiral system of the branch chain UPR at the initial position is obtained by analysis as follows:

$$\begin{aligned}
\$_{11} &= (s_{11};0,0,0) = (1,0,0;0,0,0) \\
\$_{12} &= (s_{12};r_{12}\times s_{12}) = (0,1,0;0,0,A) \\
\$_{13} &= (0,0,0;s_{13}) = (0,0,0;A-a,0,-e) \\
\$_{14} &= (s_{14};r_{14}\times s_{14}) = (0,1,0;-e,0,a)
\end{aligned} \tag{1}$$

The branch chain UPU: The kinematic spiral system of the branch chain UPU at the initial position is obtained by analysis as follows:

$$\begin{aligned}
\$_{21} &= (s_{21};0,0,0) = (0,1,0;0,0,0) \\
\$_{22} &= (s_{22};r_{22}\times s_{22}) = (1,0,0;0,0,A) \\
\$_{23} &= (0,0,0;s_{23}) = (0,0,0;0,A-\mathrm{a},-\mathrm{e}) \\
\$_{24} &= (s_{24};r_{24}\times s_{24}) = (1,0,0;0,e,-a) \\
\$_{25} &= (s_{25};r_{25}\times s_{25}) = (0,e,A-a;-e^2+aA-a^2,0,0)
\end{aligned} \tag{2}$$

The spindle branch chain UR: The kinematic spiral system of the spindle branch chain UR at the initial position is obtained as follows:

$$\begin{aligned}
\$_{31} &= (s_{31};0,0,0) = (1,0,0;0,0,0) \\
\$_{32} &= (s_{32};0,0,0) = (0,1,0;0,0,0) \\
\$_{33} &= (s_{33};0,0,0) = (0,0,1;0,0,0)
\end{aligned} \tag{3}$$

In conclusion, the constrained spiral system of the moving platform of the vector propulsion mechanism is obtained as follows:

$$\begin{aligned}
\$^r_{11} &= (0,0,0;0,0,1) \\
\$^r_{12} &= (0,1,0;0,0,0) \\
\$^r_{21} &= (0,0,0;0,0,1) \\
\$^r_{31} &= (1,0,0;0,0,0) \\
\$^r_{32} &= (0,1,0;0,0,0) \\
\$^r_{33} &= (0,0,1;0,0,0)
\end{aligned} \tag{4}$$

The antispiral is solved again through the constrained spiral system of vector propulsion mechanism:

$$\begin{aligned}
\$^{pm}_1 &= (0,0,0;1,0,0) \\
\$^{pm}_2 &= (0,0,0;0,1,0)
\end{aligned} \tag{5}$$

According to the formula (5), the obtained parallel mechanism UPR-UPU-UR has two degrees of freedom of rotation. According to the formula (7), There are six constraints in the constrained spiral system, which constitute four series spirals in practice, so the redundant constraint number v=2. From the schematic diagram of UPR-UPU-UR parallel mechanism, the number of components n=7, the total number of motion pairs g=8, and the sum of relative degrees of freedom of all motion pairs are $\sum_{i=1}^{g} f_i$=12 , local degree of freedom **ζ=0**. The common constraint λ=0, so the order of mechanism of the mechanism d=6. The above analysis replaces the modified Kutzbach-Grübler formula and brings each parameter into the formula. The degree of freedom of the UPR-UPU-UR parallel mechanism is as follows [9]:

$$F = d(n-g-1)+\sum_{i=1}^{g} f_i + \upsilon - \zeta \tag{6}$$
$$=6\times(7\text{-}8\text{-}1)+12+2\text{-}0=2$$

The calculation results prove the correctness of solving the degree of freedom based on the constrained spiral theory. The mechanism does have two degrees of freedom. The degree of freedom of rotation of the moving platform around the X axis of the fixed platform and the degree of freedom around the Y axis of the fixed platform.

III. Position Modeling

The position modeling analysis is to solve the relationship between input and output of the mechanism. The positive position solution is the process of solving the output parameters with known input parameters, whereas the inverse position solution is the process of solving the output parameters with known output parameters.

The moving platform expresses the position change through two rotations around the axis. At the initial position, the moving coordinate system coincides with the static coordinate system, and the α angle is rotated around the Y axis, and then the β angle is rotated around the X axis. In order to facilitate the expression, it is stipulated that *sinΦ=sΦ*, *cosΦ=cΦ, tanΦ=tΦ*, *Φ* can be elements in (*α*, β). Then the rotation matrix of the mechanism can be expressed as follows:

$${}^{B}_{m}R = rot(x,\beta)rot(y,\alpha) = \begin{pmatrix} c_\alpha & 0 & s_\alpha \\ s_\alpha s_\beta & c_\beta & -c_\alpha s_\beta \\ -s_\alpha c_\beta & s_\beta & c_\alpha c_\beta \end{pmatrix} \tag{7}$$

According to the rotation transformation rules:

$${}^{B}_{m}T = \begin{bmatrix} {}^{B}_{m}R & {}^{B}_{m}p_{oORG} \\ 0\ 0\ 0 & 1 \end{bmatrix} = \begin{bmatrix} c_\alpha & 0 & s_\alpha & {}^{B}O_x \\ s_\alpha s_\beta & c_\beta & -c_\alpha s_\beta & {}^{B}O_y \\ -s_\alpha c_\beta & s_\beta & c_\alpha c_\beta & {}^{B}O_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{8}$$

In the initial state, the coordinates of D_1, D_2, d_1 and d_2 are obtained as follows

$$d_1^m = (a,0,0),\ d_2^m = (0,a,0) \tag{9}$$

The coordinates of d_1 and d_2 of the moving platform are obtained after the rotation transformation. From the coordinates of D_1=(A, 0, 0) and D_2 = (0, A, 0) on the fixed platform, the vectors of the two branches are as follows:

$$d_1^B = \begin{pmatrix} ac_\alpha + es_\alpha \\ as_\alpha s_\beta - ec_\alpha s_\beta \\ -as_\alpha c_\beta + ec_\alpha c_\beta \end{pmatrix},\ d_2^B = \begin{pmatrix} es_\alpha \\ ac_\beta - ec_\alpha s_\beta \\ es_\beta + ec_\alpha c_\beta \end{pmatrix} \tag{10}$$

According to the formula (11), the lengths L_1 of branch chain UPR and the lengths L_2 of branch chain UPU are as follow:

$$\begin{aligned} L_1 &= \sqrt{(ac_\alpha + es_\alpha - A)^2 + (as_\alpha s_\beta - ec_\alpha s_\beta)^2 + (-as_\alpha c_\beta + ec_\alpha c_\beta)^2} \\ L_2 &= \sqrt{(es_\alpha)^2 + (ac_\beta - ec_\alpha s_\beta - A)^2 + (es_\beta + ec_\alpha c_\beta)^2} \end{aligned} \tag{11}$$

The rotation range of the U pair in the mechanism is limited, and the L_1 and L_2 are not negative values during the movement of the moving platform, which are taken as positive values.

In the main shaft branch chain UR, because of Oo branched chain length is constant, the coordinates of o on the moving platform is $o^B=(es_\alpha, -ec_\alpha s_\beta, ec_\alpha c_\beta)$.

$$L_3 = \sqrt{(es_\alpha)^2 + (-ec_\alpha s_\beta)^2 + (ec_\alpha c_\beta)^2} = e \tag{13}$$

Through the above calculation and derivation, the pose of the mechanism is expressed by two independent parameters (*α*, β). When (*α*, β) is determined, the pose of the moving platform origin point o in the fixed coordinate system is obtained as $o^B=({}^{B}o_x, {}^{B}o_y, {}^{B}o_z)$, and the length L_1 of the branch chain UPR and the length L_2 of the branch chain UPU can be obtained by using the inverse solution expression (11) of the mechanism.

IV. Simulation

Workspace modeling

The workspace of vector propulsion mechanism is the working area that the moving platform of the mechanism can reach, and its size is an important index to measure the motion performance of the mechanism. The workspace is divided into reachable workspace and flexible workspace. This paper only studies the reachable workspace of the mechanism. Taking into the constraints of workspace account, the reachable workspace is solved by numerical search method. The main influencing factors of the reachable workspace of the parallel mechanism are as follows: the structural parameters of the mechanism, the rotation angle limitation of the motion pair and the singular configuration.

(a) The structural parameters of the mechanism

The distance from the center point of the spindle branch chain U pair to the center point of the branch chain U pair on the fixed platform is A=270mm, the distance from the center point of the spindle branch chain R pair to the center point of the branch chain R pair (U pair) on the moving platform is a=47mm, and the distance between the upper and lower motion pairs of the spindle branch chain is e=220mm.

(b) The limitations on the rotation angle of the mechanism

In fact, the motion of rotating pair and universal joint of parallel mechanism are limited by the structure itself. Therefore, the influence of the rotation angle of the motion pair should be considered when calculating the reachable workspace.

Rotation pair R: the rotation angle of the rotating pair at the moving platform d_1 is determined by the direction vector ***u*** = (1, 0, 0) located on the moving platform and the vector L_1 of the connecting member. Its constraints can be expressed as follows:

$$\gamma = arccos\frac{L_1 \cdot u}{|L_1|} \le \gamma_{max} \tag{14}$$

The maximum rotation angle $\boldsymbol{\gamma_{max}}$, of the rotating pair has a wide range of pendulum angles, and the existence of the OD_1, It is impossible to reach the maximum rotation angle, and the constraint condition is not taken into account.

The first kind of U pair: the angle $\boldsymbol{\theta_i}$ of the U pair located on the fixed platform is determined by the base normal unit vector $\boldsymbol{n_{Ti}}$=(1, 0, 0) and the connecting axis direction vector L_1 in the moving state, where the rotation angle $\boldsymbol{\theta_i}$ should meet the following conditions:

$$\theta_i = arccos\frac{L_i \cdot n_{Ti}}{|L_i|} \le \theta_{i\ max} \tag{15}$$

the maximum rotation angle $\boldsymbol{\theta_{imax}}$ of each universal joint on the fixed platform is more than 45°, so it is necessary to consider this constraint.

The second kind of U pair: U pair located on the moving platform, which specifies that the initial time moving platform is parallel to the fixed platform and compares the initial state with the moving state. S_1 represents the unit direction vector of the rotating shaft directly connected to the moving platform in the U pair at d_1 in the initial state, and S_2 represents the unit direction vector of the shaft connected to the member on the Hook joint at d_1 in the moving state, then the angle $\boldsymbol{\delta_1}$ of L_2 around S_2 can be expressed as follows:

$$\delta_1 = arccos\frac{(S_2 \times S_1) \cdot L_2}{|L_2|} \le \delta_{1\,max} \tag{16}$$

By comparing the state of motion, the maximum rotation angle $\boldsymbol{\delta_{1max}}$=15° of the branch is obtained, and the range of the pendulum angle is very large. Because of the existence of the OD_2, it is impossible to reach the maximum rotation angle, and the constraint condition is not consideration.

（ c ）The influence of singular configuration

When the vector propulsion mechanism is in the singular configuration, the degree of freedom of the vector propulsion mechanism may change, and the singular configuration should be avoided as far as possible.

As described in paragraphs (a), (b) and (c), we need to consider the following constraints:

$$\begin{cases} \theta_i = arccos\dfrac{L_i \cdot n_{Ti}}{|L_i|} \le 45° \\ \beta \ne \arctan(-e/a) \qquad ,(i=1,2) \\ \alpha \ne \arctan(e\cos\beta / a) \end{cases} \tag{17}$$

Workspace simulation

MATLAB was used to conduct numerical search and calculation to solve the pose $(es_\alpha, -ec_\alpha s_\beta, ec_\alpha c_\beta)^T$ of the origin o of the moving platform in the fixed platform coordinate system, and draw a three-dimensional diagram to obtain the accessible workspace of the moving platform of UPR-UPU-UR vector propulsion mechanism as shown in Fig.3 below. Under the branched chain length limit, the origin of the moving platform in the workspace as part of the curved surface, the Fig.3(a) shows its stereogram in O-XYZ, Fig.3(b) shows its projection in the XOY plane, and Fig.3(c) shows its projection in the XOZ plane. Fig.3(d) shows its projection in the YOZ plane. The figure looks like the shape of a spherical surface. The workspace is symmetrical for the X axis and about the Y axis.

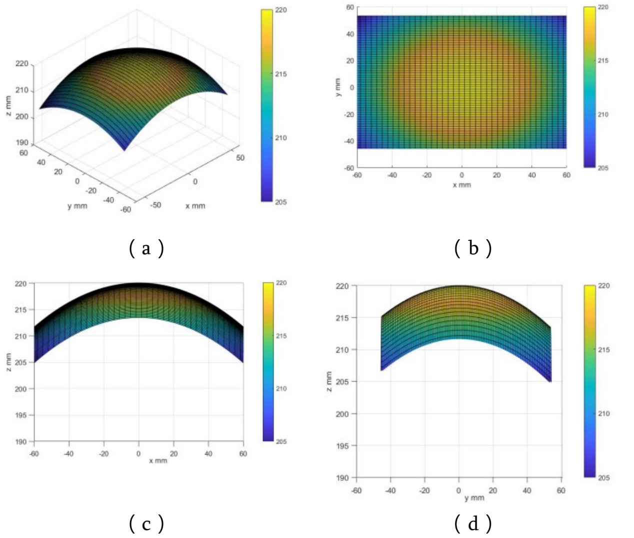
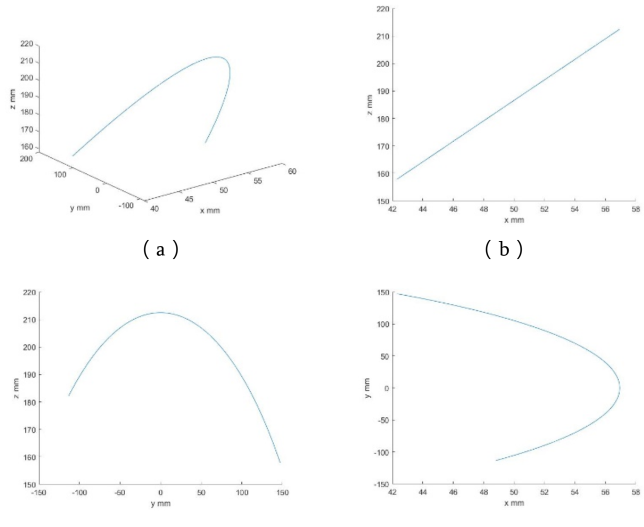


Fig.3. Mechanism moving platform Workspace and its three view drawing

Trajectory projection simulation

As for UPR-UPU-UR vector propulsion mechanism, the dynamic coordinate system is coincident with the static coordinate system at the initial position, the rotate angle α around y axis, then rotate angle β around x axis. When the range value of the angle α is -45°~45°, the value of the angle β of fixed value 5°, The trajectory of the moving platform of the mechanism is shown in Fig.4. The trajectory of the origin of the moving platform is a curve in the workspace of the mechanism. Fig.4(a) shows its stereoscopic diagram in O-XYZ, Fig.4(b) shows its trajectory projection in the XOZ plane, and Fig.4(c) shows its trajectory projection in the XOY plane. Fig. 4(d) shows its trajectory projection in the YOZ plane, and its trajectory shape looks like a parabola.



(c)   (d)

Fig.4. Mechanism moving platform trajectory diagram and its three views drawing

The length of the branch chains simulation

By driving the origin of the moving platform, the position of the moving platform can be changed. The driving angular can be expressed as: α=45sin(πt/2) and β=45sin(πt/2), the value of time t is (0, 12s). The length of the two branch chains can be solved. Using MATLAB programming, the variation curve of the length of the two branch chains about time are obtained as shown in Fig.5.

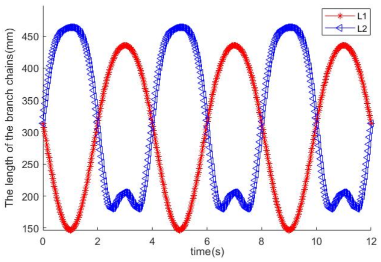


Fig.5. the variation curve of the length of branch chains simulated in MATLAB

V. CONCLUSION

According to the characteristics of the parallel mechanism, this paper designed the UPR-UPU-UR parallel mechanism, established the corresponding coordinate system, calculated the degree of freedom of the mechanism by using the spiral theory. This parallel mechanism has two rotational degrees of freedom. The inverse solution of position is solved by analytical method. The correctness of UPR-UPU-UR vector propulsion mechanism design and theoretical derivation are proved through analysis and simulation with MATLAB. The organization needs to design an experimental platform, conduct a series of experiments, and use experimental data to verify the propulsion effect of the organization, for example, under the action of floating waves in the water, the origin of the reference coordinate system of the mechanism is not fixed, and the influence on the propulsion effect of the mechanism. The UPR-UPU-UR vector propulsion mechanism has great advantages. The parallel mechanism can achieve multiple directions attitude swing in the narrow space, which provides a reliable theoretical basis for underwater vehicle.

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