Unmanned Underwater Vehicle Single Vectored Thruster System’s Structural Design and Kinematics Analysis

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ABSTRACT

Put forward a new type of Unmanned Underwater Vehicle Vectored Thruster, can produce controllable propulsion both on directions and power, realization of Unmanned Underwater Vehicle’s high mobility under the condition of low speed. Through two sets of push rod slider mechanism, to achieve rotations on two orthogonal direction (yaw and pitch), and movements on two orthogonal direction are not affected with each other. Completed the overall design of the vectored thruster, and the kinematics model is established. The simulation based on Adams is taken. The simulation results show that through the three motors’ control, can make the propeller shaft produces controllable propulsion both on directions and power, thus laid a foundation for further research of the vectored thruster.

INTRODUCTION

Unmanned Underwater Vehicle (UUV) is a kind of self-propelled or gliding underwater navigation device controlled by telecontrol or autonomously control, which can be recycled repeatedly. Currently it is showing broad application prospects in the fields of military and civilian. One of the problems needs to be solved is UUV’s steering control, and there are three ways to solve. Firstly, using the rudder to control the steering; secondly, laying multiple propellers to achieve steering on differential speed; thirdly, installing vectored thruster to control the steering. Related studies show that: the first method shows poor performance on the steering when UUV is on the...
condition of slow sailing, even sometimes barely to generate sufficient steering torque; although the second method can achieve flexibility steering, it must to arrange at least two thrusters on UUV, so that it cannot be used for the UUV with single thruster; the third method suit wide range, especially in the case of UUV’s low speed, which can generate additional control torque and flexible steering.

**SYSTEM COMPONENTS**

The overall structure of the system is shown in Figure 1. Its main component comprises: two linear actuators, one propulsion motor, two push rods, two linkages, one cardan joint, one spherical joint, one duct connector, one duct base, one duct, one propeller shaft and one propeller.

Both ends of the housing are connected by end caps and hoops, sealed with O-rings. The signal lines and power lines lead through out of the housing by a watertight plug. The duct base forms spherical kinematic pair with the housing, sealed by slip ring and O-ring, and the slip ring is made of PTFE.

**STRUCTURAL DESIGN AND ANALYSIS**

Propeller shaft can do motions on three directions in space, namely the pitch motion, the yaw motion and the spin motion circles its own axis, the entire mechanism needs to have three degrees of freedom. The topological structure of the vector propulsion system is shown in Figure 2.

The entire mechanism totally has seven components, including five $V$ kinematic pairs ($P_1, P_2, R_1\sim R_3$), two $IV$ kinematic pairs($C_1, C_2$)and two $III$ kinematic pairs($S_1, S_2$). Thus, the degree of freedom of the mechanism is:

$$F = 6n - (5p + 4p_2 + 3p_3) = 6\times7 - (5\times5 + 4\times2 + 3\times2) = 3$$

The mechanism is equipped with three prime motors, that is the linear actuator I, the linear actuator II and the propulsion motor, the number of the prime motors is equal to the number of degrees of freedom, so this mechanism will do positive motions. Thus, the entire mechanism can be divided into three parts: the pitch transmission system, the yaw transmission system and the propeller spin system.

The pitch transmission system controls the propeller shaft’s pitch motion, which consists of the linear actuator I, cardan joint, linkage, linear bearing, duct base and housing. The duct base forms spherical kinematic pair with the housing. The linear actuator I and the linkage is connected by the cardan joint, pushing the linkage, and making the slider which is connected to the linkage do linear motion on the bare shaft,
thereby enabling the duct base rotating around the sphere, making the duct base and the propeller shaft pitching.

The yaw transmission system controls the propeller shaft’s yaw motion, which consists of the linear actuator II, spherical joint, linkage, linear bearing, duct base and housing.

The propeller spin system controls the rotation of the propeller shaft, which is fixedly connected to the duct base. The propulsion motor drives the propeller shaft directly.

**KINEMATICS ANALYSIS**

As shown in Figure 3.1, the $O$ point is the rotational center of the propeller shaft, namely the rotational center of the spherical pair $S_1$ in Figure 2.1. The $R$ point is the end of the propeller shaft. The pitch transmission system drives the propeller shaft rotation around the $x$-axis; the yaw transmission system drives the propeller shaft in a circular motion around the $z$ axis. Both coincide with the centers of rotation, are $O$ point. The planes of rotation are orthogonal to each other, so the two trajectories make up a sphere. Pitching and yawing motion of the propeller shaft decoupled from each other, and do not implicated, so it is possible to study their kinematics characteristics respectively.

**Inverse Kinematics Analysis**

When the push rod moves to the right, the state of pitch transmission system is shown in Figure 3.2.

In figure, $x$ is the displacement of linear actuator's push rod; $l$ is the length of the link; $s$ is the vertical distance from the push rod to the rotation center $O$. Displacement equation can be get from the geometric relationship shown in the figure:
\[
\begin{aligned}
    b_1 + b_2 &= \frac{l}{\cos \alpha} \\
    b_2 &= s \cdot \tan \alpha \\
    x &= l - b_1
\end{aligned}
\Rightarrow \quad x = s \cdot \tan \alpha + l - \frac{l}{\cos \alpha}
\tag{3.1}
\]

The pitch transmission system and the yaw transmission system have the same law of motion. \(x_1\) is delimited as the displacement of the pitch transmission system's linear actuator, and \(x_2\) as the displacement of the yaw transmission system's linear actuator. \(\alpha\) is pitch angle, and \(\beta\) is yaw angle.

\[
\begin{aligned}
    x_1 &= s \cdot \tan \alpha + l - \frac{l}{\cos \alpha} \\
    x_2 &= s \cdot \tan \beta + l - \frac{l}{\cos \beta}
\end{aligned}
\tag{3.2}
\]

Both \(l\) and \(s_3\) are constants determined by the mechanical structure. Now we have to take the derivative of time \(t\) in Equation 3.2, then the speed equation is get:

\[
\begin{aligned}
    \frac{dx_1}{dt} &= \frac{s - l \cdot \sin \alpha}{\cos^2 \alpha} \cdot \frac{d\alpha}{dt} \\
    \frac{dx_2}{dt} &= \frac{s - l \cdot \sin \beta}{\cos^2 \beta} \cdot \frac{d\beta}{dt}
\end{aligned}
\tag{3.3}
\]

Equation 3.2 and Equation 3.3 are the inverse kinematics results. If the pitch (yaw) angle and angular velocity are known, we can get the displacement and the speed of the linear actuator's push rod from the two equations above, and this result can be further used to calculate the control parameters of the linear actuator.

Take pitch transmission system as the research object, in the mechanism designed, the length of the linkage is 35mm \((l=35\text{mm})\), the vertical distance from the push rod to the rotational center \(O\) is 30mm \((s=30\text{mm})\). According to Equation 3.2, draws its figure as shown in Figure 3.3.
In this case, when the pitch angle takes maximum value, that is $\alpha = 15^\circ$, the displacement of push rod is about 6.8mm ($x \approx 6.8\text{mm}$).

**Positive Kinematics Analysis**

Use the half-angle formula to replace the formula 3.1, delimiting $u = \left(tan\alpha/2\right)$.

\[
x = l + \frac{-lu^2 + 2us - l}{1 - u^2} \Rightarrow u = \frac{s - \sqrt{x^2 - 2lx + s^2}}{2l - x} \Rightarrow \alpha = 2\arctan\left(\frac{s - \sqrt{x^2 - 2lx + s^2}}{2l - x}\right)
\]

\[
\begin{align*}
\alpha &= 2\arctan\left(\frac{s - \sqrt{x_1^2 - 2lx_1 + s^2}}{2l - x_1}\right) \\
\beta &= 2\arctan\left(\frac{s - \sqrt{x_2^2 - 2lx_2 + s^2}}{2l - x_2}\right)
\end{align*}
\]

(3.4)

Take the derivative of time $t$ in Equation 3.4, then the speed equation is get:

\[
\begin{align*}
\frac{d\alpha}{dt} &= \frac{-s^2 + 2l^2 - lx_1 + s\sqrt{x_1^2 - 2lx_1 + s^2}}{\sqrt{x_1^2 - 2lx_1 + s^2}\left[-s\sqrt{x_1^2 - 2lx_1 + s^2} - 3lx_1 + s^2 + 2l^2 + x_1^2\right]} \cdot dx_1 \\
\frac{d\beta}{dt} &= \frac{-s^2 + 2l^2 - lx_2 + s\sqrt{x_2^2 - 2lx_2 + s^2}}{\sqrt{x_2^2 - 2lx_2 + s^2}\left[-s\sqrt{x_2^2 - 2lx_2 + s^2} - 3lx_2 + s^2 + 2l^2 + x_2^2\right]} \cdot dx_2
\end{align*}
\]

(3.5)

Equation 3.4 and Equation 3.5 are the positive kinematics results. If the displacement and velocity of the linear actuator's push rod are known, we can get the pitch (yaw) angle and angular velocity from the two equations above.

Take pitch transmission system as the research object, according to Equation 3.4, draws its figure as shown in Figure 3.4.
KINEMATICS SIMULATIONS

Using Adams software to do kinematics simulation to verify if the mechanism meets the requirements of the design movement, and also verify if the results of kinematic analysis is correct.

Firstly, the pitch push rod is applied only to drive. Respectively, to get how the pitch and yaw angle vary with the displacement of pitch push rod, as shown in the Figure 4.1 and 4.2. Then, the yaw push rod is applied only to drive. Respectively, to get how the yaw angle and the pitch angle vary with the displacement of yaw push rod, as shown in the Figure 4.3 and 4.4.

Compare figure 4.1, 4.3 and 3.4, we can find that kinematics simulation figure and kinematics analysis figure are identical. Kinematics simulation results verify the correctness of the results of kinematics analysis.

CONCLUSIONS

This vectored thruster has mature design theory, and manufacturing technology meets the demand. Mathematical model is provided for control algorithm by aid of kinematics equation, which is established by the kinematics analysis. Through simulation software Adams to verify the results of kinematics analysis, by controlling the displacement of two linear actuators, the propeller shaft can change its direction in space, while the propeller shaft can rotate around its own axis, outputting propulsion.
Both of the propellers’ pitch and yaw angle is ± 15°, and the rate can be controlled at 30°/s. According to this, the performance of the whole system meets the specification.

REFERENCES