Analysis of docking tolerance capability of underwater tool-switching device

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Abstract: As part of the Underwater Mechanical hand and Tool Box System, the underwater tool-switching device can carry variety kinds of tools that have general interfaces during one-time underwater operation, like polisher, driller, cutting saw, torque wrench. By operating the underwater ROV Mechanical hand using the remote control system on the land, the workers are able to switch all kinds of tools quickly so that they can enhance the work ability and improve the efficiency of the Underwater Mechanical hand. In this paper, the geometric conditions required for the docking of the mobile end and the fixed end of the docking device are analyzed. Through the projection method, the three-dimensional docking process is transformed into the two-dimensional position equation on the main docking plane, and the mathematical model is established to obtain the docking tolerance range. Then, the simulation experiment is carried out by Adams to verify the correctness of the tolerance theoretical calculation.

1. Introduction
Nowadays, with the exploiting and consuming of ocean resources, human have more and more operations on the sea bed. Because of the particularity of the ocean’s environment, the underwater operations of human like assembling, checking and repairing underwater equipment and structure are always accomplished by UVMS (Underwater Vehicle-Manipulator System). UVMS consists of underwater mechanical arm, underwater tool box, a series of operation tools, tool-switching device and other support devices. Now, it is a major trend to complete as more underwater operation missions as possible during one dive. To make that possible, it is necessary to design an underwater fast-switching operation tool to improve its ability to work. While switching the operation tools, the underwater tool-switching device that connects the underwater mechanical arm and underwater operation tools should not only lock up the mechanical connection between the mechanical arm and tools, but also complete the connecting mission between tools and the deep water hydraulic source carried by ROV. The point is to achieve the big-tolerance precise docking technology in the current environment. This paper mainly discusses the docking tolerance of tool-switching device in deep water operation system and designs a set of docking device, and then verifies its tolerance capability through theoretical analysis and simulation research.
2. The overall design of the underwater tool-switching device

Used in a complicated environment of 500 meters underwater, the fast-tool-switching device suffer from so many disturbances that cannot achieve an accurate docking just guided by control system. To overcome the above difficulties, the fast-tool-switching device is consist of two main parts: mobile end and fixed end (solution shown in Figure 1). In this solution, the mobile end is connected to operation tools, while every kind of operation tools that take part in the docking is carried with the same mobile end. The fixed end connect the power source and the control signal. When the docking process starts, grabbed by the mechanical arm, the mobile end is docked towards the fixed end so that the connection among tools, power source and signal can be fulfilled after the docking succeed. The specific structure of the docking device is shown in Figure 2.

Figure 1   fixed end (left) and mobile end (right)

1.locking sleeve 2.flange plate of the fixed end 3.guide post of the fixed end
4.shell of the fixed end 5.female Hydraulic Tube Fittings ( HTFs) 6.guide ring
7.guide shell 8.guide plate 9.guide post of the locking shaft 10.male HTFs
11.limit ring 12.limit block 13.handle 14.support handle
15.guide post of the mobile end 16.flange plate of the mobile end
17.middle shell 18. locking shaft19.support shell 20.guide block
21.driving nut 22. square shaft 23.handle shell

Figure 2   fixed end (left) and mobile end (right)

When the underwater robot mechanical hand grabs and connects the mobile end and fixed end of the fast-tool-switching device, because of the underwater current disturbance and position and orientation deviation lying between the mobile end and fixed end before docking, the mobile end and fixed end cannot finish docking successfully or, even worse, cause jamming and wedging. The docking correction device needs to be convenient for the docking between the mobile end and the fixed end, and it needs to have a large tolerance of position and orientation to facilitate the underwater robot to control the docking process of the device. In this way, not only can the probability of successful docking be improved, but also the device can avoid from getting damaged while docking the mobile end and fixed end.

The docking correction device uses the initial docking to correct most of the position and orientation deviation, and corrects the remaining position and orientation deviation through fine docking to achieve
accurate alignment. This design can improve the probability of successful docking, and has larger tolerance of position and orientation. The design of two docking rectification can avoid jamming or wedging to the greatest extent, and reduce the machining accuracy requirements of parts.

3. Analysis of docking tolerance capability

There are three steps in the docking process. The first step is the docking stage. At this time, the mobile end and the fixed end are gradually approaching each other. During the docking stage, there will inevitably be some position and orientation deviation between the mobile end and the fixed end. The second step is the initial position and orientation adjustment stage, which adjusts most of the position and orientation deviation before docking. The third step is the precise position and orientation adjustment stage to adjust the deviation after the initial docking, so as to facilitate the next step operation of the device.

Based on the coordinate transformation method, in order to facilitate the analysis of the situation before the docking of the fixed end and the mobile end, the coordinate systems are established respectively at the fixed end and the mobile end as $O_1X_1Y_1Z_1$ and $O_2X_2Y_2Z_2$ as is shown in Figure 3.

Figure 3   coordinate system of fixed end (left) and mobile end (right)

The homogeneous transformation matrix $^A_B T$ from vector in coordinate system $O_1X_1Y_1Z_1$ to coordinate system $O_2X_2Y_2Z_2$ is:

$$^A_B T = \begin{bmatrix}
  \cos \alpha \cos \beta & \cos \alpha \sin \beta \sin \gamma - \sin \alpha \sin \gamma & \cos \alpha \sin \beta \cos \gamma + \sin \alpha \sin \gamma & a \\
  \sin \alpha \cos \beta & \sin \alpha \sin \beta \sin \gamma + \cos \alpha \cos \gamma & \sin \alpha \sin \beta \cos \gamma - \cos \alpha \sin \gamma & b \\
  -\sin \beta & \cos \beta \sin \gamma & \cos \beta \cos \gamma & c \\
  0 & 0 & 0 & 1
\end{bmatrix} \quad (1)$$

In the equation: $a$, $b$, $c$--- position deviation between two coordinate systems, $\alpha$, $\beta$, $\gamma$--- orientation deviation between two coordinate systems.

In order to facilitate the analysis, it is necessary to unify the moving end circle $A$ and the fixed end circle $B$ in one spatial coordinate system where circle $A$ of the mobile end is projected into the plane $O_2X_2Y_2Z_2$ where circle $B$ of the fixed end lies. First the plane $O_1X_1Y_1$ is represented by the space coordinate system $O_2X_2Y_2Z_2$. In the space coordinate system $O_2X_2Y_2Z_2$, the plane $O_1X_1Y_1$ is equivalent to a plane passing through point $O$ ($a$, $b$, $c$). Here is the equation:

$$(\cos \alpha \sin \beta \cos \gamma + \sin \alpha \sin \gamma)(x - a)$$

$$+(\sin \alpha \sin \beta \cos \gamma - \cos \alpha \sin \gamma)(y - b)$$

$$+(\cos \beta \cos \gamma)(z - c) = 0 \quad (2)$$

The equation of the boundary curve of plane $A$ on the mobile end in coordinate system $O_2X_2Y_2Z_2$ is:

$$\begin{cases}
x^2 + y^2 = r^2 \\
z = h
\end{cases} \quad (3)$$

The projection of the boundary curve of plane $A$ on the mobile end on the plane $O_2X_2Y_2$ is composed of the intersection line of two planes. The plane $O_2X_2Y_2$ is selected as one of the planes, and the cylinder passing through the boundary curve is selected as the other plane. The projection equation is:
\[
\begin{aligned}
\begin{align*}
& x^2 + y^2 = r^2 \\
& (\cos \alpha \sin \beta \cos \gamma + \sin \alpha \sin \gamma)(x - a) \\
& + (\sin \alpha \sin \beta \cos \gamma - \cos \alpha \sin \gamma)(y - b) \\
& + (\cos \beta \cos \gamma)(z - c) = 0 \\
\end{align*}
\end{aligned}
\]

(4)

Transform it into parameter form:

\[
A_{O_2} = \begin{cases}
    x = r \cos t \\
    y = r \sin t \\
    z = c - \frac{(\cos \alpha \sin \beta \cos \gamma + \sin \alpha \sin \gamma)(r \cos t - a)}{\cos \beta \cos \gamma} \\
    - \frac{(\sin \alpha \sin \beta \cos \gamma - \cos \alpha \sin \gamma)(r \sin t - b)}{\cos \beta \cos \gamma} \\
    (0 \leq t \leq 2\pi)
\end{cases}
\]

(5)

Then the curve parameter equation \(A_{O_2}\) is transformed into the coordinate system \(O_1X_1Y_1Z_1\) by using the homogeneous transformation matrix. Thus, the curve equation \(A\) in the coordinate system \(O_1X_1Y_1Z_1\) can be obtained by projecting the boundary curve of plane \(A\) onto the plane \(O_2X_2Y_2\):

\[
A_{O_1} = \frac{\Delta}{\beta} T^{-1} A_{O_2}
\]

(6)

\[
A_{O_1} : \begin{cases}
    x = x(t) \\
    y = y(t) \\
    z = z(t)
\end{cases} \\
(0 \leq t \leq 2\pi)
\]

(7)

The transformed curve projection equation should be in the boundary curve of plane \(B\):

\[
x(t)^2 + y(t)^2 \leq R^2 \quad (0 \leq t \leq 2\pi)
\]

(8)

There is also a guide post on the mobile end. In the analysis, the guide post on the mobile end is simplified as a straight line. In the coordinate system \(O_2X_2Y_2Z_2\), the expression of the straight line where the guide column lies is:

\[
l_2 : \begin{cases}
    x = 0 \\
    y = t \quad (\infty < t < +\infty) \\
    z = h
\end{cases}
\]

(9)

The expressions of any two points \(P_1\) and \(P_2\) on line \(L_1\) in plane \(O_2X_2Y_2Z_2\) are:

\[
\overrightarrow{P_1} = (0, a_1, h) (a_1 \in R)
\]

(10)

\[
\overrightarrow{P_2} = (0, a_2, h) (a_2 \in R)
\]

(11)

Then the expressions of points \(P_1\) and \(P_2\) in the coordinate system \(O_1X_1Y_1Z_1\) are:

\[
\overrightarrow{P'_1} = \frac{\Delta}{\beta} T^{-1} \cdot \overrightarrow{P_1}
\]

(12)

\[
\overrightarrow{P'_2} = \frac{\Delta}{\beta} T^{-1} \cdot \overrightarrow{P_2}
\]

(13)

The straight line formed by the points \(P'_1\) and \(P'_2\) is expressed as:

\[
l_1: y = y_0 + k(x - x_0)
\]

(14)

Through the numerical calculation of projection equation (4) - (14), the projection of the moving end on the \(O_1X_1Y_1\) plane where the fixed end is located before docking is obtained, so as to verify whether the docking correction device can meet the requirements of pose deviation range. The calculation model is shown in Figure 4. Through calculation, the existence of the guide groove is transformed into an arc on the fixed end.

**Figure 4** Simulation diagram with deviation of 5mm, 5mm, 5mm, 0 °, - 5 ° and 5 °
Since the position deviation is the superposition of the attitude deviation caused by X-axis and Y-axis and the previous position deviation, the maximum tolerance range of docking correction device is measured without considering the orientation deviation of X-axis and Y-axis, and then the tolerance capability is analyzed based on the orientation deviation of X-axis and Y-axis. According to the projection of the device before docking, the geometric tolerance range is analyzed, and the tolerance capability index of the device is obtained. The maximum position tolerance range (shown in Figure 5) is obtained by verifying multiple groups of position deviations.

![Figure 5: position tolerance range](image)

It is obvious from figure 5 that most of the radius of the position tolerance range of the device is 14mm. Because the exist of the guide groove enlarges the range of the fixed end, the position tolerance range of the guide groove on the fixed end is a little larger. In addition, according to the deviation, the range of the guide groove is larger, so the z-axis angle deviation has little influence on the tolerance range. Finally, the maximum tolerance radius of the device is 14mm.

Based on this, the influence of the angle deviation of X-axis and Y-axis on the maximum tolerance radius is calculated. The angle deviation of X-axis and Y-axis will become position deviation:

\[
\delta = Z_h \cdot \sin(\alpha + \theta) + \frac{d}{2} \left(1 - \frac{1}{\cos \theta}\right)
\]

\[
\cos \theta = \cos \lambda \cdot \cos \sigma
\]

In this equation,

- \(Z_h\) --- Z axis deviation
- \(\delta\) --- Radial deviation
- \(\theta\) --- Angle around Z axis
- \(\lambda\) --- Angle around X axis
- \(\sigma\) --- Angle around Y axis

From equation (15), it can be seen that the angle deviation of X-axis and Y-axis is transformed into 3.65mm position deviation, so the maximum tolerance radius of the device is 10.35mm.

### 4. Simulation analysis of docking process

The study of the docking tolerance between the mobile end and the fixed end of the underwater fast-tool-switching device is done above. Here comes the docking tolerance ability research by using dynamics analysis software Adams. By modeling the docking process, the theoretical analysis is further verified. After the simplified device is imported into Adams, constraints are added between parts. A fixed constraint is applied to the fixed end. The spring damper is added to other rotation and translation directions except the axial butt joint direction in the moving end to prevent it from moving randomly. Spring stiffness is set to 1N/mm. Damping coefficient is set to 0.5N·s/mm. Static friction coefficient is set to 0.25. Dynamic friction coefficient is set to 0.2. Static translational velocity is 0.1mm/s. Dynamic translation speed is 10 mm/s. Moving speed of the mobile end is set to 2mm/s.

After adding constraints and loads to the model, the virtual simulation platform is built by Adams (shown in Figure 6).
After the simulation model is established, the tolerance range of the device docking is verified. The initial position and orientation deviation is obtained by adjusting the spatial position of the mobile end. The initial docking conditions are set according to the data in Table 1, combined with the position and orientation tolerance index of the fast-tool-switching device.

Table 1  Initial docking simulation test combination

| Number | position deviation /mm | orientation deviation /° | result |
|--------|------------------------|--------------------------|--------|
|        | X  | Y  | Z   | X  | Y  | Z  |        |
| 1      | 5  | -5 | 150 | 5  | 3  | 1.5 | Figure 7 (a) |
| 2      | 3  | -7 | 150 | 5  | 1.5| 3   | Figure 7 (b) |
| 3      | 14 | 0  | 150 | 1  | 0  | 1   | Figure 7 (c) |
| 4      | 0  | 14 | 150 | 0  | 1  | 0   | Figure 7 (d) |

Adams is used to simulate the position and orientation deviation in the above table. The real-time correction process of position deviation and orientation deviation in the simulation process is shown in Figure 7.
From the simulation results shown in Fig. 6, the position deviation and orientation deviation are corrected at the same time during the docking process. All four groups of simulations have been successfully completed the docking, and the effective tolerance range of the docking correction device has been verified, which shows that the analysis of the tolerance range mentioned above is correct.

5. Conclusion
In this paper, a kind of underwater fast-tool-switching device is designed, and the docking tolerance of the fast-tool-switching device is studied. This paper analyzes the geometric conditions for the successful docking of the mobile end and the fixed end in the fast-tool-switching device, and deduces the projection equation through the homogeneous transformation equation. Finally, Adams is used to simulate the
docking of the fast-tool-switching device under various typical limited Position and orientation deviations, which verifies the correctness of the model.

Acknowledgments
This article is one of the periodic achievements of Reliable docking of fast-switching toolbox of deep water operation system and experimental research of the Hei Longjiang Natural Science Fund (E2018021) and the Fundamental Research Funds for the Central Universities (3072020CFT0704).

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