Adaptive multi-mode switching strategy for the spherical underwater robot with hybrid thrusters

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Abstract

The conventional autonomous cruise and tracking system cannot transition and change its motion mode according to the underwater environment during operation, so it is of great significance to study the multi-mode switching of cruise control for Autonomous Underwater Vehicles (AUVs). In this paper, a Multi-Mode Adaptive Switching (MMAS) strategy for the Spherical Underwater Robot with Hybrid Thruster (HPSUR) was proposed, which provided the possibility for the robot to choose optimal control mode according to the unpredictable operating environment. Then, the dynamic and force of the hybrid thruster are analyzed to improve the accuracy of multi-mode switching, and the MMAS strategy is developed linking the attitude adjustment and switching problems. Furthermore, a series of multi-mode switching experiments were conducted using water-jet mode, propeller mode and hybrid mode. Finally, the experimental result was discussed, which verified the effectiveness and accuracy of the proposed MMAS strategy. The proposed control strategy has a certain reference value for the multi-mode switching of propulsion devices.

1. Introduction

Ocean exploration and discovery in unknown environments have become a mainstream trend in the development of AUVs [1–2]. This provides a variety of system forms and performances for AUVs in different working environments. Simultaneously, autonomy, intelligence and sharing have become new technology in AUVs development [3–5]. This emerging technology provides great convenience for improving the working efficiency, safe driving and flexible movement of AUVs. Although some underwater vehicles equipped with automated systems have been proposed, such as adaptive navigation control, obstacle avoidance system, adaptive monitoring, tracking and hovering, fully adaptive strategies are not easy to realize in the short term [6]. It will face problems of the complex underwater environment, external environment disturbance, immature technology, nonlinearities and single motion mode [7]. In addition, adaptive control for the AUV should also consider characteristics such as safety, stability, efficiency, etc. A key adaptive research problem hence involves the interaction between AUVs and complex environments [8–9].

As one of the most basic adaptive behavior, multi-mode switching control provides a guarantee for improving execution efficiency and flexibility, ensuring operational safety, which has become an active research field for AUVs [10–11]. There are two main ways to realize multi-mode switching for underwater vehicles: (1) The operator actively intervenes to provide instructions to change the motion mode to adapt to the underwater environment; (2) Integrating an adaptive switching assistance system, AUV perceives the external environment in real-time to continuously share information with the system to achieve multi-mode switching. For AUVs, adaptive multi-mode switching control is more important, which helps to save energy, reduce workload and improve the safety of AUVs. Furthermore, considering the nonlinearity and multiple Degrees of Freedom (DoF) of AUVs, smooth transitions between multiple modes and parameter optimization facilitate coordinated motion control, which in turn improves the velocity and control accuracy of the robot. Therefore, it becomes particularly important to solve the problem of AUV multi-mode switching.

As one of the features of AUVs, the hybrid propulsion device is common. Compared with traditional AUVs, AUVs with hybrid thrusters are more convenient for multi-mode control and application. Hybrid thrusters, with the advantages of long-lasting, high-efficiency, multi-functionality and strong-adaptability, play an increasingly important role in the fields of underwater resource exploration, rescue and...
reconnaissance. Li et al. [12] evaluated the performance of a hybrid thruster for the spherical underwater robot using fluid mechanics to determine the relative distance. Gu et al. [13] developed a spherical underwater robot with a hybrid propulsion device, which can realize multiple motion modes to adapt to unknown environments. Chen et al. [14] designed a hybrid-driven underwater glider with foldable propellers. Kadiym et al. [15] proposed a hybrid propulsion device for underwater detection and observation. Chocron et al. [16–17] developed the magnetic coupling propulsion device with radial reconfigurable function for AUVs. Fugt et al. [18] designed reconfigurable and redundant propulsion systems for underwater vehicles to improve motion capability. Most of the above-mentioned hybrid propulsion devices for AUVs are mainly studied for their structural design and motion mode characteristics, and the adaptive multi-mode control system is relatively lacking. However, adaptive switching control systems are worth considering for AUVs with hybrid propulsion devices performing underwater missions, which can achieve rapid conversion and high efficiency.

Researchers, over the years, have focused on the study of adaptive control for various robot systems. For instance, the multi-mode adaptive shared control methods are used to achieve the design of the Lane Changing Assistance System (LCAS), which can achieve a low accident rate and traffic unimpeded [19–21]. However, existing works on multi-mode adaptive control strategies are mainly aimed at ensuring driving safety, while relatively neglecting the existence of external disturbance in an underwater environment. Furthermore, for nonlinear and unmanned underwater vehicles, the changing parameter adaptive controller is proposed to resist external disturbances based on dynamic models of AUV [22–24]. However, existing works on the nonlinear and unmanned AUVs are mainly oriented to the changing parameter adaptive or tracking, while ignoring issues such as the parameter changing of thrusters and mode switching.

In our previous research, the SUR with multi-water-jet thrusters was proposed, aiming to achieve underwater manipulation in narrow space exploration [25–26]. Considering the nonlinearity and time-varying of the SUR, the hydrodynamic and static mechanical are analyzed to improve the estimated parameters [27–28]. Then, [5,12–13], designed the HPSUR to verify its propulsion performance through hydrodynamic analysis. HPSUR also has the concealment, low-noise, strong-stability of the water-jet, and flexibility, high-velocity of the propeller. This brings convenience for HPSUR to operate in the ocean, quickly search and resist ocean currents. In addition, autonomous switching between multiple modes allows the HPSUR to approach the target quickly and efficiently, reduce noise and improve stability, as shown in Fig. 1. Thus, we will focus on the study of the adaptive switching for HPSUR in this paper to improve the adaptability, flexibility and safety, and ensure the underwater ecological balance.

Considering the nonlinearity and time-varying feature of the HPSUR, how to achieve its stability and safety based on a dynamic model and hybrid thrusters remains an urgent issue to be solved. Thus, to improve the ability of underwater operations, this paper proposes the MMAS strategy for HPSUR combining the advantages of hybrid thrusters. In addition, adaptive control and smooth transition between multiple modes are solved. The main contributions of this paper are as follows:

(i) Firstly, considering the adaptability and safety requirements of HPSUR to the unknown environment, intending to execute missions efficiently and switch mode accurately. Alternative modes can quickly close to the target with efficiency and energy-saving using hybrid thrusters. Hence, to improve the operating efficiency of HPSUR, a MMAS strategy is proposed based on the advantages of hybrid thrusters, which realizes the smooth transition between the three motion modes (water-jet mode, propeller mode and hybrid mode).

(ii) Secondly, based on the kinematic and dynamic models of the HPSUR, the hybrid propulsion device is analyzed. Considering the complexity and nonlinearity of the AUV’s model, the mechanical model is an important basis and premise to determine the HPSUR design and control strategy. The kinematic and dynamic models, and force and moment of HPSUR are derived to improve the control strategy of HPSUR with hybrid thrusters.

(iii) Finally, based on the proposed MMAS strategy, linking the dynamic model, attitude adjustment, multi-mode smooth transition, multi-mode triggering, etc., which is an extremely critical issue. In addition, some comprehensive evaluation experiments in real environment are realized, which is a challenge for small underwater robots in practical applications.

The remainder of the paper is organized as follows: In Section 2, the mechatronic model of the HPSUR is analyzed, and the motion mode using hybrid thrusters is introduced. The MMAS control strategy is constructed for the HPSUR in Section 3. Then, in Section 4, a series of experiments are performed to analyze the performance of the HPSUR, which validates the effectiveness of the proposed strategy. Next, we discuss the effectiveness and practical value by comparing the MMAS with other methods in Section 5. Our conclusion will be presented in Section 6.

2. Mechatronic model of the HPSUR

In this section, the hybrid thruster of HPSUR (integrated water-jet thruster and propeller) is introduced. In order to enhance the
effectiveness of the control strategy, the kinematic and dynamic models, force and moment of the considered HPSUR are represented.

### 2.1. Related work

In this part, we describe the features of HPSUR. Previously, we designed the SUR with hybrid thrusters, see [12] for details. Table 1 reveals the specific parameters of the HPSUR, which has multiple motion modes. The characteristics of the hybrid thruster are as follows: The water-jet mode has the advantage of low-velocity, low-noise, and high-stability; The propeller mode has the advantage of high-velocity and flexible-movement; The hybrid mode has the advantage of high-velocity, strong-flexibility, and long-navigation-distance.

Fig. 2 compares the motion mode of the HPSUR with the previous research. Li et al. designed a SUR with four water-jet thrusters and analyzed the motion characteristics with low-noise which have great significance in ocean detection [2]. Gu and Guo et al. proposed a SUR with a hybrid propulsion device, and carried out the hydrodynamic evaluation [13,28]. Then, we evaluated the performance of the hybrid thruster considering the relative distance between hybrid thrusters, and measured the maximum thrust using fluid mechanics, detailed in [12]. The maximum thrust of the hybrid thruster we developed can reach 5.12 N, which increased about 138.6% stronger than the water-jet thruster, and 88.7% stronger than the propeller. Compared with [13], enhanced by 11% and 8%, respectively.

Next, the developed hybrid thruster will be used to design and analyze the MMAS strategy for the HPSUR, which can be switched according to the experimental environment in performing underwater tasks.

#### 2.2. Kinematic and dynamic model analysis

In this part, the dynamic model of the HPSUR is illustrated. The considered coordinate system for the HPSUR, including Earth-fixed frame \( \{O_e-X_eY_eZ_e\} \) and Body-fixed frame \( \{O_b-X_bY_bZ_b\} \), is shown in Fig. 3, which follows the right-hand rule.

As we all know, the rotation matrix of the Body-fixed frame with respect to the Earth-fixed frame can be given using Euler angles \( (\phi, \theta, \psi) \), as follows.
estimating the attitude, as follows:

The nematic model of the HPSUR can be simplified, which can be used for

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\[ \phi = \rho + q \tan \theta \sin \phi + r \tan \theta \cos \phi \]

\[ \psi = q \cos \phi - r \sin \phi \]

\[ \psi = q \sin \phi / \cos \theta + r \cos \phi / \cos \theta \]

(4)

2.3. Force and moment analysis

The force of the hybrid propulsion device is shown in Fig. 4. The distance between the steering gear and the center of HPSUR is defined as

\[ F_X = F_{X_{waterjet}} + F_{X_{propeller}} = -F_1 s_1 c_1 \beta_1 + F_2 s_1 c_2 \beta_2 -F_3 c_1 \beta_3 + F_4 c_1 \beta_4 + F_5 c_1 \beta_5 + F_6 c_1 \beta_6 \]

\[ F_Y = F_{Y_{waterjet}} + F_{Y_{propeller}} = -F_1 c_1 \beta_1 - F_2 c_1 \beta_2 + F_3 c_1 \beta_3 - F_4 c_1 \beta_4 - F_5 c_1 \beta_5 - F_6 c_1 \beta_6 \]

\[ F_Z = F_{Z_{waterjet}} + F_{Z_{propeller}} = F_1 s_2 \alpha_1 + F_2 s_3 \alpha_3 + F_3 s_4 \alpha_4 + F_4 s_5 \alpha_5 + F_5 s_6 \alpha_6 \]

(5)

Hence, the force matrix along the X, Y, Z axis can be described as:

\[ [F_X \ F_Y \ F_Z] = M_F \begin{bmatrix} F_1 \\ F_2 \\ F_3 \\ F_4 \\ F_5 \\ F_6 \end{bmatrix} \]

(6)

where \( M_F \) as:

\[ M_F = \begin{bmatrix} -s_1 c_1 \beta_1 & s_3 c_1 \beta_2 & -s_3 c_1 \beta_3 & -s_4 c_1 \beta_4 & s_4 c_1 \beta_4 & s_5 c_1 \beta_5 & s_6 c_1 \beta_6 \\ s_1 c_1 \beta_1 & c_2 c_1 \beta_2 & c_2 c_1 \beta_3 & c_2 c_1 \beta_4 & s_4 c_1 \beta_4 & c_2 c_1 \beta_5 & c_2 c_1 \beta_6 \\ -s_2 c_1 \beta_1 & s_3 c_1 \beta_2 & s_3 c_1 \beta_3 & s_4 c_1 \beta_4 & s_4 c_1 \beta_4 & s_5 c_1 \beta_5 & s_6 c_1 \beta_6 \\ -s_2 c_1 \beta_1 & -s_3 c_1 \beta_2 & s_3 c_1 \beta_3 & -s_4 c_1 \beta_4 & s_4 c_1 \beta_4 & -s_5 c_1 \beta_5 & s_6 c_1 \beta_6 \\ -s_2 c_1 \beta_1 & -s_3 c_1 \beta_2 & s_3 c_1 \beta_3 & s_4 c_1 \beta_4 & s_4 c_1 \beta_4 & s_5 c_1 \beta_5 & s_6 c_1 \beta_6 \\ -s_2 c_1 \beta_1 & -s_3 c_1 \beta_2 & s_3 c_1 \beta_3 & -s_4 c_1 \beta_4 & s_4 c_1 \beta_4 & -s_5 c_1 \beta_5 & s_6 c_1 \beta_6 \\ l(c_1 s_1 c_3) \beta_1 - l(c_1 s_1 c_2) \beta_2 & l(c_1 s_1 c_3) \beta_3 - l(c_1 s_1 c_2) \beta_4 & l(c_1 s_1 c_3) \beta_5 - l(c_1 s_1 c_2) \beta_4 & l(c_1 s_1 c_3) \beta_5 - l(c_1 s_1 c_2) \beta_4 & l(c_1 s_1 c_3) \beta_5 - l(c_1 s_1 c_2) \beta_4 & l(c_1 s_1 c_3) \beta_5 - l(c_1 s_1 c_2) \beta_4 \end{bmatrix} \]

(7)

\[ \alpha_1 \]

\[ \alpha_2 \]

\[ \alpha_3 \]

\[ \alpha_4 \]

\[ \alpha_5 \]

\[ \alpha_6 \]

\[ l \]

(3)

Then, the moment matrix \([T_X \ T_Y \ T_Z]^T\) can be expressed as:

\[ [T_X \ T_Y \ T_Z]^T = \begin{bmatrix} T_1 \\ T_2 \\ T_3 \end{bmatrix} \]

(9)

Thus, the vector (force and moment) of the HPSUR can be concluded as:

\[ \begin{bmatrix} s_1 c_1 \beta_1 \\ s_1 c_1 \beta_1 \\ s_1 c_1 \beta_1 \\ -s_3 c_1 \beta_3 \\ s_2 c_1 \beta_2 \\ s_2 c_1 \beta_2 \\ s_3 c_1 \beta_3 \\ -s_4 c_1 \beta_4 \\ c_2 c_1 \beta_2 \\ c_2 c_1 \beta_2 \\ c_2 c_1 \beta_2 \\ c_2 c_1 \beta_2 \\ s_4 c_1 \beta_4 \\ s_4 c_1 \beta_4 \\ c_2 c_1 \beta_5 \\ c_2 c_1 \beta_5 \\ c_2 c_1 \beta_5 \\ c_2 c_1 \beta_5 \\ s_6 c_1 \beta_6 \\ s_6 c_1 \beta_6 \\ s_6 c_1 \beta_6 \\ s_6 c_1 \beta_6 \\ l(c_1 s_1 c_2) \beta_1 - l(c_1 s_1 c_2) \beta_2 & l(c_1 s_1 c_2) \beta_3 - l(c_1 s_1 c_2) \beta_4 & l(c_1 s_1 c_2) \beta_5 - l(c_1 s_1 c_2) \beta_4 & l(c_1 s_1 c_2) \beta_5 - l(c_1 s_1 c_2) \beta_4 \end{bmatrix} \]

(10)

3. Multi-mode adaptive controller

This part describes the architecture of the proposed MMAS strategy and attitude estimation method. For underwater missions, the challenging topic is how to maintain the robot’s stability and execution safety. The main goal of the proposed MMAS strategy is to provide the optimal control mode according to different task requirements and ensure driving safety. In addition, for the underactuated AUVs, it is necessary to consider attitude adjustment in multi-mode switching.
3.1. Proposed MMAS strategy

The primary task of adaptive switching is to ensure moving and executing safety \([32-33]\). On this basis, the MMAS strategy for HPSUR is developed to meet different task requirements. Three control modes are considered, including water-jet mode with low-noise and low-velocity, propeller mode with high-flexibility, and hybrid mode with high-velocity. Fig. 5 depicts the sketch of the MMAS strategy for HPSUR to switch and smooth its locomotion.
When performing missions, the control mode can be switched as the task requirements, as demonstrated in Fig. 6, the control mode is switched n-1 times in total. The idea of mode switching in this paper is: Controlling the HPSUR drive a certain distance alone in a certain mode. For instance, driving from position \((x_0, y_0)\) to position \((x_f, y_f)\) in control mode \(T_{\text{mode}1}\). When HPSUR reaches position \((x_f, y_f)\), switching the control mode to \(T_{\text{mode}2}\). Then, using \(T_{\text{mode}2}\) as the control mode to reach position \((x_0, y_0)\).

Firstly, smooth transition between multi-modes is important compared to individual control modes. Thus, this paper transforms the individual control of each mode into overall control to avoid the above-mentioned problem. The comprehensive performance index of the MMAS strategy are as follows [19,34]:

\[
T = T_{\text{mode}1} + T_{\text{mode}2} + \cdots + T_{\text{mode}n}
\]

The continuous linkage is given as:

\[
\begin{align*}
S_{i, \text{ave}(n-1)} &= S_{i, \text{ave}(n)} \\
U_{i, \text{ave}(n-1)} &= U_{i, \text{ave}(n)}
\end{align*}
\]

where \(T_{\text{mode}} (i = 1, 2, \ldots n) \in \{T1, T2, T3\}\) represent the performance indexes corresponding to the above three control modes, which is converted individual control into an overall control with \(T\). \(T\) is affected by each performance index by changing the maximum allowable value.

Define \(U(t)\) as the control of switching process, which can be expressed as follows:

\[
U(t) = \begin{cases} 
U_1(t), t \leq t_1 \\
U_2(t), t_1 < t \leq t_2 \\
U_3(t), t > t_2
\end{cases}
\]

where \(U_i = [F^*, \psi]^T\) is the control signal of mode switching, which can be expressed as follows:

\[
U_i = \begin{bmatrix} F \\ \psi \end{bmatrix} = \left[ \sqrt{\left( f_1^*(t) \right)^2 + \left( f_2^*(t) \right)^2} \right] \frac{\arctan(f_2^*(t)/f_1^*(t))}{u}
\]

where \(f^*(i = 1, 2, \ldots 6)\) represents the force of hybrid thrusters generated in horizontal model \(f_1^*\) and vertical model \(f_2^*\), the detailed solving steps of thrusters in [31,35].

Secondly, to solve the jump problem of multi-mode switching, an activation function based on soft switching is proposed. Another activation method is hard switching, which is widely used in industrial control. Compared with hard switching, soft switching avoids that the AUV cannot sail smoothly due to the instantaneous jump of the control signal. In this paper, the steady-state outputs in the three modes are used as the upper and lower bounds of the sigmoid function. The mode switching process is reached before and after the switching time. Fig. 7 is the Sigmoid activation function for multi-mode switching.

Sigmoid is a nonlinear activation function with properties such as smoothness and saturation. The expression for multi-mode switching can be expressed as [36]:

\[
P(x, \epsilon, \lambda) = \frac{\Delta}{1 + e^{-(\epsilon + \lambda)}} + d
\]

where \(\epsilon\) is the tilt parameter, which controls its tilt, and \(\lambda\) and \(d\) are offset compensations on the \(x\) and \(y\) axes, respectively. Switching between the three modes can be denoted by \(\Delta\), satisfies: \(\Delta = u_1 - u_2\). In [36], the calculation method of the parameters \(\epsilon\) and \(\lambda\) has been described. Here, the parameter of \(\epsilon\) and \(\lambda\) in this paper are given as \(-1.2\) and \(380\), respectively.

Assume the water-jet mode is 1, the output is \(u_1\), the propeller mode is 2, the output is \(u_2\), and the hybrid mode is 3, the output is \(u_3\). When switching from mode 1 to mode 2, \(\Delta\) can be represented as \(\Delta = u_1 - u_2\), and the offset compensations on the \(y\) axes is \(d = u_3\). Before and after the mode switching time, mode 1 fades out and mode 2 fades in.

3.2. Optimization of thrust distribution

The thrust of the thruster is determined by the input voltage. In order to avoid the phenomenon of thrust saturation, the control voltages in the horizontal plane and vertical plane are normalized.

The desired control voltages in horizontal and vertical planes are given as:

\[
\begin{align*}
\delta_{h1} &= |u_{h1}|/u_{h1} \\
\delta_{h2} &= |u_{h2}|/u_{h2} \\
\delta_{h3} &= |u_{h3}|/u_{h3}
\end{align*}
\]

where \(u_{h1} = |u_{h1}| + |u_{h2}| + |u_{h3}|, u_{h2} = |u_{h2}| + |u_{h3}| + |u_{h4}|\) are the sum of the control voltage corresponding to the horizontal and vertical planes. \(\delta_{h1}, \delta_{h2}\) are the normalized longitudinal control voltage, lateral control voltage and yaw control voltage, respectively. \(\delta_{h1}, \delta_{h2}\) are the normalized desired vertical control voltage, roll control voltage and pitch control voltage, respectively.

Then amplify the normalized desired control voltage:

\[
\begin{align*}
x &= k_1 u_{h1} \delta_{h1} \\
y &= k_2 u_{h2} \delta_{h2} \\
N &= k_3 u_{h3} \delta_{h3}
\end{align*}
\]

where \(X, Y, N, Z, K\) and \(M\) are the desired longitudinal thrust, the desired lateral thrust and the desired yaw moment, respectively. \(k_1, k_2, k_3\) are the weight coefficients for longitudinal moment, lateral moment, and yaw moment, respectively.

According to the symmetrical characteristics of HPSUR thrusters and the principle of thrust synthesis, the horizontal plane thrust distribution (longitudinal thrust, lateral thrust, and yaw thrust) and vertical plane distribution (vertical thrust, roll thrust, and pitch thrust) can be deduced respectively, as follows:

\[
\begin{align*}
T_{xh1} &= X + Y + N, T_{xh2} = Z - K - M \\
T_{xh3} &= X + Y - N, T_{xh4} = Z - K + M \\
T_{yh1} &= -X - Y - N, T_{yh2} = Z - K - M \\
T_{yh3} &= -X - Y + N, T_{yh4} = Z - K + M \\
T_{zh1} &= -X - Y + N, T_{zh2} = Z - K + M \\
T_{zh3} &= -X + Y + N, T_{zh4} = Z + K + M
\end{align*}
\]

3.3. EKF-based attitude estimation

In order to solve the problem of unstable attitude output and large difference between the true value and measured value during multi-mode switching locomotion, this paper uses the Extended Kalman Filter (EKF) to optimize the HPSUR attitude measurement [29,37–39]. Common filtering techniques are mainly Kalman Filter (KF), Unscented Kalman Filter (UKF) and EKF. Compared with the KF, the state transition matrix and observation matrix of the EKF are Jacobian matrix of state information, which is more conducive to describing the state of underactuated underwater vehicles. Both EKF and UKF adopt the idea of
linearization, but UKF belongs to posterior linearization, which is not conducive to underwater real-time state estimation. Therefore, this section will use the EKF filtering technique to estimate the HPSUR attitude filtering problem.

The 3 \times 1 state vector of the HPSUR’s attitude angles can be expressed as:

\[ x = [\phi \ \theta \ \psi]^T \]  \hfill (19)

The process model and measurement model can be expressed as:

\[
\begin{align*}
\hat{x}(k) &= f(\hat{x}(k-1), k-1) + \xi(k-1) \\
z(k-1) &= H\hat{x}(k-1) + \eta(k-1) \\
\end{align*}
\]  \hfill (20)

where \( f(\cdot) \) represents the nonlinear state transition function from the previous state to the current state. \( \xi \) and \( \eta \) represent the process and measurement zero-mean Gaussian noise, respectively. \( z \) is a 3 \times 1 measurement vector derived from the equation. \( H \) is a 3 \times 3 measurement matrix.

The state vector \( x \) can be estimated, yields:

\[
\hat{x}(k) = \hat{x}(k-1) + K(k) \times (z(k) - H\hat{x}(k-1)) \\
\]  \hfill (21)

In the predictive model, the extrapolation value satisfies:

\[
\hat{x}(k-1) = f(\hat{x}(k-1), k-1) \\
\]  \hfill (22)

The gain \( K \) of the filter is a 3 \times 3 matrix, yields:

\[
K(k) = P(k/k-1)H^T S^{-1}(k) \\
\]  \hfill (23)

where \( S^{-1}(k) = [HP(k/k-1)H^T + R(k-1)]^{-1} \), \( R(\cdot) \) is the measurement noise covariance matrix.

The covariance matrix of error in predictive process can be expressed as,

\[
P(k/k-1) = \frac{\partial f(\hat{x}(k-1), k-1)}{\partial x(k-1)} \times P(k-1/k-1) \times \frac{\partial f(\hat{x}(k-1), k-1)}{\partial x(k-1)} + Q(k) \\
\]  \hfill (24)

where \( Q(\cdot) \) is the process noise covariance matrix.

Then, the covariance matrix of error in updated process can be expressed as,

\[
P(k/k) = (I - K(k)H(k))P(k/k-1) \\
\]  \hfill (25)

Noted that in the designed filter, the key parameters to achieve stability and logic of the system. It consists of four parts: Power Supply Unit (PSU), Decision-Making Unit (DMU), Sensor Unit (SU) and Driving Unit (DU). Among them, three rechargeable batteries are used to supply power for the SU, DMU and DU respectively. The external waterproof switch is used to turn on the internal power supply. To prevent the triggering of sudden surge current, the principle satisfied that the DU firstly and the DMU secondly. While moving underwater, the HPSUR receives FW signals form the controller to control the velocity of hybrid thrusters.

4.2. Locomotion experiments of the HPSUR

In [12], the relationship between the input voltage and the output thrust of thrusters is deduced using the experimental method. The measurement errors for positive rotation of the water-jet, propeller and hybrid modes are less than 2.7%, 3.6% and 5%, respectively, which lays a good foundation for MMAS strategy.

Before performing the multi-mode switching experiments, the locomotion experiment in the three modes is performed to verify the performance of hybrid thrusters. Fig. 10 shows the locomotion experiment in the hybrid mode. The starting position of the SUR in each mode is the same. Fig. 11 shows the trends in velocity and distance over time. It can be seen that the average velocity of the HPSUR is calculated about 0.12 m/s, 0.16 m/s and 0.23 m/s, respectively. HPSUR can reach the high-velocity quickly using hybrid mode at the beginning 2 s.

4.3. Multi-mode switching experiments

After testing each control mode, multi-mode switching experiments under 3-D waypoints are conducted, including the straight-line waypoints switching (Scenario 1) and the triangle waypoints switching (Scenario 2).

(1) Scenario 1: 3-D straight-line waypoints switching control

In this experiments, adaptive multi-mode switching is realized via 3-D waypoints tracking. The HPSUR started from the defined initial
position A (0 cm, 0 cm, −17 cm) shown in Fig. 12 (a), and then moved to three given positions B (100 cm, 60 cm, −20 cm), C (200 cm, 120 cm, −25 cm) and D (300 cm, 180 cm, −20 cm) in turn, respectively. We defined that when the distance to each target waypoint is less than 15 cm, the robot started mode switching control. The HPSUR began to move from quadrant waypoint A to quadrant waypoint B, as shown in Fig. 12 (b). Then, in the quadrant waypoint B to C, the HPSUR switched to propeller propulsion mode, as shown in Fig. 12 (d). Next, the HPSUR switched to hybrid propulsion mode until move to the target position D (50 cm, 50 cm, −20 cm) using the hybrid mode, as shown in Fig. 15 (f). The robot started to switch next locomotion mode with a yaw angle of 90 deg and 45 deg in turn, respectively. Fig. 16 showed the 3-D trajectory tracking result of the HPSUR in triangle waypoint experiments. It can be seen that the HPSUR can safely and quickly conduct the multi-mode switching and reach the target position smoothly.

In addition, from the curve of Scenario 2 in Fig. 14, it can be seen that the pitch angle and roll angle change in a similar range compared to Scenario 1. The yaw angle varies greatly, especially when turning, but the attitude angle can be estimated in time. After calculation, the maximum deviations of the pitch and roll angles are 2.4 deg and 3.3 deg, respectively. The maximum deviation of the yaw angle is about 4.3 deg.

(2) Scenario 2: 3-D triangle waypoints switching control

Next, the triangle waypoints switching experiment is carried out in Fig. 15. The HPSUR started from the defined initial position A (50 cm, 50 cm, −17 cm), and moved to the position B (150 cm, 50 cm, −20 cm), which used the water-jet mode in this quadrant point, as shown in Fig. 15 (b). Next, the HPSUR switched to the propeller mode, and moved to the position C (150 cm, 150 cm, −25 cm), as shown in Fig. 15 (d). Then, the HPSUR moved to waypoint D (50 cm, 50 cm, −20 cm) using the hybrid mode, as shown in Fig. 15 (f). The robot started to switch next locomotion mode with a yaw angle of 90 deg and 45 deg in turn, respectively. Fig. 16 showed the 3-D trajectory tracking result of the HPSUR in triangle waypoint experiments. It can be seen that the HPSUR can safely and quickly conduct the multi-mode switching and reach the target position smoothly.

5. Discussion

In order to further verify the effectiveness and practicality of the proposed MMAS strategy, the experimental results are evaluated, including time, velocity and errors. Then, the proposed MMAS strategy is compared with other strategies, which validate the performance of the MMAS strategy from the overall performance.

5.1. Time and velocity change in switching experiments

In each locomotion mode measurement experiment, see Fig. 10, the HPSUR can reach the maximum velocity in about 2.8 s, which is 32.6% stronger than the propeller mode and 47.8% stronger than the water-jet mode. After adopting the hybrid mode, the total thrust is optimized, and the energy loss is reduced. The deflection angle error of the hybrid mode under the acceleration state is reduced by 3° − 8°.

Next, the velocity change during multi-mode switching experiments is analyzed to verify the smooth transition of velocity, as shown in Fig. 17. It can be seen that the velocities in Scenarios 1 and 2 is...
significantly improved. When the mode is switched, the velocity changes smoothly and there is a transition period. The velocity fluctuation errors in Scenarios 1 and 2 are less than 7.1% and 6.8%, respectively.

HPSUR saves operating time after using the MMAS strategy. In Scenarios 1 and 2, we also measured the time of individual thrusters as shown in Fig. 18. It can be concluded that if the water-jet mode is used, the time required in Scenarios 1 and 2 are about 30 s and 29.5 s, respectively. If using propeller mode, the total time is about 24 s and 25 s, respectively. Compared with the individual thruster mode, the optimization times of the hybrid mode are about 7 s and 1 s in Scenario 1, about 7.5 s and 3 s in Scenario 2, respectively. Furthermore, if the experiment is carried out outdoors, the performance will be more pronounced with a longer range.

5.2. Comparative experiments in presence of disturbances

In the switching experiment, a part of external disturbance was added by changing the position of the quadrant points on the z-axis. In this paper, the maximum change distance in z-axis between adjacent quadrant points was 5 cm. To further verify the performance of the MMAS strategy in the presence of external disturbances, we added external disturbances at a specific quadrant point B, which is realized by controlling the water wave changes through an external propeller. In Scenario 2, the transition from the water-jet mode to the propeller mode and the transition from the hybrid mode to the propeller mode are performed, as shown in Fig. 19.

Fig. 20 shows the comparative experimental results of HPSUR under different mode switching when the external disturbance is added at quadrant point B. When the mode switching is completed, about 1.5 s, the tracking trajectory of HPSUR becomes smooth. Furthermore, it can be seen from Fig. 21 that there will be a certain fluctuation in velocity with ±0.05 m/s, especially before and after mode switching, from 9 s to 11 s, and 6 s to 8 s. The total time required for switching from the water-jet mode to the propeller mode is about 17 s. Compared with switching from the water-jet mode to the propeller mode, the total time required to switch the hybrid mode to the propeller mode is about 12 s. It can be seen from the multi-mode switching that the time is optimized for about 5 s, which further verifies the practical value of proposed MMAS strategy.

5.3. Compared with other strategies

In this part, the attitude angle measurement error of the KF and EKF is calculated, as shown in Fig. 22. The maximum error RMSE does not exceed 0.27 deg. The estimated errors of the pitch angle, roll angle and yaw angle measured by the KF are 0.052, 0.078, and 0.266, respectively. The estimated errors of the pitch angle, roll angle and yaw angle measured by the EKF are 0.045, 0.063, and 0.125, respectively. Compared with KF, the accuracy of attitude angles is improved by 13.5%, 19.2%, 53%, respectively. In [39], the authors introduced the attitude estimation error measurement based on autonomous navigation system, the proposed VBAKF method was compared with the KF method, the accuracy of the estimation errors of pitch, roll and heading angle were improved by 1.5%, 62.4% and 49.8%, respectively. In contrast, the accuracy of pitch and yaw angles are improved by 12% and
3.2%, respectively. The difference in the accuracy of the roll angle is mainly caused by the measurement environment and the robot’s motion characteristics. The turning of the HPSUR is mainly controlled by changing the yaw angle. Its performance is also evident from Fig. 22.

Furthermore, based on multi-mode switching strategy, it is mainly used in human-automatic shared control system [19–20], multi-thruster design of underwater robot [8,13–15], multi-mode switching system.
However, the research on multi-mode switching systems is relatively scarce, especially its application for AUVs. In [13], the authors designed a hybrid thruster for SUR, analyzed and measured its dynamic performance, but lacked the design of the controller. The velocity of the HPSUR using hybrid thruster is 15% higher than that of the SUR. In [36], the authors proposed a multi-mode switching for AUV’s heading. The authors carried out simulation and real environment experiments using AUV, and divided the control mode through the two-level mode method. The proposed method has certain value for underwater applications, but it still lacks the consideration of multiple DoF. In [40], the authors proposed an adaptive controller for DUV in order to tackle dual-modal switching and observe the target ocean continuously. External environmental disturbances, model uncertainties and dynamic models are considered. The deep-sea experiment was conducted using the self-adaptive controller, which lays a good foundation for the future underwater application of the multi-mode switching system. Despite the promising results obtained in this paper, attention remains to be paid to experiments and applications in complex waters. Secondly, the controller can also consider other modes and test in different complex waters to determine the mode switching level. This will make our future major work.

6. Conclusions

Considering efficiency, traveling safety and environmental adaptability of underwater tasks, we proposed a MMAS strategy for the HPSUR. This paper discussed the kinematic and dynamic models, analyzed the force and moment of the HPSUR. In the control system, three control modes were proposed (i.e., water-jet mode, propeller mode and hybrid mode). To make multi-mode switching smoothly, thrust distribution, smooth transitions and triggering, and attitude adjustment were optimized. Besides, locomotion and multi-mode switching experiments were performed to verify the performance of the proposed MMAS strategy. We evaluated the performance of the hybrid thruster in each mode by the locomotion experiment. Moreover, the 3-D straight-line and triangle waypoints switching control were performed. The time, velocity error and angle were used to analyze the stability and smoothness of the proposed MMAS strategy. Finally, we analyzed the proposed MMAS strategy by comparing experiments such as adding external disturbance, compared with other strategies to validate the effectiveness and practicability of the proposed strategy.

The study clearly proved that multi-mode switching can significantly reduce execution time and can autonomously adapt different control commands. The research results can provide valuable references and technical support for multi-mode switching control.

CRediT authorship contribution statement

Chunying Li: Conceptualization, Methodology, Software, Investigation, Funding acquisition, Writing - original draft. Shuxiang Guo: Supervision, Writing – review & editing, Resources, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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Fig. 22. The measurement error of the KF and EKF.


