

Design and Control Strategy for a Solar-Powered Autonomous Underwater Vehicle with an Unconventional Shape

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ABSTRACT

Solar-powered autonomous underwater vehicles (SAUVs) can harness sustainable natural energy, meaning that they are capable of providing long-term mission support. This paper describes ongoing development work on the overall design of a SAUV. It outlines the design goals for the vehicle, with a particular focus on the unconventional shape resulting from the integration of solar panels within the body of the SAUV. It is equipped with an array of commonly used sensors as its perception system, thus ensuring comprehensive environmental awareness. Due to its unique negative lift shape and its reliance on a single vector thruster for propulsion, the difficulty of motion control of this SAUV is significantly increased. In response to this aspect, and based on practical considerations, this paper proposes a control strategy that divides the vector thrust into three major control forces: thrust () for regulating speed; thrust () for changing the heading, and thrust () for controlling depth. To address the varying levels of difficulty presented by speed control, heading control, and depth control, differentiated control methods are designed based on Proportional-Integral-Derivative (PID) and active disturbance rejection control (ADRC) algorithms, respectively. Through a series of experiments in a water tank, the validity and applicability of the proposed algorithms are verified for practical applications.

Keywords: autonomous underwater vehicles; solar-powered; vectored thruster; robotics operating system; active disturbance rejection control

INTRODUCTION

The issue of comprehending current oceanic conditions is of great importance in in order to cope with global environmental problems such as food and energy crises, insufficient ecology protection, and global climate change [1]. Unmanned underwater robots have the ability to carry various sensors to perform underwater tasks in inaccessible environments for humans [2].

Unmanned underwater robots are typically classified into two groups: remotely operated vehicles (ROVs) and autonomous underwater vehicles (AUVs) [3]. The task

efficiency and the operation range of an ROV are limited by its infrastructure and hardware, whereas AUVs can perform a wider range of underwater surveys since they are cable-free. The continuous developments in the areas of underwater communication, artificial intelligence, multi-sensor fusion, and control science and technology have considerably increased the autonomy of AUVs, although this has also made the design of their systems more complex and the manufacturing costs higher.

The configuration and shape of an AUV is determined by the payload and task requirements [4], and its range and endurance are determined by the power it carries. Novel

vehicles such as solar-powered AUVs (SAUVs) can use sustainable natural energy, which allows them to perform ocean survey missions that last for weeks or months [5]. In general, in order to harness sufficient solar energy, an SAUV requires the installation of solar panels with a sufficiently large area, which unfortunately has an adverse impact on its originally optimised hydrodynamic shape [6]. As a result, the adoption of vector thrust propulsion has emerged as one solution, as this enables simultaneous control over both the AUV's propulsion and attitude adjustment [7]. However, this approach introduces coupling issues between the thrust used for propulsion and that used for attitude adjustment, giving rise to a need for high-precision control systems to ensure precise control over the thrust force and direction. This adds to the complexity and operational challenges associated with AUV motion control.

In terms of control strategies, PID control is a commonly used method for AUVs; however, as the AUV's shape becomes more complex, its hydrodynamic characteristics become more uncertain, and under external disturbances, the performance of PID can degrade. Consequently, when designing and implementing control strategies, it is imperative to thoroughly consider the impact of shape variations on the hydrodynamic characteristics and control performance of an AUV [8]. The active disturbance rejection control (ADRC) method can compensate for the uncertainties in hydrodynamic characteristics and unknown external disturbances during the control process of AUVs [9]. As an innovation in the field of PID control algorithms, ADRC was first proposed by Han in 1998. Inspired by the profound research achievements in this field, PID and ADRC are combined in this study to control the speed, heading, and depth of AUVs.

This article describes ongoing development work on the overall design of an SAUV. The main purpose of this research is not only to construct a fully autonomous underwater vehicle that can be manufactured relatively inexpensively, but also to develop an intelligent unmanned platform that can achieve a variety of specified missions in key areas and operate continuously for long periods of time. The rest of this paper is structured as follows. Section 2 presents an overview of the SAUV and its design goals. In Section 3, we describe the vector technology developed for this SAUV. The strategy used by the sensors in the SAUV is presented in detail in Section 4. Section 5 introduces the design of the speed, heading, and depth controllers for the SAUV, based on the PID and ADRC algorithms. Experiments conducted in a water tank are also presented to verify the applicability of these algorithms.

DESCRIPTION OF THE PROPOSED SAUV

The SAUV described in this research is significantly less expensive than those developed by other research institutions and commercial organisations, and the energy system of the vehicle can be recharged using a solar panel, thus confirming the possibility of using solar power for an SAUV. The overarching goals of this system design are to develop

a reliable platform for mobile communication nodes on the water and below the surface, and to produce an SAUV that is capable of performing long-term detection and monitoring along coasts or at ports.

The latter tasks are typically carried out in surface waters or shallow water areas, meaning that the selection of an appropriate solar panel is essential. The efficiency of solar panels of different brands varies with depth, and as the depth increases, the efficiency of the panels decreases significantly. However, at the water surface, the maximum charging power of the solar panel selected for this study can exceed 160 W in practical use conditions. AUVs without additional energy sources have limited operational ranges and require frequent redeployment, leading to higher operational costs. Although the SAUV described in this study does not have a high efficiency of energy replenishment under low light conditions, it does have an energy replenishment channel. Through reasonable planning, it can be arranged that the SAUV performs tasks under low lighting conditions, as far as possible, and recharges under high lighting conditions. When energy is insufficient, it can stay afloat on the sea surface to wait for favourable lighting conditions. Compared to traditional AUVs, the proposed SAUV can perform long-distance and long-duration missions, thus reducing both the operational and labour costs. The hull dimensions and appearance of the SAUV are determined by these missions. The key performance specifications for the SAUV are given in Table 1 below.

Tab.1 Specifications of the SAUV

Parameter	Specifications
Weight	210 kg
Dimension	2391 × 830 × 519 mm
Max. depth	300 m
Max. speed	1 m/s
Solar panel	Singfosolor SEM-230 (230 W)
Electricity storage	18650 lithium batteries
Thrusters	Designed by our team
Sensors	INS, GPS, sonar, DVL, USBL, CTD
Control	3 DOF (surge, pitch, yaw)
Computer	Raspberry Pi

The most striking features of the SAUV are the use of vectored thrust, negative lift, and solar energy. Figs. 1 and 2 show the SAUV in its concept form and the actual prototype. The physical configuration of the SAUV is different from conventional torpedo-style and open-frame AUVs.

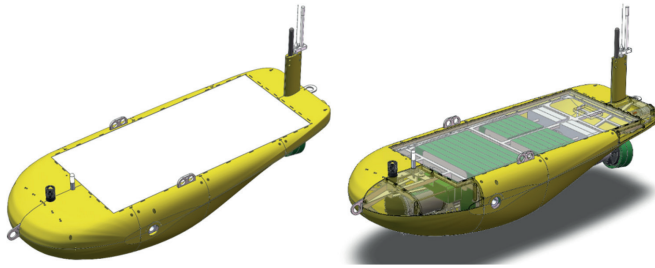


Fig. 1 3D drawing of the proposed SAUV

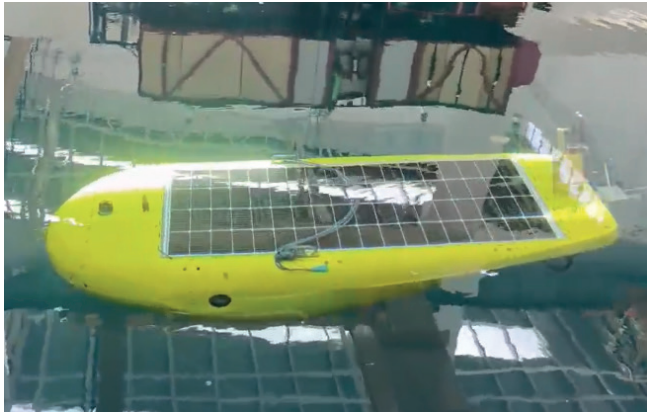


Fig. 2 Photograph of the actual SAUV

The requirements for a certain level of long endurance for an AUV can be accomplished through various means, such as increasing the energy capacity, improving the energy efficiency, or reducing the power consumption. Increasing the energy capacity of an AUV necessitates altering its size to give sufficient internal space for energy sources and related equipment, which may introduce other issues such as increasing its total mass and potentially altering its original hydrodynamic characteristics. In addition, this modification will have uncertain impacts on the AUV's propulsion performance and manoeuvrability.

Hence, improved energy efficiency and reduced power consumption are the primary factors to consider when aiming to achieve the important technical indicator of high endurance or long-range navigation for an AUV. The shape is one of the most effective parameters for reducing navigation resistance, enhancing stability, and lowering energy consumption during a mission. Designing a reasonably hydrodynamic shape and optimisation are indispensable steps for improving the energy efficiency or reducing power consumption.

In general, a streamlined, torpedo-style AUV has better endurance, whereas a well-actuated open-frame-style AUV has better manoeuvrability. The SAUV design presented in this paper represents a compromise between manoeuvrability and endurance. Since the batteries of the SAUV need to be recharged using a solar panel, to increase efficiency and decrease operating costs, the upper surface of the SAUV

needed to offer a sufficient area for the solar panel, which resulted in an unconventional vehicle shape.

From the side view in Fig. 3, it can be seen that the overall outline of the hull of the SAUV is shaped like an aircraft wing. The LA2573A airfoil profile was selected as the geometric shape for the vertical cross-section of the SAUV, as this generates a negative lift effect during the operation of the SAUV. The positive buoyancy can be counteracted by the negative lift or hydrodynamic downforce produced during operation of the SAUV. The hull provides the negative lift, which plays an important role in improving the flexibility and agility of the vehicle. In addition, to avoid equipment loss in the case of an emergency, the SAUV has positive buoyancy to allow it to float to the sea surface. This positive buoyancy is overcome through the use of the lifting surfaces of the hull of the AUV to generate a negative lift (or hydrodynamic downforce) during movement.

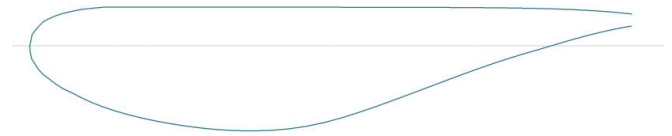


Fig. 3 Side view of the SAUV

VECTORIAL THRUSTER OF THE SAUV

A vectorial thruster is used in the proposed SAUV to overcome the limitations of the traditional type of propulsion, in which an AUV is controlled by a single thruster and rudders. The vectorial thruster controls the 3-DOF motion of the SAUV, namely pitch, yaw, and forward motion. According to the design objectives for the vehicle, the vectorial thruster must have power drive, attitude realisation, and posture holding capabilities. The vectorial thruster designed in this work consists of two steering engines and a propulsion unit, as shown in Fig. 4.

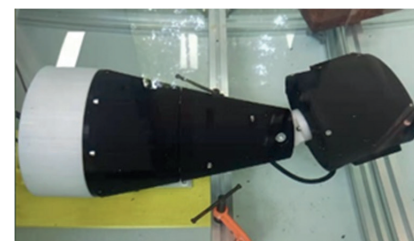
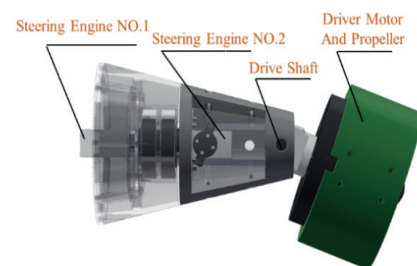


Fig. 4 Vectorial thruster designed in this work

The vectorial thruster is mounted below and on the right of the SAUV, to produce 130 N of thrust. The space posture of the vectorial thruster is adjusted and maintained by steering engines No. 1 and No. 2. One steering engine enables a yaw movement of the thruster, while the other enables rotational movement. By working together, these engines allow the thruster to achieve a wide range of spatial postures.

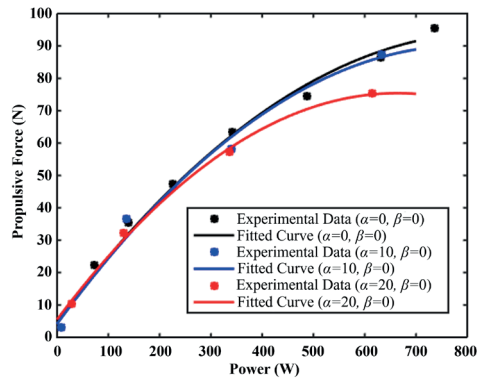


Fig. 5 Thrust performance of the vectorial thruster

To evaluate the propulsion performance of the thruster and to improve the precision of control, a series of open water experiments was conducted in a water tank, giving the thrust performance curve shown in Fig. 5. The controllable vectorial thrust is generated by the vectorial thruster, an approach that achieves more propulsion than a traditional propeller. The vectorial thruster also greatly simplifies the complexity of the propulsion system.

SENSORS AND SOFTWARE ARCHITECTURE OF THE SAUV

SENSORS

The perception system consists of multiple sensors, which are permanently mounted on the AUV and used to collect scientific data. Fig. 6 shows the sensors used in this platform and their locations.

The GNW (SurPass-A500C) and WIT(WT901C485) are the basic inertial navigation system (INS) sensors used for navigation and manoeuvring. The first of these sensors was developed by the GLONAVIN corporation for an unmanned aerial vehicle, and contains angular rate gyros, accelerometers, and global positioning system (GPS). WIT is an attitude sensor produced by Shenzhen Wit Intelligent Technology Co., Ltd. It contains angular rate gyros, accelerometers, and magnetometers. The pressure sensor is a piezoelectric sensor that can be used to measure depths of up to 300 m. To obtain the exact position of the SAUV in the sea, an ultra-short baseline (USBL) positioning system is mounted at the top of the vehicle. The temperature, depth, and conductivity are measured and recorded by conductivity, temperature, and depth (CTD) sensor. Sonar is typically used for obstacle avoidance, but in this study, it is employed to monitor the distance between the SAUV and the seabed. A doppler velocity log (DVL) sensor is mounted on the outside of the pressure hull under wet conditions, and measures the velocity in three directions.

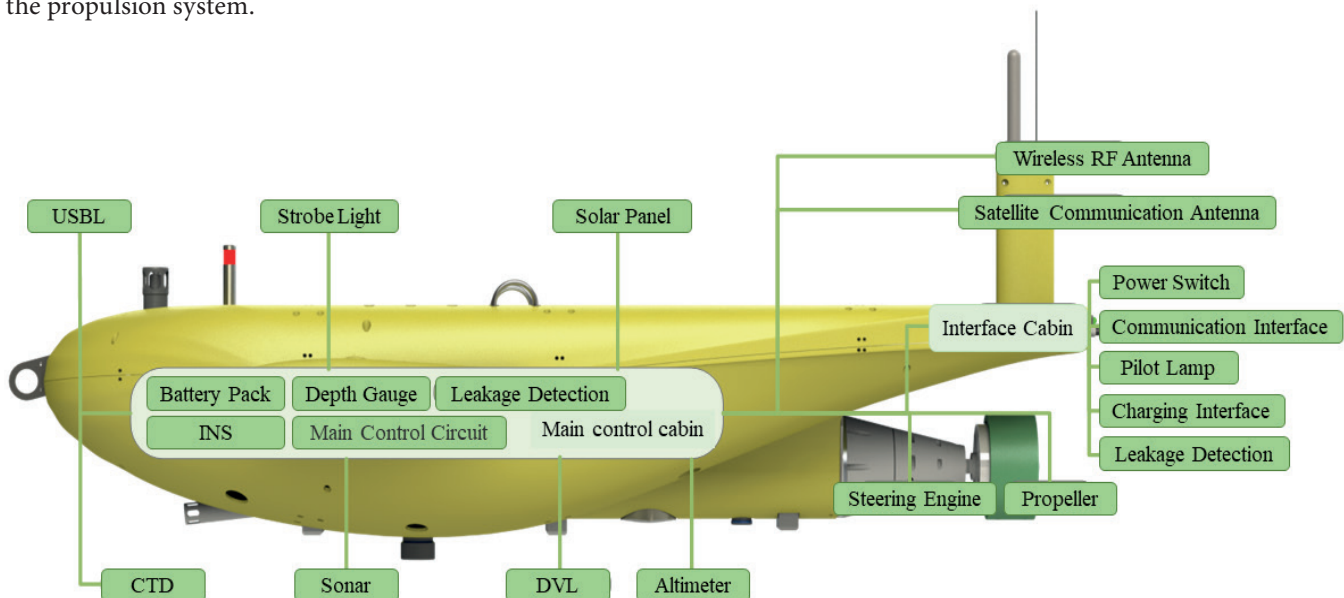


Fig. 6 Types and locations of sensors

SOFTWARE ARCHITECTURE

Autonomous operation of the SAUV, including communication, navigation, state inspection, and motion control, is achieved by using an open-source robotics platform called Robotics Operating System (ROS), which provides the software for the vehicle with the underlying functionality. Fig. 7 illustrates the software structure of the SAUV, which can be divided into five nodes (or parts), as follows: (1) system state monitoring node; (2) obstacle avoidance and navigation nodes; (3) motion control node; (4) wireless and satellite communication nodes; (5) sensor nodes.

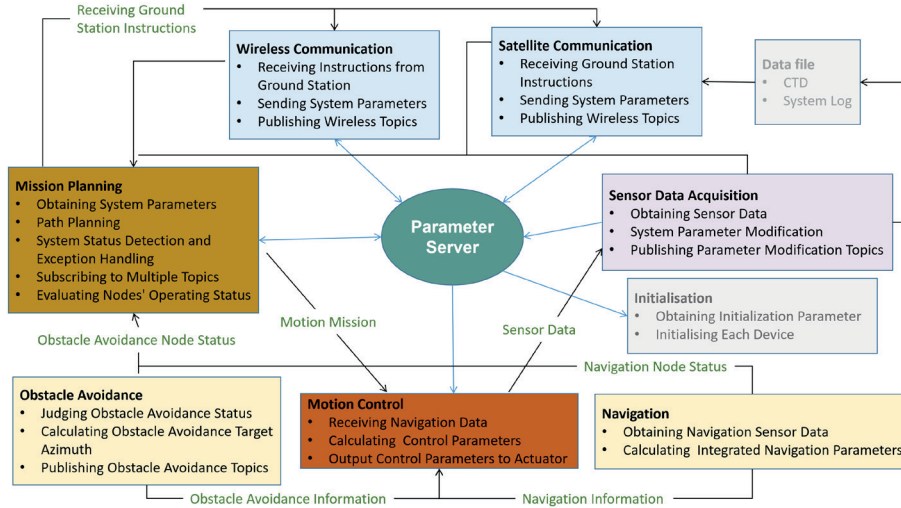


Fig. 7 Logical architecture diagram of the software system for the SAUV

RESULTS AND DISCUSSION

DESCRIPTION OF THE VECTORED-THRUSTER-BASED SAUV MODEL

This section presents a motion control system for an SAUV propelled by a vectorial thruster using a PID-ADRC controller. Before the application of the controller, it is necessary to establish a mathematical model of the SAUV to improve the performance of the controller.

Fig. 8 shows three reference frames that were designed as a basis for the 6-DOF differential equations of the motion of the SAUV. The first is the North-East-Down (NED) frame, which defines the positions and attitudes of the SAUV $[x, y, z, \phi, \theta, \psi]$. The second is the body frame, which defines the velocity of the SAUV $[u, v, w, p, q, r]$. The origin of the body frame coincides with the centre of gravity of the SAUV. The third reference frame is the thruster frame, which defines the thrust force and the relative tilt angles of the thruster and SAUV $[T, \alpha, \beta]$.

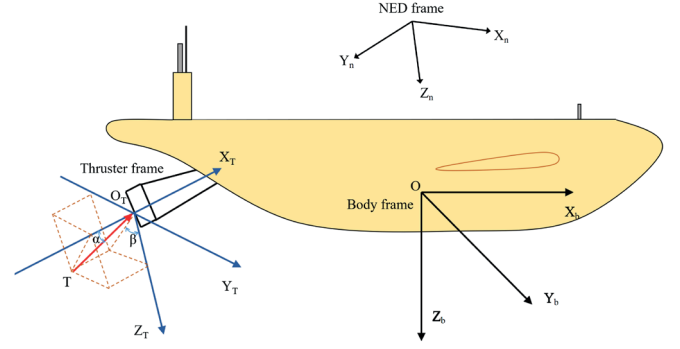


Fig. 8 Reference frames for the SAUV

The red arrow in Fig. 8 indicates the thrust T provided by the vectored thruster, which can be rotated by adjusting α and β . The components of the forces and moments acting on the SAUV can be expressed as follows:

$$\tau = \begin{bmatrix} F_x \\ F_y \\ F_z \\ M_x \\ M_y \\ M_z \end{bmatrix} = \begin{bmatrix} T \cos \alpha \\ T \sin \alpha \sin \beta \\ T \sin \alpha \cos \beta \\ 0 \\ F_z \times r_x \\ -F_y \times r_x \end{bmatrix} \quad (1)$$

where r_x, r_y, r_z denote the distance from the centre of gravity of the SAUV to the centre of the thruster-vectoring mechanism. After simplification, the dynamic model of the AUV is described by the following six equations.

1. Surge motion

$$\left(m - \frac{1}{2} \rho l^3 X'_u\right) \dot{u} + m z_g \dot{q} = m x_g q^2 + \frac{1}{2} \rho l^2 X'_{uu} u^2 - (W - B) \sin(\theta) + F_x \quad (2)$$

2. Sway motion

$$\begin{aligned} \left(m - \frac{1}{2} \rho l^3 Y'_v\right) \dot{v} \\ = m y_g r^2 + \left(-m + \frac{1}{2} \rho l^3 Y'_r\right) u r + \frac{1}{2} \rho l^2 (Y'_v u^2 + Y'_v u v + Y'_v v |v|) \\ + (W - B) \cos(\theta) \sin(\phi) + F_y \end{aligned} \quad (3)$$

3. Heave motion

$$\begin{aligned} \left(m - \frac{\rho}{2} l^3 Z'_w\right) \dot{w} \\ = \left(m + \frac{1}{2} \rho l^3 Z'_q\right) u q + m z_g q^2 + \frac{1}{2} \rho l^2 (Z'_w u^2 + Z'_w u w) \\ + (W - B) \cos(\theta) \cos(\phi) + F_z \end{aligned} \quad (4)$$

4. Roll motion

$$\begin{aligned} & -(\dot{r})I_{xz} + (r^2)I_{yz} + m[-z_g(\dot{v} + ur)] \\ & = \frac{1}{2}\rho l^5(K'_r \dot{r}) \\ & + (y_g W - y_b B) \cos(\theta) \cos(\phi) - (z_g W - z_b B) \cos(\theta) \sin(\phi) \end{aligned} \quad (5)$$

5. Pitch motion

$$\begin{aligned} & (I_y - \frac{\rho}{2} l^5 M'_q) \dot{q} \\ & = (-mx_g + \frac{1}{2}\rho l^4 M'_q) uq - mz_g wq + \frac{1}{2}\rho l^3 (M'_u u^2 + M'_w uw) \\ & - (z_g W - z_b B) \sin(\theta) - (x_g W - x_b B) \cos(\theta) \cos(\phi) + M_y \end{aligned} \quad (6)$$

6. Yaw motion

$$\begin{aligned} & (I_z - \frac{1}{2}\rho l^5 N'_r) \dot{r} \\ & = (-mx_g + \frac{1}{2}\rho l^4 N'_r) ur - my_g vr + \frac{1}{2}\rho l^3 (N'_u u^2 + N'_v uv + N'_v |v| |v|) \\ & + (x_g W - x_b B) \cos(\theta) \sin(\phi) + (y_g W - y_b B) \sin(\theta) + M_z \end{aligned} \quad (7)$$

The 6-DOF kinematic model of the AUV is described by the following equations:

$$\begin{aligned} \dot{x} &= u \cos \psi \cos \theta + v[\cos \psi \sin \theta \sin \phi - \sin \psi \cos \phi] \\ & + w[\sin \psi \sin \phi + \cos \psi \cos \phi \sin \theta] \\ \dot{y} &= u \sin \psi \cos \theta + v[\cos \psi \cos \phi + \sin \phi \sin \theta \sin \psi] \\ & + w[\sin \theta \sin \psi \cos \phi - \cos \psi \sin \phi] \\ \dot{z} &= -u \sin \theta + v \cos \theta \sin \phi + w \cos \theta \cos \phi \\ \dot{\phi} &= p + q \sin \phi \tan \theta + r \cos \phi \tan \theta \\ \dot{\theta} &= q \cos \phi - r \sin \phi \\ \dot{\psi} &= q \frac{\sin \phi}{\cos \theta} + r \frac{\cos \phi}{\cos \theta}, \theta \neq \pm 90^\circ \end{aligned} \quad (8)$$

CONTROLLER DESIGN BASED ON PID AND ADRC

In the previous section, the motion model and control method of the SAUV were presented. Based on these equations, we designed speed, heading, and depth controllers for the SAUV, according to the characteristics of the vector thruster, and these are presented in this section. More specifically, as shown in Eq. (1), the speed of the SAUV can be effectively controlled by directly adjusting the force components $F_x = T \cos \alpha$ of the vector thruster. The speed control of SAUV is relatively simple: the adoption of a PID controller as the speed control strategy ensures the precision and stability of speed control, as shown in Fig. 9. The three parameters of a PID are $K_p = 1.3$, $K_i = 0.15$ and $K_d = 3$.

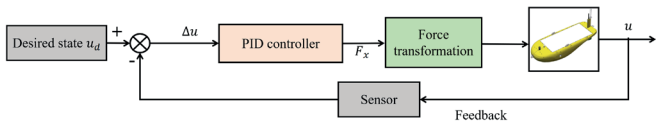


Fig. 9 PID controller scheme for the speed u

The heading of the SAUV is controlled by the moment $M_z = -T \cdot \sin \alpha \cdot \cos \beta \cdot r_x$, which is related not only to the thrust T but also to the attitude angles α and β of the vector thruster. Similarly, m_0 is dependent on T , α and β . As indicated by Eq. (1), there is a coupling between the control inputs F_x , M_y and M_z of the AUV. As can be seen from the expression for yaw motion in Eq. (6), when other kinematic variables such as u , v , r , etc., change, coupled hydrodynamic forces are generated. Compared to speed control, the heading control for the AUV involves more uncertainties. In view of this, ADRC is selected as the heading controller, and the control scheme is shown in Fig. 10 below.

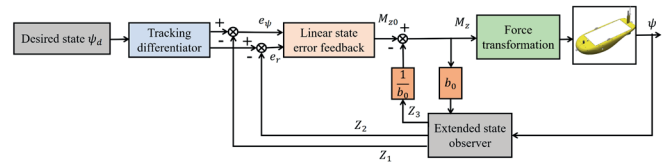


Fig. 10 ADRC controller scheme for yaw motion

The depth of the SAUV is controlled through the moment $M_y = -T \cdot \sin \alpha \cdot \sin \beta \cdot r_x$, which also has a coupling relationship with F_x and M_z . In addition, due to the SAUV's negative lift shape, an increase in its velocity u generates a significant coupled pitch moment in the direction of pitch motion. When the other kinematic variables change, an even greater coupled hydrodynamic force emerges in the pitch direction, making it relatively challenging to control. As a result, a dual-loop control method is employed for the depth controller. The inner loop, also known as the angle loop, utilizes an ADRC controller to regulate the SAUV's pitch angle, while the outer loop employs a PID controller to control the SAUV's depth by converting the desired depth into a target tracking pitch angle. The control methodology is illustrated in Fig. 11 below.

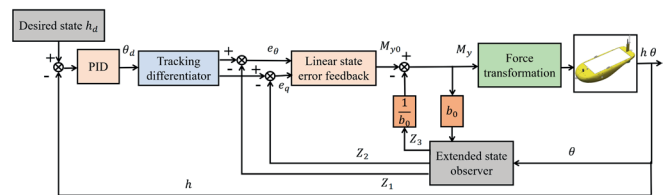


Fig. 11 PID-ADRC controller scheme for depth

The speed, heading, and depth controllers of the SAUV output the thrust F_x , moment M_z , and moment M_y , respectively. These need to be converted into control inputs T , α and β for the vector thruster. The moments M_z and M_y are first converted into the thrusts F_y and F_z using Eqs. (9) and (10):

$$F_y = \frac{M_y}{r_x} \quad (9)$$

$$F_z = -\frac{M_z}{r_x} \quad (10)$$

The thrusts F_x , F_y , and F_z are then converted into the control inputs T , α and β for the vector thruster, as shown in Eq. (11) below. The control logic of the SAUV is illustrated in Fig. 12.

$$\begin{bmatrix} T \\ \alpha \\ \beta \end{bmatrix} = \begin{bmatrix} F_x^2 + F_y^2 + F_z^2 \\ \arctan((F_y^2 + F_z^2)^{1/2}/F_x) \\ \arctan(F_y/F_z) \end{bmatrix} \quad (11)$$

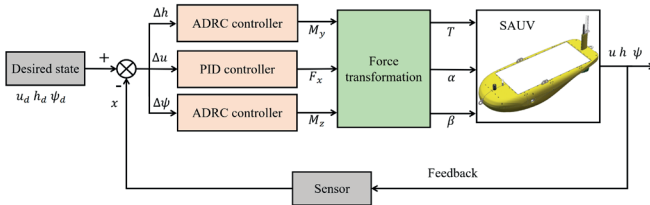


Fig. 12 Schematic diagram of the motion control scheme for the SAUV

The ADRC controller consists of three main parts: the tracking differentiator, the extended state observer, and the linear error state feedback. The use of a tracking differentiator is a widely used technique in control theory and signal processing, primarily for estimating the derivative of an input signal and tracking the input signal itself, even in the presence of noise. The discrete form of the tracking differentiator is expressed as shown in Eq. (12):

$$\begin{aligned} fh &= fhan(v_1(k) - v_2(k), v_2(k), r, h) \\ v_1(k+1) &= v_1(k) + hv_2(k) \\ v_2(k+1) &= v_2(k) + hfh \end{aligned} \quad (12)$$

In the equation above, $fhan()$ is defined as:

$$\begin{aligned} fhan(x_1, x_2, r_0, h) &= - \begin{cases} r_0 \text{sign}(a), |a| > d \\ r_0 \frac{a}{d}, |a| \leq d \end{cases} \\ d &= r_0 h \\ d_0 &= h d \\ y &= x_1 + h x_2 \\ a_0 &= \sqrt{d^2 + 8r|y|} \\ a &= \begin{cases} x_2 + \frac{a_0 - d}{2} \text{sign}(y), |y| > d_0 \\ x_2 + \frac{y}{h}, |y| \leq d_0 \end{cases} \end{aligned} \quad (13)$$

It can be seen from Eq. (13) that the dynamic tracking performance of the tracking differentiator is related to the parameter r_0 .

The larger the value of the parameter r , the faster the tracking speed of the input signal. The most crucial part of

the ADRC controller is the extended state observer, a discrete expression for which is given in Eq. (14) below. The extended state observer can provide estimates of the state variables (z_1 and z_2) for the controlled object, as well as estimates of unknown disturbances and uncertainties in the system (z_3). In this context, the uncertainties of the system can be regarded as modeling errors of the SAUV, while the unknown disturbances can be seen as environmental interferences.

$$\begin{aligned} z_1(k+1) &= z_1(k) + h(z_2 - \beta_{01}e) \\ z_2(k+1) &= z_2(k) + h(z_3 - \beta_{02}fe + b_0\tau_s) \\ z_3(k+1) &= z_3(k) + h(-\beta_{03}fe1) \\ e &= z_1 - y \\ fe &= fal(e, 0.5, \delta) \\ fe1 &= fal(e, 0.25, \delta) \\ fal(e, \alpha, \delta) &= \begin{cases} \frac{e}{\delta^{1-\alpha}}, |e| \leq \delta \\ |e|^\alpha \text{sign}(e), |e| > \delta \end{cases} \end{aligned} \quad (14)$$

In this paper, controllers for the pitch and yaw motions of the SAUV are designed based on ADRC. To facilitate the ADRC-based controller design, it is necessary to simplify the original SAUV dynamics model, which is inherently nonlinear and coupled. Since the vehicle does not undergo roll motion, we can assume $\phi = 0$, from which can be derived the expressions $\cos\phi = 1$ and $\sin\phi = 0$. With this assumption, the pitch kinematic equation of the SAUV, denoted as $\dot{\theta} = q\cos\phi - r\sin\phi$, can be simplified to $\dot{\theta} = q$. This leads to the following equation:

$$\begin{aligned} \dot{\theta} &= q \\ \dot{q} &= f(q, w, t) + b_\theta M_y \end{aligned} \quad (15)$$

where

$$\begin{aligned} f(q, w, t) &= \left[\left(-m x_g + \frac{1}{2} \rho l^4 M_q' \right) u q - m z_g w q + \frac{1}{2} \rho l^3 (M' u^2 + M'_{uw} u w) - (z_g W - z_b B) \sin(\theta) \right. \\ &\quad \left. - (x_g W - x_b B) \cos(\theta) \cos(\phi) \right] / \left(I_y - \frac{\rho}{2} l^5 M_q \right) \end{aligned} \quad (16)$$

and

$$b_\theta = \frac{1}{\left(I_y - \frac{\rho}{2} l^5 M_q \right)} \quad (17)$$

The linear error state feedback of the ADRC controller takes a linear combination of the error in the state and the derivative of the error as its input. For pitch motion, the pitch angle error is defined as $e_\theta = v_1 - z_1$, and the pitch angular velocity error is defined as $e_q = v_2 - z_2$. The linear error state feedback for pitch motion is expressed as follows:

$$M_y = \text{beta1} \cdot e_\theta + \text{beta2} \cdot e_q - \frac{z_{3,\theta}}{b_\theta} \quad (18)$$

The same simplification can be applied to the yaw motion of the SAUV, leading to Eq. (19):

$$\begin{aligned}\dot{\psi} &= r \\ \dot{r} &= g(r, w, t) + b_\psi M_z\end{aligned}\quad (19)$$

where

$$g(r, w, t) = \left[\left(-m\dot{x}_g + \frac{1}{2}\rho l^4 N'_r \right) u_r - m\dot{y}_g v_r + \frac{1}{2}\rho l^3 (N'_r u^2 + N'_{rv} uv + N'_{v|v}|v|) \right. \\ \left. + (x_g W - x_b B) \cos(\theta) \sin(\phi) + (y_g W - y_b B) \sin(\theta) \right] / \left(I_z - \frac{1}{2}\rho l^5 N'_r \right) \quad (20)$$

and

$$b_\psi = \frac{1}{\left(I_z - \frac{1}{2}\rho l^5 N'_r \right)} \quad (21)$$

Assuming that the heading angle error is $e_\psi = \psi - \psi_1$ and the heading angular velocity error is $e_r = r - r_2$, the linear error state feedback for yaw motion is expressed as shown in Eq. (22):

$$M_y = \text{beta3} \cdot e_\psi + \text{beta4} \cdot e_r - \frac{z_{3,\psi}}{b_\psi} \quad (22)$$

The ADRC method for heading control and depth control consists of three components: the tracking differentiator (TD), extended state observer (ESO), and linear error state feedback (LESF). Due to the slow movement speed of the SAUV, the control frequency of the system is set to 2 Hz, and the time step for the discrete system is therefore configured as $h = 0.5$ s. From Eq. (12), we see that the parameters that need to be adjusted for TD are r and h , while from Eq. (14), the parameters that need to be adjusted for the ESO are β_{01} , β_{02} , β_{03} and δ . LESF also takes the state error and the derivative of the state error as feedback. The parameters that need to be adjusted are beta1 , beta2 and b_θ in Eq. (18) (or beta3 , beta4 and b_ψ in Eq. (21)). The specific values for these parameters are shown in Table 2 below.

Tab. 2. Specific values for each parameter in the ADRC method

Parameter	r	h	β_{01}	β_{02}	β_{03}	δ	beta 1 (or beta 3)	beta 2 (or beta 4)	b_ψ (or b_θ)
Heading	2	0.5	4	3.4	0.25	0.5	2	0.1	0.003
Depth	4	0.5	4	2.3	0.18	0.5	0.3	0.01	0.002

FIELD EXPERIMENTS

It was necessary to conduct underwater testing on the actual SAUV in order to determine the effectiveness of the designed control strategy. A validation test was therefore conducted in a water tank, which was provided by the test pool of the Institute of Deep Sea Science and Engineering, Chinese Academy of Sciences. The SAUV was placed underwater in the tank, as shown in Fig. 13, and tests were carried out that included speed control, heading control, and depth control. However, these three controls do not exist independently; when applying a thrust F_x in the forward direction, stable heading progress for the SAUV cannot be guaranteed. Hence, when performing speed control tests, it is necessary to ensure

the stability of the SAUV's heading, and when performing depth control tests, it is necessary to ensure the stability of the SAUV's heading and speed. The experimental scope of the pool tests covered surface speed-heading control and underwater speed-heading-depth control. For surface speed-heading control, the angle α of the vector propeller was fixed, and only the thrust T and angle β were changed. For underwater speed-heading-depth control, T , α , and β were controlled simultaneously. The surface speed-heading control can be regarded as a special case of underwater speed-heading-depth control where the depth is zero. The data presented here therefore the results of underwater speed-heading-depth control tests.

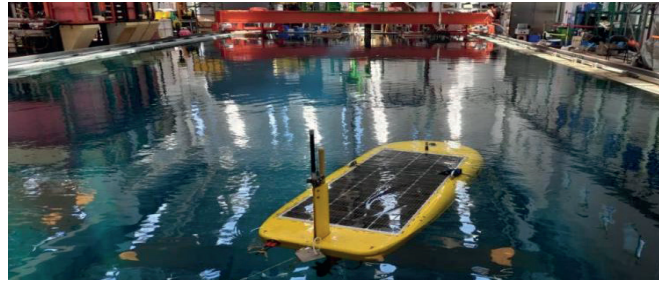


Fig. 13 Experimental testing of the SAUV in a water tank

In the following, we describe the simultaneous testing of speed, heading, and depth for the SAUV. The results of the two selected tests are shown in Fig. 14 below.

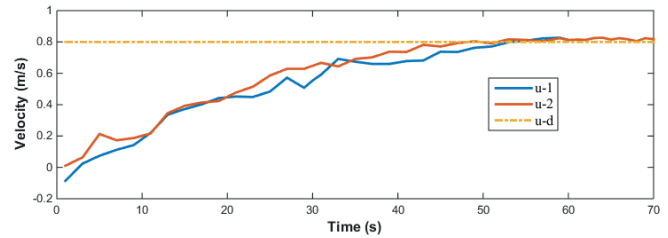


Fig. 14 Results for velocity control based on PID

In a still water environment, the vector thruster was able to provide a maximum thrust of approximately 100 N, enabling the SAUV to reach a maximum speed of 1 m/s.

In the experimental design, three distinct target speeds were considered (0.5, 0.8, and 1 m/s). Due to the use of the vector propellers, when the controlled target speed is too low, the required thrust (T) also decreases. Consequently, the forces $T \sin \alpha \sin \beta$ and $T \sin \alpha \cos \beta$, which are used for controlling the heading and depth, respectively, will diminish. When the control speed is set to 1 m/s, the energy consumption needed for control is high; hence, a speed of 0.8 m/s was chosen for the pool testing process. Since testing was conducted in the still water environment of an indoor pool, disturbances could be neglected.

To validate the speed control performance, a target speed of 0.8 m/s was set, and two tests were conducted, with results

labelled as u-1 and u-2 in Fig. 14, respectively. The speeds were acquired by a DVL. Notably, the dynamic equation for the SAUV in the forward direction is less significantly affected by coupling with other state variables, making it relatively easier to control the vector thrust in this direction. Thanks to this characteristic, a PID controller can achieve precise and effective control of the SAUV's speed.

For the heading and depth control of the SAUV, both the GNW and WIT sensors were used to acquire angles and angular velocities (as described in Section 5). The GNW is a six-axis sensor that can only provide angular acceleration and acceleration, while the WIT is a nine-axis sensor that can directly provide angles. These two sensors were used in conjunction with each other.

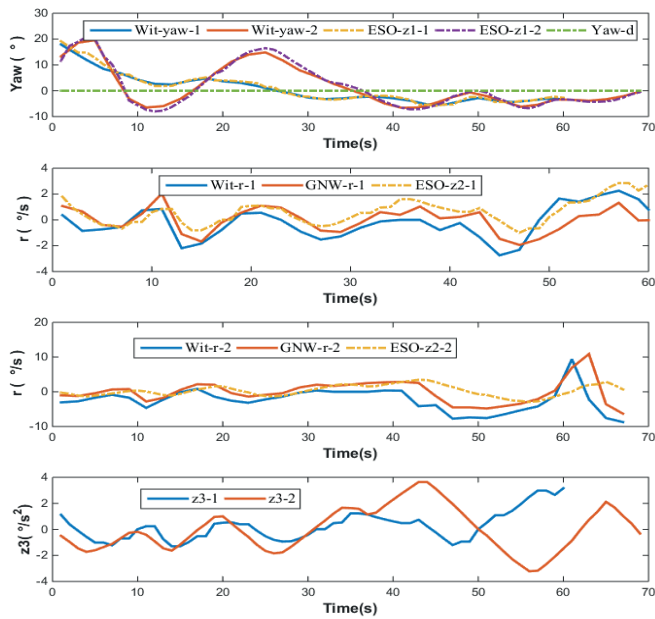


Fig. 15 Results for yaw control based on ADRC

The results for heading control based on ADRC are shown in Fig. 15. An initial heading angle was given to the SAUV, and the target heading angle Yaw-d was set to 0°. Wit-yaw-1 and Wit-yaw-2 represent the heading angles provided by the WIT during the two tests. ESO-z1-1 and ESO-z1-2 indicate the observations of the heading angle, respectively. From Fig. 15, it can be seen that the error between the observed heading angle z1 and the true value is relatively small. Wit-r, GNW-r, and ESO-z2 represent the heading angular velocity r obtained from the WIT and GNW sensors, and the observation of r , respectively. In both tests, it could be observed that there was a significant deviation between the data collected by the two sensors, Wit-r and GNW-r, and there was also a certain error between the observed heading angular velocity z2 and the true value r . This suggests that there are inherent errors in the sensors themselves, rather than these necessarily being observation errors of the extended state observer. z3-1 and z3-2 are the observed disturbances and uncertainties

in the heading control, and by using these observations as compensation for the linear error state feedback, we can ensure that the heading control error of the SAUV remains within 5°.

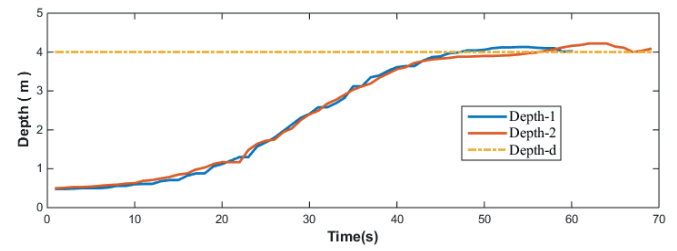


Fig. 16 Depth control curve based on PID-ADRC

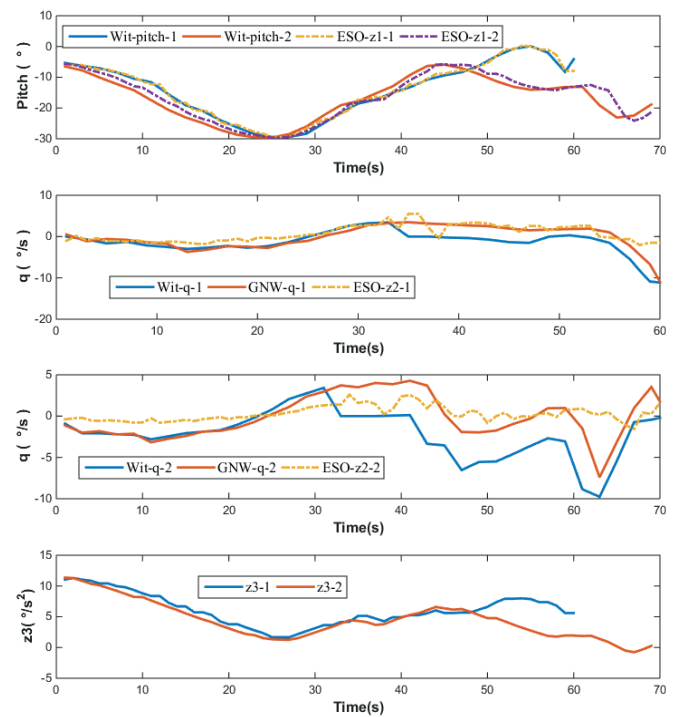


Fig. 17 Pitch response for depth control based on PID-ADRC

Fig. 16 shows the results of two tests based on the PID-ADRC dual-loop depth control, with the target depth Depth-d set to 4 m. During the depth control process, attention needs to be paid to the inner loop control based on ADRC, as shown in Fig. 17. Similarly to the heading control, Wit-pitch represents the pitch angle provided by the WIT during the test. ESO-z1 represents the observation of the pitch angle, and from Fig. 17, it can be seen that ESO-z1 can accurately reflect the true pitch angle Wit-pitch. For the pitch angular velocity q , there is also an error between the observed value z2 and the value of q obtained by the sensor. z3-1 and z3-2 are the observed disturbances and uncertainties in the pitch motion during the depth control process. The use of these observations as compensation for the linear error state feedback can ensure a certain level of depth control accuracy for the SAUV.

CONCLUSION

An SAUV was developed in this study with the aim of improving the operational duration. The proposed vehicle has an unconventional shape, due to the need for the integration of solar panels. A vectorial thruster consisting of two steering engines and a propulsion unit was successfully used to achieve the basic motion of the SAUV, which was equipped with numerous commonly used sensors as a perception system to offer the potential for collecting data.

Compared to SAUVs with conventional shapes, the proposed design has a significantly increased difficulty of motion control, due to its complex shape and reliance on a single vector thruster for propulsion. To address this challenge, the motion of the SAUV was decomposed into three degrees of freedom, and corresponding controllers were designed based on PID and ADRC algorithms. Through experimental validation in a water tank, the applicability of the designed controllers was proven, and it was also confirmed that this new shape for an SAUV has a certain degree of rationality and feasibility for both technical and practical applications.

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