To cite this article: AN J X, YANG S L, XIANG X B, et al. Seabed collision emergency decision-making of AUV based on safety domain model [J/OL]. Chinese Journal of Ship Research, 2023, 18(2). http://www.ship-research.com/en/article/doi/10.19693/j.issn.1673-3185.02533.

DOI: 10.19693/j.issn.1673-3185.02533

Seabed collision emergency decision-making of AUV based on safety domain model

AN Jinxin, YANG Shaolong, XIANG Xianbo, DONG Donglei*

School of Naval Architecture and Ocean Engineering, Huazhong University of Science and Technology, Wuhan 430074, China

Abstract: [**Objectives**] To ensure safety and prevent seabed collisions in complex unknown underwater environments, this study proposes a seabed safety domain model and tiered emergency response strategies. [**Methods**] A vertical motion simulation model was established and verified by surpassing the test results and then used to calculate the active and passive safety domain distance of an autonomous underwater vehicle (AUV), thus establishing a seabed safety domain model. An AUV emergency control system and emergency strategies are then built on the basis of the dynamic safety domain model. The trim and distance from the seabed of the AUV were used to calculate the current and future risk factors. Based on the weighted sum, the comprehensive risk factor was employed to provide the AUV with emergency response strategies. [**Results**] By analyzing the lake test of fixed-depth and fixed-height navigation, the correlation between the comprehensive risk factor and the seabed height is stronger when the seabed height is closer to the AUV active safety domain reach boundary, and weaker vice versa. The results show that the proposed AUV emergency control system can reduce emergency false alarms. The results show that the AUV emergency control system can reduce false alarms in emergency decision-making when operating in undulating terrain and reduce missed alarms in emergency decision-making in seabed navigation. In such cases, reasonable emergency strategies can be realized under complex rough terrain. [**Conclusions**] The AUV seabed safety domain model and tiered emergency response strategies based on vertical motion equations proposed in this paper can be applied to evaluate seabed collision risk in various cases. Finally, this paper provides emergency response strategies to avoid seabed collision accidents, which can enhance the safety of AUV underwater autonomous navigation.

Key words: autonomous underwater vehicle; safety domain model; seabed collision risk; emergency decision-making

CLC number: U674.941

0 Introduction

The autonomous underwater vehicle (AUV) [1] has become a research hotspot in marine engineering with its advantages of large exploration and operation range and flexibility. It can be adapted to various underwater operation scenarios, such as marine environment investigation, submarine resource surveys, and deep-sea scientific experiments [2]. However, if the AUV hits the seabed bottom during underwater operation, it can lead to mission failure or equipment damage or loss [3]. Therefore, in the development of AUV, it has been an important issue to enhance its ability to avoid seabed collision and improve its safety [4-5].

To improve the safety of AUV, scholars in China

Received: 2021－09－18 **Accepted**: 2022－01－19

Supported by: National Natural Science Foundation of China (52071153); Special Funds for Basic Scientific Research Business of Central Universities (2018KFYYXJJ015, 2021yjsCXCY007)

Authors: AN Jinxin, male, born in 1998, master degree candidate. Research interests: underwater vehicle emergency system and route planning. E-mail: an_jinxin@hust.edu.cn

YANG Shaolong, male, born in 1988, Ph.D., associate professor. Research interests: unmanned vehicle route planning and intelligent control. E-mail: yangsl@hust.edu.cn

***Corresponding author**: YANG Shaolong

and abroad have proposed various effective collision avoidance strategies for the vehicle based on safety domain models. In ship safety domain, for example, in 1971, Japanese scholars Fujii et al. [6] first put forward for a safety domain model for ship obstacle avoidance and obtained a safety domain model for elliptic ships applicable to narrow waters and factors influencing waterway capacity by traffic survey and probability statistics. Goodwin [7], inspired by collision avoidance procedures in aviation, defined the concept of the ship safety domain as the safe distance that a pilot expects to keep from other ships or fixed objects on water. For years, the size, shape, and area of the ship safety domain have been evolving as the research further develops [8 – 11]. A number of reports have been made on safety domain models in automobile, ship, aerospace, and other domains [12]. For instance, the safety space of a vehicle is called the safe driving area in the automobile domain. Kuchar et al. [13] set the envelope in the automobile safety domain to avoid collisions between the vehicle and obstacles; Erlien et al. [14] set the envelop in the safety domain according to the driving modes of surrounding vehicles, based on which the steering angle and longitudinal acceleration of the vehicle were controlled to ensure the safe distance between the vehicle and surrounding vehicles. These studies suggest that when an obstacle is detected by the sensor in a safety domain, the vehicle will take emergency response measures in time to make itself away from the obstacle and improve its safety.

Receiving these stimulus, domestic and foreign scholars have also carried out preliminary exploration in the safety of underwater vehicles in the safety domain. Wang et al. [15] defined the forbidden area and potential collision area of the AUV in the presence of obstacles by motion safety analysis in global route planning of the AUV, and proposed AUV safe navigation guidelines for local route planning; the feasibility of the method was verified by simulation results, but there was no full-scale test. Suh et al. [16] came up with an indicator for evaluating the collision risk of the remote operated vehicle (ROV), in other words, the collision risk of the ROV was determined by collision time, average collision time, and average collision energy; the indicator was proved to be able to evaluate the overall risk in the route but was not used in actual tests. Hegde et al. [17] proposed a safety domain model based on fuzzy reasoning of sensor data, and the simulation test demonstrated that the fuzzy logic could play a role in improving the safety of underwater vehicles. Hegde et al. [18], again, designed a static safety domain model by using the octree, where the underwater vehicle was surrounded by a three-dimensional virtual protective barrier to ensure the safe navigation of the vehicle. However, the static safety domain model requires to preset a fixed threshold artificially and is not self-adaptive to the navigation safety under multi-mission and complex rough terrain.

In view of these problems, this paper proposes a seabed safety domain model and emergency response strategies to avoid the seabed collision risk. First, a vertical motion simulation model is established and verified by lake tests; then, the active and passive safety domain distance is calculated. The results are compared with the active and passive safety domain distance according to current motion status and future motion trend of AUV, and comprehensive risk factor is calculated to provide seabed emergency response strategies. An AUV independent emergency control system is designed, with its ability to avoid seabed risk under complex terrain being verified by lake tests.

1 AUV vertical motion simulation model and verification

1.1 AUV vertical motion simulation modeling

The motion coordinate system of the AUV is established, which consists of the geodetic coordinate system and body-fixed coordinate system, as shown in Fig. 1. The notation of the AUV is shown in Table 1.

Ref. [19] shows that when the origin O of the appendage coordinate system overlaps the gravity center G, and the AUV is bilaterally symmetrical

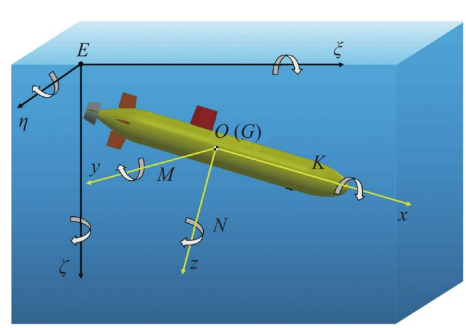


Fig. 1 Geodetic coordinate system and body-fixed coordinate systems of AUV

Table 1 Notation of AUV in geodetic coordinate system and body-fixed coordinate system

		Position /m	Attitude angle/rad	Linear velocity /(m·s^{-1})	Angular velocity	Force/N	Moment
Geodetic coordinate system	ξ axis	x	φ	$\dot{x}$	$\dot{\phi}$	X_E	K_E
	η axis	y	θ	$\dot{y}$	$\dot{\theta}$	Y_E	M_E
	ζ axis	z	ψ	$\dot{z}$	$\dot{\psi}$	Z_E	N_E
Body-fixed coordinate system	x axis	x'	γ	u	p	X	K
	y axis	y'	a	v	q	Y	M
	z axis	z'	β	w	r	Z	N

and approximately symmetrical longitudinally and anteroposteriorly, then the moment of inertia is $I_{zx} = I_{xz} = I_{zy} = I_{yz} = I_{xy} = I_{yx} = 0$.

AUV spatial motion can be decomposed into vertical and horizontal motion. Since this paper focuses on seabed safety, it is simplified as AUV vertical motion. In other words, after ignoring pitch rate (p = 0), roll rate (r = 0), lateral velocity (v = 0), roll angle (φ = 0), and course angle (ψ = 0), the forward velocity is set as a constant (u = 0), and then the vertical motion model Eq. (1) and dynamical model Eq. (2) were obtained

$$\begin{cases}\dot{z} = -u\sin\theta + w\cos\theta \\ \dot{\theta} = q\end{cases} \tag{1}$$

$$\begin{cases}Z = m(\dot{w} - uq - x_G\dot{q} - z_G q^2) \\ M = I_{yy}\dot{q} + mz_G wq - mx_G(\dot{w} - uq)\end{cases} \tag{2}$$

where the acting force Z and moment M are

$$\begin{aligned}Z = {} & Z_{\dot{w}}\dot{w} + Z_{\dot{q}}\dot{q} - X_{\dot{u}}uq + Z_{w|w|}w|w| + Z_{uw}uw + Z_{q|q|}q|q| + \\ & Z_{uq}uq + Z_{uuds}u^2\delta_s + Z_{uudb}u^2\delta_b + (W - B)\cos\theta \\ M = {} & M_{\dot{w}}\dot{w} + M_{\dot{q}}\dot{q} - (Z_{\dot{w}}w + Z_{\dot{q}}q)u + X_{\dot{u}}uw + M_{w|w|}w|w| + \\ & M_{uw}uw + M_{q|q|}q|q| + M_{uq}uq + M_{uuds}u^2\delta_s + M_{uudb}u^2\delta_b - \\ & (z_G W - z_B B)\sin\theta - (x_G W - x_B B)\cos\theta\end{aligned} \tag{3}$$

By substituting Eq. (3) into the dynamic model Eq. (2), we obtain Eq. (4)

$$\begin{aligned}& (m - Z_{\dot{w}})\dot{w} - (mx_G + Z_{\dot{q}})\dot{q} = muq + mz_G q^2 - \\ & X_{\dot{u}}uq + Z_{w|w|}w|w| + Z_{uw}uw + Z_{q|q|}q|q| + Z_{uq}uq + \\ & (W - B)\cos\theta + Z_{uuds}u^2\delta_s + Z_{uudb}u^2\delta_b - \\ & (mx_G + M_{\dot{w}})\dot{w} + (I_{yy} - M_{\dot{q}})\dot{q} = -mz_G wq - mx_G uq - \\ & (Z_{\dot{w}}w + Z_{\dot{q}}q)u + X_{\dot{u}}uw + M_{w|w|}w|w| + M_{uw}uw + \\ & M_{q|q|}q|q| + M_{uq}uq - (z_G W - z_B B)\sin\theta - \\ & (x_G W - x_B B)\cos\theta + M_{uuds}u^2\delta_s + M_{uudb}u^2\delta_b\end{aligned} \tag{4}$$

where $Z_{u|u|}$ is the resistance in z direction; $X_{\dot{u}}$ is the added mass coefficient in the x direction, and the expression forms of fluid resistance and added mass coefficient of other degrees of freedom are shown in Ref. [19]; Z_{uq}, M_{uq} et al. are the resultant force of added mass and tab forces; M_{uw}, Z_{uw} et al. are the mechanical coefficient of the lifting forces of tab, lifting forces of rudder, and torque. Definitions of other related variables are shown in the appendix to Ref. [20]. Numerical simulation was carried out in Matlab based on Eqs. (1) and (4), the initial trim angle θ and initial velocity u of the AUV in the simulation environment were consistent with those in the lake test, and the initial rudder angle was the response rudder angle corresponding to lake test. Real-time depth and trim changes were compared between the simulation environment and lake test.

1.2 Verification of AUV vertical motion model

The AUV vertical motion is conducted in the lake test for overtaking maneuver, and the results are compared with the digital simulation results. Fig. 2 shows the comparison of the rudder angle curve.

In Fig. 2, affected by the lagged response of the steering engine, the executed rudder angle lags behind the expected rudder angle instruction by about 3 s in the lake test. To this end, in numerical simulation, the homogeneous effect of steering engine lag is simulated by delay link to make the response output of the simulated rudder angle (blue curve) close to the data in the lake test. A set of trim and depth response data from the simulation test and field test (3 m/s) are further compared, and the results are shown in Fig. 3, where E_{rp} is the peak error, and E_{rr} is the difference error.

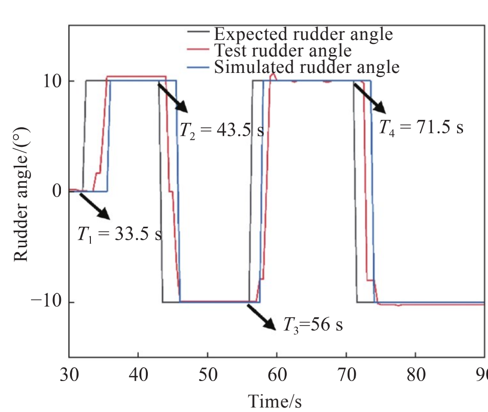
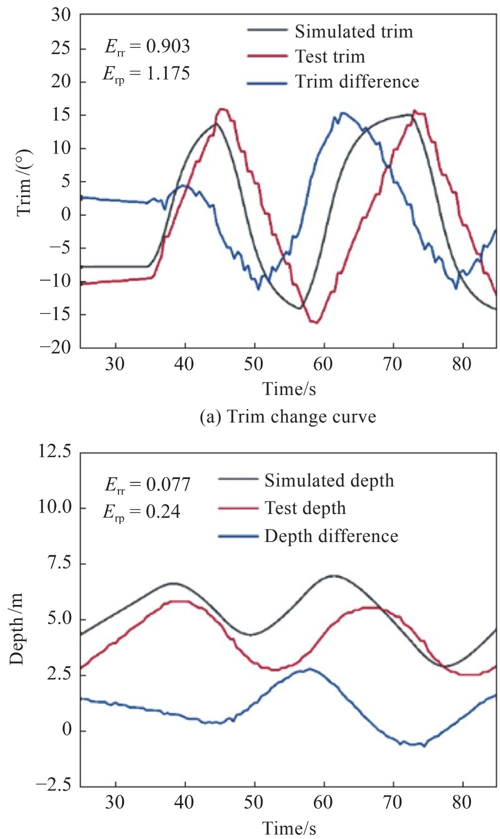


Fig. 2 Comparison of rudder angle curve



(a) Trim change curve

(b) Depth change curve

Fig. 3 Comparison of AUV vertical motion response simulation with lake test results

To quantify the comparison results, E_{rp} and E_{rr} are selected to calculate the deviation between simulation and test data [19]. The simulation data is assumed to the function $S(t)$, and the test data to $S'(t)$, then the definition equations of E_{rp} and E_{rr} are

$$E_{rr}=\left|\frac{\max[S'(t)-S(t)]}{2\max[S(t)]}\right|+\left|\frac{\min[S'(t)-S(t)]}{2\min[S(t)]}\right| \tag{5}$$

$$E_{rp}=\frac{1}{2}\times\left\{\left|\frac{\max[S'(t)]-\max[S(t)]}{\max[S(t)]}\right|+\left|\frac{\min[S'(t)]-\min[S(t)]}{\min[S(t)]}\right|\right\} \tag{6}$$

In this paper, it is agreed that the bow of the AUV is upwards when the trim angle is greater than 0°. After comparison, the peak errors of the depth and trim of the AUV is 0.24 and 1.175, and the difference errors are 0.077 and 0.903, respectively, in the simulation and lake test. In addition, feature parameters for overtaking maneuver are further compared, as shown in Table 2, where u is the navigational speed; δ_r is the stern rudder angle; θ is the trim angle; θ_{ov} is the trim angle in the overtaking maneuver; ξ_{ov} is the depth in the overtaking maneuver.

Table 2 shows that errors of θ_{ov} and ξ_{ov} in both conditions are within 30%. Based on the comparison

Table 2 Comparison of feature parameters between simulation and lake test for the overtaking maneuver

u/ (m·s⁻¹)	δ_r/ (°)	θ/ (°)	θ_{ov}/ (°)			ξ_{ov}/m		
			Simulation	Lake tests	Error/%	Simulation	Lake tests	Error/%
3	10	10	5.83	5.9	1.2	0.988	1.40	29.40
1	20	20	2.49	2.9	14.1	0.100	0.11	9.09

of peak errors, difference errors, and feature parameters for the overtaking maneuver, the vertical motion simulation model can basically reflect the motion response features of the AUV within the acceptable deviation range of the experimental study, and it can be used for subsequent safety domain calculation. The experimental errors are mainly caused by the wave, stream, and other interferences in the lake test.

2 Seabed safety domain model

2.1 Descending depth rule of AUV

When the trim of the AUV is greater than the angle between the seabed and water level or the distance from the seabed is greater than 0, the vertical motion of the AUV is generally considered to be safer. Therefore, when the initial trim is less than 0°, the response time of the AUV from the completion of rudder turning to the restoration of the trim to 0 ° is defined as T_θ. Due to the lag of the steering engine response, there will be a time delay from the receipt of the expected rudder angle instruction to the completion of rudder turning. Therefore, the lag time of the steering engine is defined as T_0 (T_0=3 s). Theoretically, shorter T_θ indicates more maneuverable AUV. Based on the AUV vertical motion simulation model, when the initial velocity and trim of the AUV change, T_θ will also change. Combined with the AUV equipment and mission scenarios in this paper, the forward velocity is assumed as 0−3.4 m/s, the trim is assumed as −10° — −90°, and the rudder turning angle is set as −25° — 25°. The T_θ in different initial state combinations is obtained by numerical simulation, and is fitted to obtain Eq. (7)

$$T_\theta=4+9.44u+0.585u^2+0.002\,5\theta^2+0.007\,7u\theta \quad (R^2=0.973) \tag{7}$$

where R^2 is the goodness of fit, and as its value is closer to 1, the degree of fitting of simulation becomes better.

From the seabed safety perspective, after the AUV executes the floating rudder instruction (10 °), it can restore from a risky initial state to a state with a higher vertical motion safety within the time T_θ. Therefore, the descending depth of the AUV within the time T_θ is defined as the active safety domain distance D_2

$$D_2 = u \times T_0 \times \sin\theta_0 + \int_0^{T_\theta} \left(u \times \sin\left(|\theta_0| - \left| \frac{\theta_0}{T_\theta} \right| \right) \right) \mathrm{d}t \quad (8)$$

Eqs. (7) and (8) are combined to obtain D_2

$$D_2 = 7.5 - 8.91u - 0.13\theta + 3.53u^2 + 0.3u\theta \quad (R^2 = 0.985) \quad (9)$$

In addition, since the steering engine maintains the original rudder angle instruction within the response lag time T_0, and the forward velocity, trim and other states of the AUV cannot change timely within this time, the descending depth of the AUV within the time T_0 is defined as the passive safety domain distance D_1

$$D_1 = u \times T_0 \times \sin\theta_0 + D_0 \quad (10)$$

where D_0 is the radius of the AUV.

The same initial state as that in active safety domain calculation is assumed to obtain the fitting function of D_1

$$D_1 = 0.001\,82u + 0.447\,22\theta - 0.019\,02\theta^2 + 0.033\,89\theta u \quad (R^2 = 0.979) \quad (11)$$

2.2 Dynamic seabed safety domain model of AUV

In view of the seabed collision risk, the concept of the dynamic seabed safety domain model of the AUV is proposed. As shown in Fig. 4, the seabed active safety domain and passive safety domain of the AUV constitute the dynamic seabed safety domain model. The boundary of the dynamic seabed safety domain model is composed of D_1 and D_2. When the forward velocity and trim of the AUV change, the dynamic seabed safety domain boundary is dynamically adjusted. When an obstacle is detected within the seabed safety domain boundary, the AUV takes corresponding emergency response strategies to change its motion state and make the obstacle away from the safety domain model boundary. The dynamic seabed safety domain model is an important dimension of the three-dimensional spatial safety domain of the AUV, and a reliable dynamic seabed safety domain model can reduce the frequency of damage, loss, and other safety incidents of the AUV due to seabed collisions.

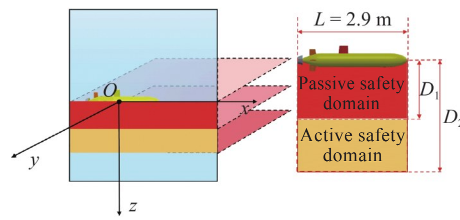


Fig. 4 Dynamic seabed safety domain model

3 Design of emergency response strategies

3.1 Emergency response framework

To ensure the independency and reliability of the security system, the proposed emergency response framework is dependent of the main control unit. As shown in Fig. 5, the framework collects typical state data such as real-time trim, forward velocity, depth, distance from the seabed acquired by the on-board sensor. After comprehensive analysis on the multi-source perception data, the emergency response decision is output to four actuators and controlled by groups, so as to realize reasonable tiered emergency response decision-making.

3.2 Comprehensive emergency decision-making

As shown in Fig. 6, motion states of AUV include three types: past state, current state, and future state. The data stored in the past state include

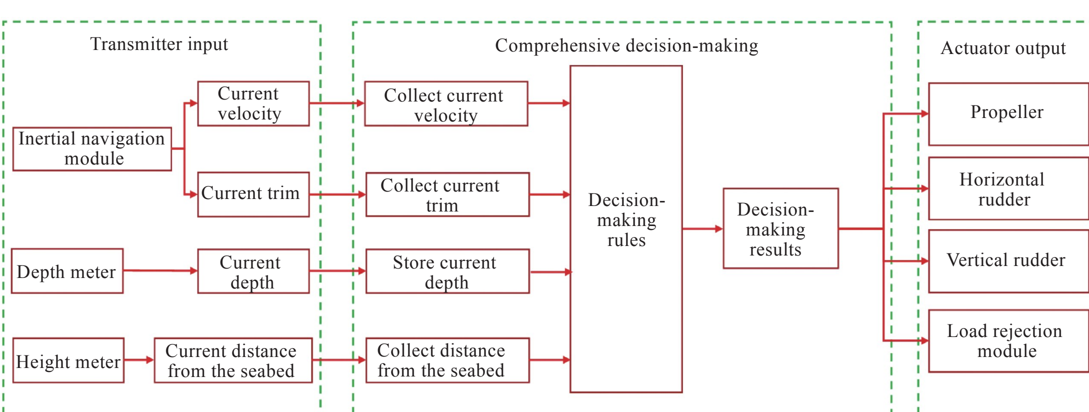


Fig. 5 AUV emergency response framework

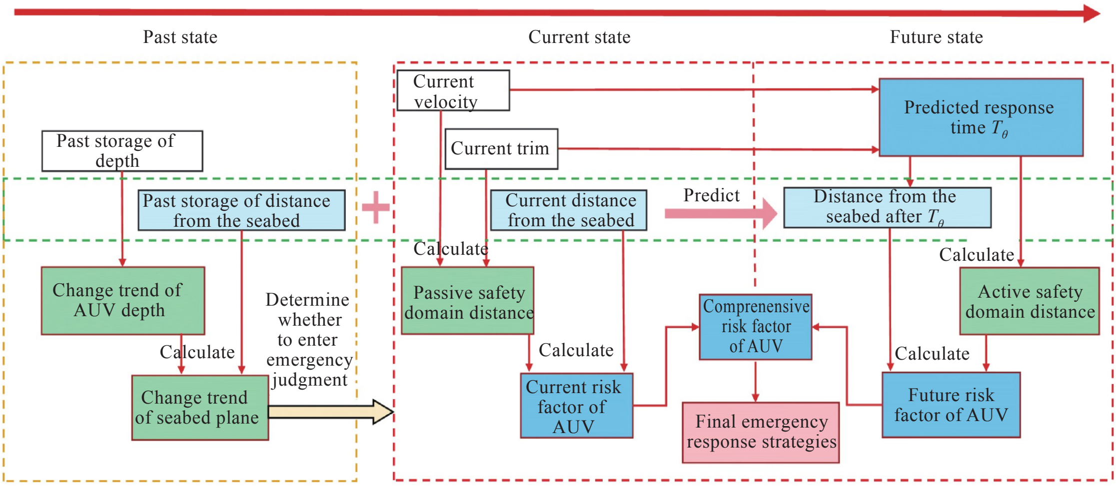


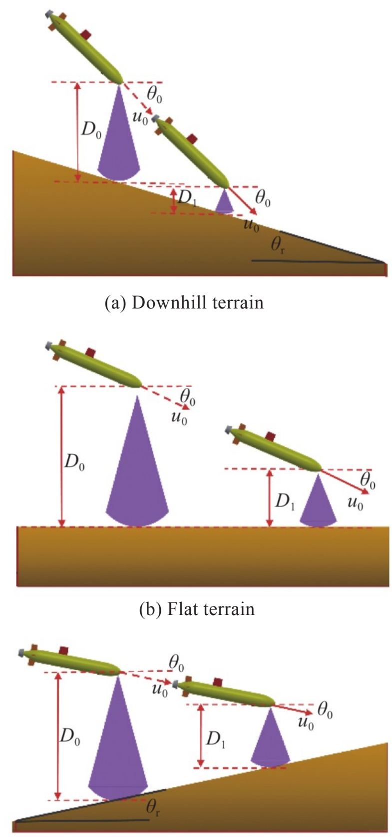
Fig. 6 AUV multi-state emergency judgment logic

the change trends of depth and distance from the seabed; the data stored in the current state include current velocity, current trim, and current distance from the seabed; the data stored in the future state include the response time T_θ predicted from the current velocity and trim, and the distance from the seabed after T_θ predicted by the past distance from the seabed and current distance from the seabed. The current risk factor and future risk factor are calculated to determine the comprehensive risk factor of AUV, which is then used for emergency decision-making.

3.2.1 Emergency response judgment framework of past state

During seabed navigation, whether the distance between the AUV and seabed is narrowing can be judged by calculating the changes of the seabed profile, thus predicting the seabed safety of the AUV and triggering emergency decision-making. As shown in Fig. 7, three relative position relations between the AUV and seabed profiles are listed, and triggering conditions of emergency decision-making are analyzed. In this figure, u_0 is the navigational speed; θ_0 is the trim angle; θ_r is the angle between seabed and water level.

First, the variation of the depth meter $\Delta S = S_{-t} - S_0$ and the variation of the distance from the seabed $\Delta D = D_0 - D_{-t}$ in a past time window (t moments ahead of the current moment) are taken, and then the change trend of the seabed profile (changes in the seabed terrain directly projected below the AUV body) is obtained, as shown in the judgment result 1 in Table 3. After the seabed change trend is judged, further decisions are made based on AUV's trim states θ_0 and θ_r (judgment condition 2) to further decide whether the AUV needs to enter the emergency response.



(a) Downhill terrain

(b) Flat terrain

(c) Uphill terrain

Fig. 7 Analysis of relative hazard position between AUV and seabed profile

Table 3 Seabed change trend and emergency judgment

Judgment condition 1	Judgment result 1	Judgment condition 2	Judgment result 2
$\Delta D < \Delta S$	Seabed is ascending	$\theta_0 \leqslant \theta_r$	Enter emergency decision-making
		$\theta_0 > \theta_r$	Do not enter emergency decision-making
$\Delta D > \Delta S$	Seabed is descending	$\lvert\theta_0\rvert \geqslant \theta_r$	Enter emergency decision-making
		$\lvert\theta_0\rvert < \theta_r$	Do not enter emergency decision-making
$\Delta D = \Delta S$	Seabed is flat	$\theta_0 \leqslant 0°$	Enter emergency decision-making
		$\theta_0 > 0°$	Do not enter emergency decision-making

3.2.2 Calculation of current risk factor

Influenced by the hysteresis of the steering engine, the AUV needs to immediately responds to avoid the obstacle in the passive safety domain, so as not to cause more serious consequences. Therefore, the current risk factor ρ_1 can be obtained by the real-time passive safety domain distance D_1 and current distance from the seabed ξ_0 of the AUV.

$$\rho_1 = \xi_0 - D_1 \tag{12}$$

When $\rho_1 \leqslant 0$, $\xi_0 \leqslant D_1$, it is suggested that due to the hysteresis response of the steering engine, the AUV fails to deflect the rudder within the following time T_0 and is highly likely to cause a seabed collision, namely, $\xi_{T_0} \leqslant 0$; when $\rho_1 > 0$, $\xi_0 > D_1$, it is suggested that the AUV can still take emergency response measures within the response time with the descending distance of $(\xi_0 - D_1) > 0$ to avoid the seabed collision risk.

3.2.3 Calculation of future risk factor

AUV's seabed safety warning capacity can be further improved by predicting the future state based on the current state, so as to avoid possible risks in advance. However, too complex state prediction and risk judgment will also make AUV less adaptable to complex underwater terrain, leading to frequent false emergency decision-making warning. To solve this problem, this paper designs a method for analyzing future risk factors based on AUV's motion state trend and the change trend of the distance from the seabed.

From Section 3.1, the response time that the AUV requires from completing the instruction of the steering engine to restoring the trim to 0 ° is T_θ, within which the AUV still maintains the component of descending speed, and the descending depth of the AUV, namely the active safety domain distance D_2, can be calculated. Hence, the future risk factor ρ_2 is calculated by the difference between the distance from the seabed ξ_{T_θ} predicted from the current time to T_θ and the active safety domain distance D_2

$$\begin{cases} \xi_{T_\theta} = D_0 + \dfrac{\Delta D}{t} T_\theta \\ \rho_2 = \xi_{T_\theta} - D_2 \end{cases} \tag{13}$$

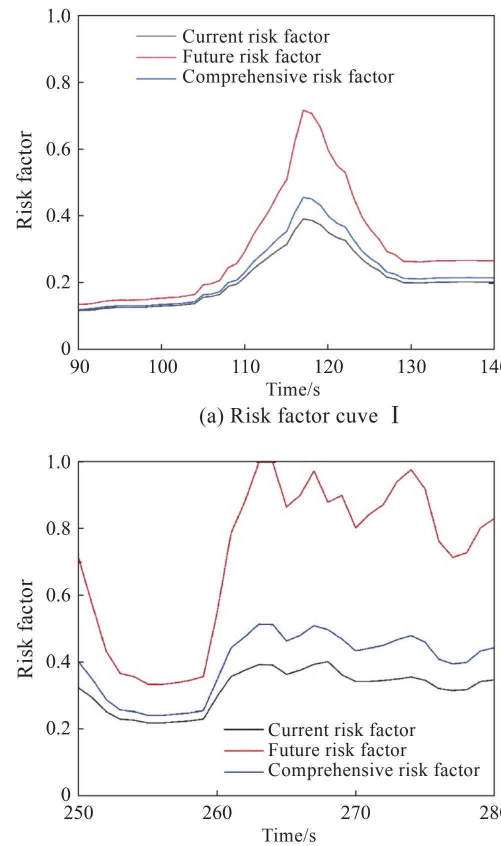
When $\xi_{T_\theta} \leqslant 0$ m $\rho_2 \leqslant -D_2$, it is suggested that at the current velocity and trim state, the distance from the seabed will be less than or equal to 0 from the time when the AUV gives the floating rudder instruction to T_θ, in other words, the AUV will collide with the seabed within T_θ.

3.2.4 Comprehensive risk factor and response logic

Comprehensive risk factors are obtained by weighted sum based on risk factors ρ_1 and ρ_2, and then risk levels are classified for tiered treatment. First, current risk factors and future risk factors are treated by dimensionless processing. In order to meet the real-time treatment requirements, the data are normalized; when $\rho_i < 0$, it is specified as 0 by the following method

$$\rho_i^* = \frac{1}{(1+\rho_i)} \left(i = 1,2;\ \ \rho_i = \begin{cases} 0, & \rho_i \leqslant 0 \\ \rho_i, & \rho_i > 0 \end{cases} \right) \tag{14}$$

Then, the rationality of the comprehensive risk factors is judged according to the emergency response triggering logic in the actual navigation test, thus determining the weight range of two risk factors, as shown in Fig. 8.



(a) Risk factor cuve Ⅰ

(b) Risk factor cuve Ⅱ

Fig. 8 Weight determination of comprehensive risk factor

At 117 s in Fig. 8(a), the current risk factor is 0.39, and the future risk factor is 0.71 at 117 s, and the AUV is artificially judged not to be risky at this point; therefore, the calculated comprehensive risk factor should be reduced to below 0.5 to avoid false emergency decision-making warning. From this, the weight range of the current risk factor is (65%, 100%); at 263 s in Fig. 8(b), the current risk factor is 0.39, while the future risk factor is up to 0.99, and the AUV is artificially judged to be risky at this point; therefore, the comprehensive risk factor should be increased to above 0.5 to avoid missed alarms in emergency decision-making. From this, the weight range of the current risk factor is (0%, 81.9%). Integrating these two ranges and the features of the current risk factor and future risk factor, the comprehensive risk factor can reduce the missed alarms in emergency decision-making warning while ensuring the timeliness of the current risk factor and the predictability of the future risk factor when the weights of the two risk factors are set as 80% and 20%, and the calculation equation of the comprehensive risk factor is finalized as

$$\rho = 0.8 \times \rho_1^* + 0.2 \times \rho_2^* \tag{15}$$

After the calculation of the comprehensive risk factor, the results are classified and the comprehensive risk level is determined, as shown in Table 4.

Tiered response measures for different risk levels are determined by on-board actuators used in emergency conditions. Fig. 9 shows the layout diagram of emergency sensors and actuators in an AUV. Common sensors equipped in the AUV include the meter of distance from the seabed, depth meter, combined inertial navigation module and so on, which are used to measure real-time velocity, position and orientation, depth and distance from the seabed; emergency control related actuators include the stern propeller, emergency rejected load, stern horizontal rudder and vertical rudder. After the rejected load is released, the AUV will have large upward positive buoyancy for rapid emergency self-rescue. However, since rejected loads are unrecyclable, and emergency load rejection is effective only once, this method is usually used for the most critical emergency response in the actual system. Other actuators, such as the horizontal rudder, vertical rudder and propeller, are main emergency response measures during normal navigation of the AUV. According to Ref. [19], the combination of multiple actuators has a better emergency response than a single actuator. Therefore, a corresponding relation-ship between emergency actuators and risk levels of the AUV is established in Table 5, in which an emergency control strategy with response measures and actuators increasing successively is formed as risk levels are elevated.

Table 4 Corresponding relationship between comprehensive risk factors and risk levels

Comprehensive risk factor ρ	Risk level
<0.25	No risk
0.25 − 0.5	Mild risk
0.5 − 0.75	Moderate risk
>0.75	Severe risk

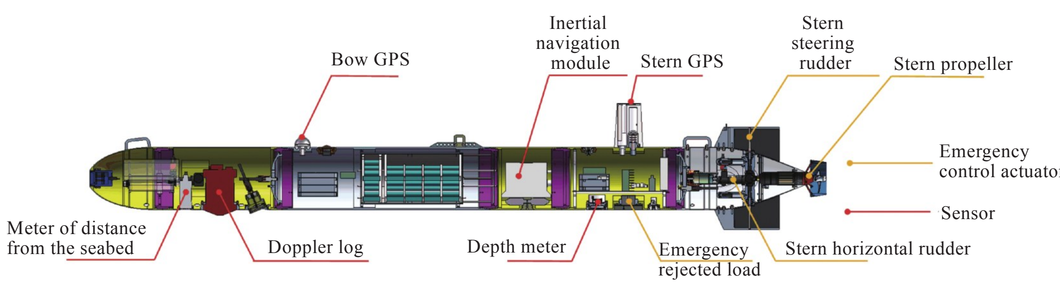


Fig. 9 Layout of AUV sensors and actuators

Table 5 Corresponding relationship between risk levels and emergency response measures

Risk level	Emergency response measures			
	Stop propeller	Full floating rudder	Full vertical rudder	Load rejection
No risk	No	No	No	No
Mild risk	Yes	No	No	No
Moderate risk	Yes	Yes	No	No
Severe risk	Yes	Yes	Yes	Yes

First, we should determine whether the AUV emergency system enters the emergency judgment according to the judgment conditions in Table 2. After it enters the emergency judgment, in case of no risk, the AUV executes the normal main control program; in case of mild risk, the AUV pauses the current mission and propeller, and then continues the main control program after the mild risk is eliminated; in case of moderate risk, the AUV stops the current mission and propeller, and fully turns the floating rudder for floating; in case of severe risk, the AUV stops the current mission and propeller, fully turns the floating rudder and vertical rudder (left rudder or right rudder), and executes emergency load rejection. The full vertical rudder aims to minimize the seabed collision relying on the "tail weight" of the AUV during turning.

4 Verification of emergency response strategies by lake tests

4.1 Introduction to test equipment

The lake test AUV and test site are shown in Fig. 10. The AUV is 2 000 mm in length, with a diameter of 240 mm, a dry weight of 89 kg, and a cruising speed of about 1.5 m/s; the size of the test site is about 384 m (length) × 116 m (width) × 20 m (depth).

(a) AUV (b) Test site

Fig. 10 Lake test AUV and test site

The AUV control system comprises the ground unit and on-board unit, as shown in Fig. 11. The ground unit consists of the operator and ground control unit, and the on-board unit includes the upper control nodes, master control nodes, lower control nodes (including bow and stern nodes) and environmental and attitude perception nodes. The AUV navigation can be divided into fixed-depth and fixed-height navigation. Before AUV sailing, the operator needs to set such parameters as mission mode, navigation time and navigation distance in the upper control nodes of the AUV via the ground control station. After parameter setting, the operator clicks in the ground control station to execute the mission. The upper control nodes start to receive the position, attitude, obstacle and other information sent by the environmental and attitude perception nodes, calculate related guidance and control instructions according to the current mission mode, and then send the distributed control instructions to the bow nodes and stern nodes, respectively. Finally, the bow nodes send the control instructions to the bow steering engine and realize closed-loop control through the real-time feedback of the steering engine and propeller.

The AUV executes the preset navigation mission with bow and stern steering engines and propellers. When the requires emergency control, the load rejection module will act, as part of actuators, following the instruction of the control system as part of actuators. The load rejection instruction of the control system given via the upper control nodes will be transmitted by the master control nodes and acts directly on the relay of the load rejection module; after the rejected load is released, the positive buoyancy of the AUV increases to rapidly float the AUV to the water surface.

In the lake test, fixed-depth and fixed-height navigations of the AUV are conducted to verify the

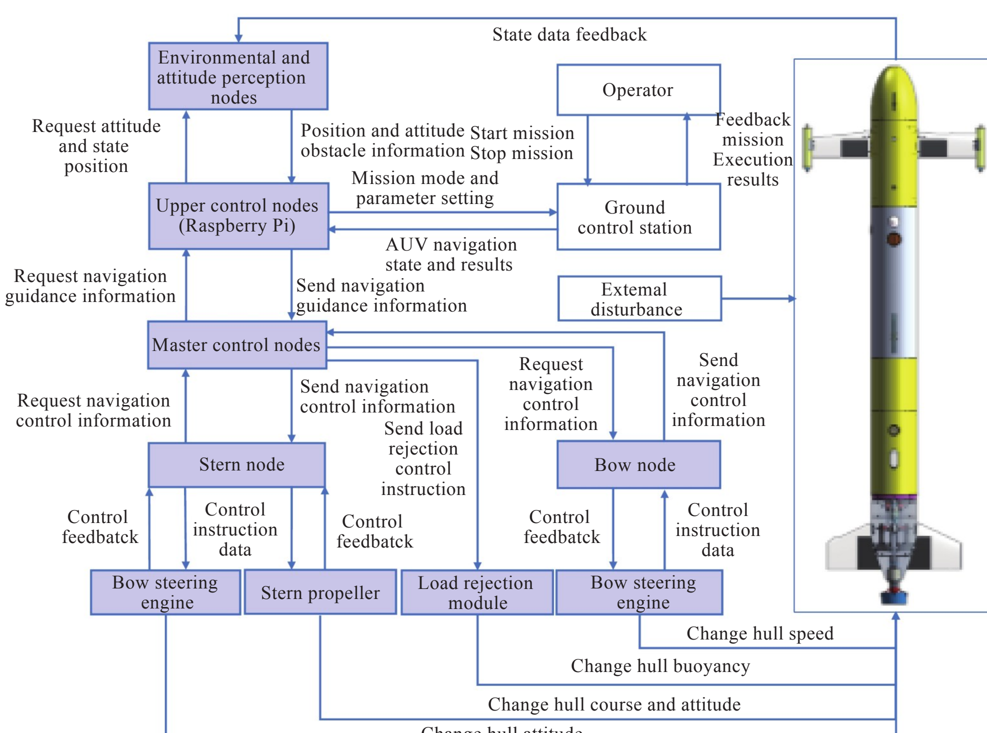


Fig. 11 Control architecture for AUV testing

rationality and effectiveness of the comprehensive risk factor and emergency response strategies.

4.2 Fixed-depth navigation and analysis

Fig. 12 shows the sequence diagram of AUV for fixed-depth navigation, where the fixed-depth of the AUV is 3 m and the speed is about 0.5 m/s. The figure shows the active and passive safety domain distances and the results of real-time depth and seabed height.

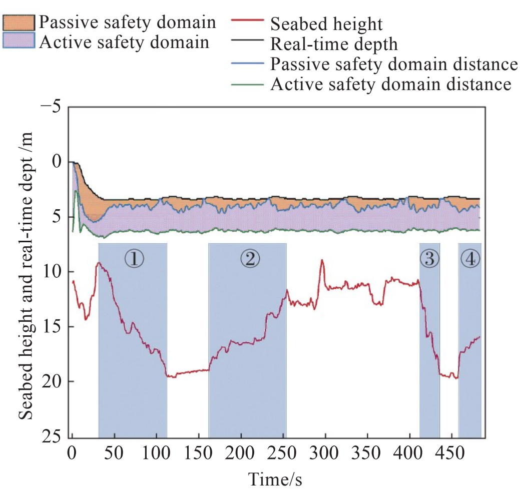


Fig. 12 Sequence diagram of AUV for fixed-depth navigation

In Fig. 12, the AUV rapidly descends to the depth of 3 m after sailing. The time frames ①−④ during fixed-depth navigation are extracted for discussion. Seabed heights in time frames ① and ③ decrease by 10.34 and 8.52 m respectively, and the active safety domain distance stabilizes at 6−7 m with velocity and trim; seabed heights in time frames ② and ④ increase by 7.3 and 3.68 m respectively, and the active safety domain distance still stabilizes at 6−7 m with velocity and trim.

Risk factors in the whole navigation are shown in Fig. 13. During the whole fixed-depth navigation, the variation range of the comprehensive risk factor is 0.05−0.13, and the maximum value appears before the time frame ①, when the seabed is shallow and the AUV is diving with negative trim. Therefore, the calculation risk factor of the emergency system increases, in other words, the seabed collision risk increases. In time frames ① and ③, seabed heights continue to decline, but comprehensive risk factors decrease only by 0.08 and 0.04, respectively; in time frames ② and ④, seabed heights continue to increase, but comprehensive risk factors increase only by 0.037 and 0.012, respectively. The results suggest that when the seabed height changes, and there is a large difference between the distance from the seabed and the seabed safety domain distance of the AUV, the comprehensive risk factor will not significantly change. According to the results of fixed-depth navigation, when the seabed height is far from the active safety domain boundary, the AUV is relatively safe, and the comprehensive risk factor at this point changes little with the seabed profile. Thus, there will not be false emergency decision-making warning, and the seabed emergency response strategies will be more effective.

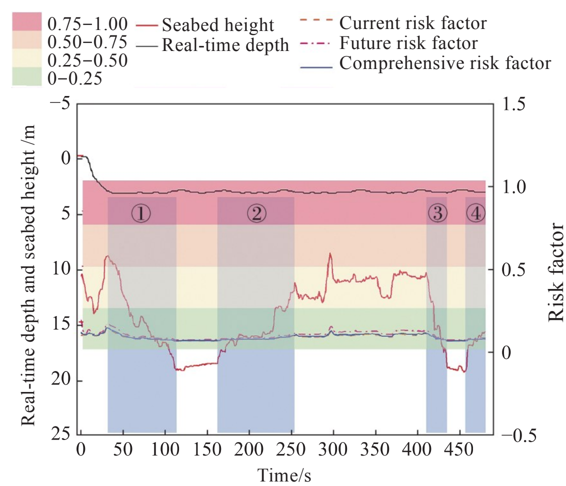


Fig. 13 Risk factor curve of fixed-depth navigation

4.3 Fixed-height navigation and analysis

By considering the requirements of safety and risk control of the lake test, the fixed-height navigation test was carried out with the emergency system in AUV's native control system used as the bottom-level security measure. The seabed emergency response strategies in this paper were embedded in the native control system without triggering emergency response measures to avoid crosstalk with the emergency system of the native control system. In a fixed-height navigation test where the emergency measures in the native control system were triggered, for example, the AUV in this navigation was of low speed and poor maneuverability. After 285 s of navigation, the emergency response measures of the system were triggered, and the AUV was forced to float and to end this mission. The comparison of the active and passive safety domain distances and real-time depth with the seabed height is shown in Fig. 14.

The seabed height is reduced in five times after 100 s, by 4.4 m, 2.85 m, 2.28 m, 1.61 m and 1.56 m in time frames ①−⑤. In the time frame ①, the minimum distance between the seabed height and the active safety domain boundary is only 0.41 m. As the AUV continues to dive with negative trim, the active safety domain boundary starts to be lower than the seabed height from the 193rd s, and their minimum difference in the time frame ② is −1.15 m, which increases the seabed collision risk of the AUV. As the AUV continues to dive with negative trim, while the seabed height in the test waters is only 20−30 m, the active safety domain boundary is frequently close to the seabed height, and the seabed height is smaller than the active safety domain distance. From the 262nd s or the time frame ④, with the continuously reduced seabed height, the active safety domain distance is close to the seabed height, further increasing the seabed collision risk. Ultimately, when the distance between the seabed height and the passive safety domain is 0.11 m, and the minimum distance between the seabed height and the active safety domain is −2.7 m, the emergency measures of the AUV are triggered to forcibly end the sailing.

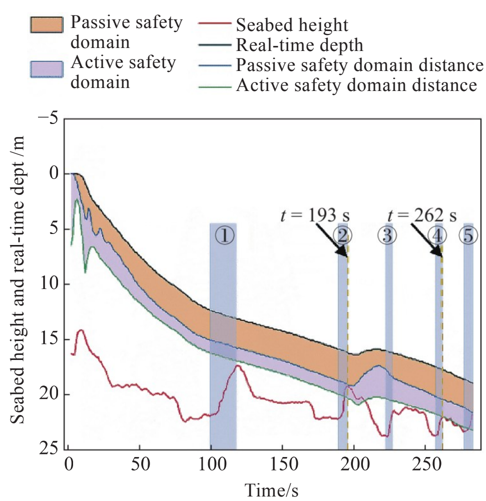


Fig. 14 Time sequence of AUV for fixed-height navigation

Then, the risk factors in the whole navigation are analyzed, as shown in Fig. 15. In time frames ①–⑤, the calculation risk factors change significantly, and the comprehensive risk factor in the five time frames changes by 0.31, 0.53, 0.15, 0.26 and 0.41. Although the maximum variation of the seabed height in the time frame ① is 4.4 m, there is no contact between the seabed height and the active safety domain boundary, and thus the AUV is less risky and the risk factor is low. In the time frame ②, the comprehensive risk factor increases to 0.79 at 193rd s, which is because the seabed height decreases sharply and is beyond the active safety domain boundary, thus increasing the seabed collision risk of the AUV; however, when the seabed height increases subsequently, the comprehensive risk factor decreases. At 262nd s or in time frame ⑤, the AUV continues to sail with negative trim, and the seabed height crosses the active safety domain boundary and is close to the passive safety domain boundary, increasing the risk factor; however, the risk factor is not the data source of the emergency response triggered by the AUV in this sailing, and the AUV sailing is ended by the bottom-level emergency response logic. According to the fixed-height navigation results (Fig. 15), in relative seabed navigation, when the seabed height crosses the active safety domain boundary, the AUV becomes more hazard. Meanwhile, the change of the comprehensive risk factor is strongly correlated with the change of the seabed height, and it can reduce the false emergency decision-making warning, Therefore, the emergency response can be triggered in time when the AUV is in actual distress, improving the seabed safety of AUV navigation.

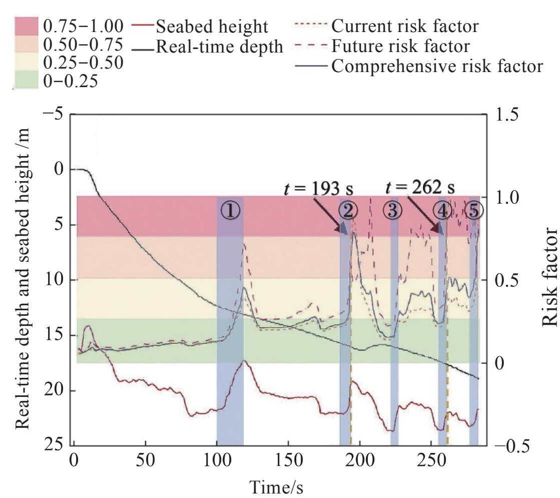


Fig. 15 Calculation of risk factor for fixed-height navigation

5 Conclusion

Inspired by the ship safety domain, this paper proposes a dynamic seabed safety domain model of the AUV based on the trim and velocity, and then establishes the tiered emergency response strategies. The lake test is also conducted under rough terrain to verify the rationality and effectiveness of the seabed emergency warning logic and framework of the AUV.

In the fixed-depth navigation, when the seabed height is far from the active safety domain, the comprehensive risk factor changes only by 0.08 although the seabed height changes by more than

10 m, suggesting that there is a weak dependency of AUV's comprehensive risk factor on the seabed height change. Therefore, the seabed emergency warning strategies will not cause false emergency decision-making warning caused by frequently changing seabed heights under rough terrain, thus improving the safety of the AUV navigation.

In the fixed-height navigation, when the seabed height is close to or beyond the active safety domain boundary, the AUV comprehensive risk factor is obviously correlated with the seabed height change. Therefore, when navigating over undulating terrain, the AUV can reduce the missed alarms in emergency decision-making by predicting the real-time state and calculating the comprehensive risk factor, thus improving the safety of the AUV navigation.

References

[1] FENG Z P. A review of the development of autonomous underwater vehicles (AUVs) in western countries [J]. Torpedo Technology, 2005, 13(1): 5−9 (in Chinese).

[2] XU Y R, PANG Y J, GAN Y, et al. AUV-state-of-the-art and prospect [J]. CAAI Transactions on Intelligent Systems, 2006, 1(1): 9−16 (in Chinese).

[3] BRITO M P, GRIFFITHS G. A Markov chain state transition approach to establishing critical phases for AUV reliability [J]. IEEE Journal of Oceanic Engineering, 2011, 36(1): 139−149.

[4] ERNITS J, DEARDEN R, PEBODY M. Automatic fault detection and execution monitoring for AUV missions [C]//2010 IEEE/OES Autonomous Underwater Vehicles. Monterey, CA, USA: IEEE, 2011: 2−4.

[5] QUIDU I, HETET A, DUPAS Y, et al. AUV (redermor) obstacle detection and avoidance experimental evaluation [C]//OCEANS 2007-Europe. Aberdeen, UK: IEEE, 2007: 1−6.

[6] FUJII Y, TANAKA K. Traffic capacity [J]. Journal of Navigation, 1971, 24(4): 543−552.

[7] GOODWIN E M. A statistical study of ship domains [J]. Journal of Navigation, 1975, 28(3): 328−344.

[8] TAM C K, BUCKNALL R, GREIG A. Review of collision avoidance and path planning methods for ships in close range encounters [J]. Journal of Navigation, 2009, 62(3): 455−476.

[9] PIETRZYKOWSKI Z, URIASZ J. The ship domain-a criterion of navigational safety assessment in an open sea area [J]. Journal of Navigation, 2009, 62(1): 93−108.

[10] LEWISON G R G. The risk of a ship encounter leading to a collision [J]. Journal of Navigation, 1978, 31(3): 384−407.

[11] DAVIS P V, DOVE M J, STOCKEL C T. A computer simulation of marine traffic using domains and arenas [J]. Journal of Navigation, 1980, 33(2): 215−222.

[12] HEGDE J, UTNE I B, SCHJØLBERG I, et al. Application of fuzzy logic for safe autonomous subsea IMR operations [C]//Proceedings of the 25th European Safety and Reliability Conference. Zurich, Switzerland: ESREL, 2015: 415−422.

[13] KUCHAR J E, DRUMM A C. The traffic alert and collision avoidance system [J]. Lincoln Laboratory Journal, 2007, 16(2): 277−296.

[14] ERLIEN S M, FUJITA S, GERDES J C. Shared steering control using safe envelopes for obstacle avoidance and vehicle stability [J]. IEEE Transactions on Intelligent Transportation Systems, 2016, 17(2): 441−451.

[15] WANG H J, ZHAO D H, BIAN X Q, et al. Research on autonomous planning for AUV in unstructured environment [C] //International Conference on Intelligent Computing. Kunming, China: Springer, 2006: 586−599.

[16] SUH J, KIM B, YI K. Design and evaluation of a driving mode decision algorithm for automated driving vehicle on a motorway [J]. IFAC-PapersOnLine, 2016, 49(11): 115−120.

[17] HEGDE J, UTNE I B, SCHJØLBERG I. Development of collision risk indicators for autonomous subsea inspection maintenance and repair [J]. Journal of Loss Prevention in the Process Industries, 2016, 44: 440−452.

[18] HEGDE J, HENRIKSEN E H, UTNE I B, et al. Development of safety envelopes and subsea traffic rules for autonomous remotely operated vehicles [J]. Journal of Loss Prevention in the Process Industries, 2019, 60: 145−158.

[19] SHI S D. Maneuverability of submarine [M]. Beijing: National Defense Industry Press, 1995: 174−177 (in Chinese).

[20] PRESTERO T. Verification of a six-degree of freedom simulation model for the REMUS autonomous underwater vehicle [D]. Boston, Massachusetts, USA: Massachusetts Institute of Technology, 2009.

基于动态安全领域的水下机器人近底应急决策

安金鑫，杨少龙*，向先波，董东磊
华中科技大学 船舶与海洋工程学院，湖北 武汉 430074

摘 要：［**目的**］为了保障复杂未知环境下自主式水下机器人（AUV）的安全，防止意外触底，提出AUV近底动态安全领域模型，建立分级应急响应措施。［**方法**］建立AUV垂直面运动模型并通过超越试验对比验证，求解主动安全领域及被动安全领域距离，建立AUV近底航行动态安全领域模型，基于该模型设计AUV应急控制系统与应急策略。基于实时纵倾和对底高度状态，计算当前及未来危险系数，通过分配权重系数求得综合危险系数，用于指导AUV应急响应决策。［**结果**］通过分析湖试定深和定高航行试验，当河床高度相距AUV主动安全领域边界较近时，综合危险系数与河床高度的相关性较强，反之则较弱。结果表明，AUV应急控制系统在起伏地形下作业时能减少应急决策虚警，而在近底航行作业时又能减少应急决策漏警，从而实现在复杂起伏地形下近底航行时的合理应急决策。［**结论**］基于垂直面运动方程建立的近底安全领域模型与应急响应策略能够用于AUV水下航行近底危险实时预测，可提高AUV水下自主航行的安全性。

关键词：自主式水下机器人；安全领域模型；近底避险；应急决策