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System Reliable Probability for Multi-AUV Cooperative Systems under the Influence of Current

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Real multi-Autonomous Underwater Vehicle (AUV) cooperative systems operate in complicated marine environments. The interaction between a multi-AUV cooperative system and its marine environment will affect the reliability of the system. Current is an important influencing factor of multi-AUV cooperative systems. A reliability index of multi-AUV cooperative systems known as System Reliable Probability (SRP) is proposed in this study. A method to calculate SRP is introduced, and the influence of current on SRP is discussed in detail. Current is considered an attack source, and the degree of its influence on SRP is calculated. As an example, the performance of this method is shown on two multi-AUV cooperative systems. Results show that the influence of the same current environment on different structures of the multi-AUV cooperative systems differs. This result provides a reference for the structure selection of multi-AUV systems. This study provides a practical method to estimate the reliability of multi-AUV cooperative systems.

KEYWORDS

1. System Reliable Probability. 2. Multi-AUV cooperative system. 3. Current.

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1. INTRODUCTION. The increasing exploitation of the oceans has prompted the development of Autonomous Underwater Vehicles (AUVs) toward small, structurally simplified, intelligent, hybridised and grouped formats. Reliability studies on multi-AUV cooperative systems are relevant to their development and are becoming increasingly important as these systems are brought into practical use (Maurelli et al., 2012; Waldmann et al., 2014; Sun et al., 2013; Li et al., 2012).

The marine environment is extremely rigorous. Marine environments include different factors, such as temperature, depth, seawater density and salinity, shock, vibration, ocean currents and noise, all of which increase the possibility of system failure. Reliability studies will help gauge the capability of multi-AUV cooperative systems to complete collaborative tasks effectively in various actual marine environments. Meanwhile, reliability studies that consider marine environment factors approach real engineering applications and guide accurate application of multi-AUV cooperative systems. In this study, current is selected as an environmental factor, and its influence on System Reliable Probability (SRP) for multi-AUV cooperative systems is studied.

Few reliability studies on multi-AUV cooperative systems are currently available (Liang et al., 2017; 2016). Reliability studies on other cooperative systems, such as multi-Unmanned Aerial Vehicle (UAV) cooperative systems, multi-robot cooperative systems, and multi-ship cooperative systems, exhibit certain reference values.

Gerkey et al. (2003) analysed the reliability of cooperative systems, improved communication protocols, and enhanced the reliability of systems within the design of a multi-robot and sensor cooperative system. On the basis of the network characteristics of multi-ship cooperative systems, Liu et al. (2006) summarised the eight main influencing factors of the reliability of multi-ship cooperative system networks and evaluated their reliability. Andrews et al. (2008) assessed the mission reliability of multi-UAV cooperative systems, wherein a whole task was divided into many stages of mission objectives and the effect of the decision-making process on mission reliability of multi-UAV cooperative systems was analysed. Furthermore, a decision-making process of high mission reliability was introduced. Liu et al. (2010) used formation pictures to depict the network topology structure of multi-Unmanned Underwater Vehicle (UUV) cooperative systems. A model of a multi-UUV cooperative system networks was described using matrix graphs based on matrix and graph theories. A multi-scale vulnerability assessment method was introduced and a vulnerability assessment method for multi-UUV cooperative systems was proposed. Rabbath and Léchevin (2010) studied the failures and errors affecting the reliability of multi-UAV cooperative systems; their health status estimation methods for improving the reliability of UAV fleets were described.

The ongoing evolution of science and technology has increased the utilisation of multi-AUV cooperative systems. In practical applications, the multi-AUV cooperative system operates in and interacts with complex marine environments. Therefore, systems must face many uncertain challenges presented by their surroundings. Modern multi-AUV cooperative systems will include not only advanced individual AUVs but also effective and complex methods of AUV collaboration. However, as the sophistication of navigation and control components in multi-AUV systems increases (Wang et al., 2018a; 2018b; Paull et al., 2014), the sensitivity of the system to its surroundings also increases. As a result, a change in marine environment considerably influences the reliability of the system.

The environmental factors that influence the reliability of multi-AUV cooperative systems include but are not limited to seawater temperature, waves, ocean currents and internal waves. The collaborative communication and detection results of each AUV within the system are affected by the vertical distribution of water temperature. When a multi-AUV system is in motion, an individual AUV will be affected by internal waves if it is in an internal wave zone, thereby causing running track fluctuations. The up and down reverse flows of internal waves will also produce vibration in the horizontal direction; this condition influences the navigational stability of a specific AUV and results in yawing (Xu and Zou, 2009). Internal waves can even lead to breaking of a specific AUV away from the system. All these possibilities show that elements of the marine environment can considerably influence the reliability of a multi-AUV cooperative system. Therefore, gaining accurate information on the marine environment and using it to analyse and produce scientific decisions on the reliability of the system are a focus of reliability studies on multi-AUV cooperative systems.

The marine environment is affected by many factors. Influence principles are complex and subject to coupling. International research on the effects of marine environment on multi-AUV cooperative systems is limited, and analysis on possible outcomes is rare and focuses on some aspects of performance indicators for a single AUV and its environmental interaction. Similarly, real-world ocean experiments involving multi-AUV cooperative systems are few, and test data on the effect of marine environmental parameters on such systems are limited. As a result, reliability analyses on multi-AUV cooperative systems under a large number of marine environmental factors are extremely difficult to conduct. Thus, a number of vital elements of the marine environment are selected in this study, and their influences are analysed. These elements are considered in the reliability indices of multi-AUV cooperative systems to obtain some functional models.

The rest of this paper is organised as follows. In Section 2, SRP is proposed as a reliability index of multi-AUV cooperative systems, and the calculation method is introduced. In Section 3, the influence of current is considered in SRP. In Section 4, two multi-AUV cooperative systems of 13 AUVs are analysed under the influence of current to show the performance of SRP. Section 5 draws some useful conclusions of this work.

2. SYSTEM RELIABLE PROBABILITY (SRP).

Invulnerability research on topological structures is important in reliability research on multi-AUV cooperative system networks (Albert et al., 2000). Attack (see Albert et al., 2000) information can be divided into three modes (Seyyedmohsen, 2010; Chen and Zhang, 2006; Deng et al., 2008): zero information, complete information and incomplete information. Zero information attack occurs when the information of the network structure is not contained in the attack information and nodes are randomly targeted by the attack. Complete information attack refers to the situation in which the attack information contains all the network structure information, and the key nodes are preferentially attacked under a certain degree of importance criteria. In reality, zero and complete information attacks are two ideal extreme cases. In most cases, especially under complex marine environments and enemy interference attacks, the attack is neither a zero-information attack nor a complete information attack. Most attacks are incomplete information attacks. In other words, one part of the information is known, and the other part of the information is unknown.

A multi-AUV cooperative system network can be abstracted to a structural graph $G = (V, E)$ (Schneider et al., 2013; Zuev et al., 2015), where $V = \{v_1, v_2, v_3, \ldots, v_N\}$ represents a collection of individual AUVs that comprise the system. $E = \{e_1, e_2, e_3, \ldots, e_W\}$ shows a collection of communication links between two individual AUVs. $N = |V|$ is the number of individual AUVs in system G. $W = |E|$ is the number of the communication links in G. d_i is defined as the communication degree of v_i, that is, the number of communication links of v_i, and $0 < d_i < N$. $\bar{k} = \frac{\sum_i d_i}{N}$ is defined as average communication degree of G, and $\bar{k} = \frac{2W}{N}$.

The individual AUVs of a multi-AUV cooperative system are rearranged by descending order according to their communication degree (Carlesi et al., 2011). When the communication degree is the same, the arrangement is random. After rearrangement, the sequence number of v_i is r_i. Then, $\{d'_1, d'_2, \ldots, d'_r, \ldots, d'_N, \}$ is the communication degree sequence of G, where $d'_1 \geq d'_2 \geq \cdots \geq d'_N$.

Under an incomplete information attack, a measurement of attack information is an important foundation and prerequisite of invulnerability modelling and analysis on multi-AUV cooperative systems. This study supposes a number of S AUVs are attacked. $S = N\alpha$, where α indicates the proportion of individual AUVs attacked, namely, the parameter of attack information range. Accordingly, a large value of α indicates that the information is extensive. Under a zero information attack ($\alpha = 0$, random failure), the attack information range is zero. Under a complete information attack ($\alpha = 1$, intended failure), the attack information range is the whole system.

For G, ε_i is defined as the state of an individual AUV (v_i) with information obtained by the attacker. If the communication degree sequence number r_i of the individual AUV (v_i) has been acquired by the attacker, then $\varepsilon_i = 0$; otherwise, $\varepsilon_i = 1$. Depending on the state of an individual AUV with information that has been obtained (the value of ε_i), a collection of individual AUVs V of G can be divided into two parts: individual AUVs with information that has been acquired V_s (when $\varepsilon_i = 1$) and individual AUVs with information that has not been obtained V_U (when $\varepsilon_i = 0$).

The precision of attack information, combined with the sequence number r of individual AUV v_i, is considered. Then, an auxiliary variable is constructed as:

$$\phi_i = r_i^{-\delta} \tag{1}$$

where $\delta \in [0, \infty)$ is the parameter of the attack information accuracy. In a single sample, the probability of the individual AUV v_i to be drawn is:

$$\eta_i = \frac{\phi_i}{\sum_{t=1}^{N} \phi_t} = \frac{r_i^{-\delta}}{\sum_{t=1}^{N} r_t^{-\delta}} \tag{2}$$

Evidently, a large value of δ indicates a high probability of obtaining the information of an individual AUV with a large communication degree, that is, the accuracy of attack information is high.

When $\delta = 0$, the probability of the individual AUV v_i to be drawn is $\eta_i = \frac{\phi_i}{\sum_{t=1}^{N} \phi_t} = \frac{r_i^{-\delta}}{\sum_{t=1}^{N} r_t^{-\delta}} = \frac{1}{N}$. In other words, the information of each individual AUV is acquired with equal probability. This kind of attack information is called random information.

When $\delta = \infty$, $\sum_{t=1}^{N} r_t^{-\infty} = \sum_{t=1}^{N} t^{-\infty} = 1$. If $r_j = 1$, then the probability of the individual AUV v_i to be drawn is $\eta_i = \frac{1}{\sum_{t=1}^{N} r_t^{-\infty}} = 1$ when $i = j$; the probability of the individual AUV v_i to be drawn is $\eta_i = \frac{r_i^{-\infty}}{\sum_{t=1}^{N} r_t^{-\infty}} \frac{r_i^{-\infty}}{1^{-\infty}+2^{-\infty}+3^{-\infty}+4^{-\infty}+\cdots+r_i^{-\infty}} = \frac{0}{1+0+0+0+\cdots+0} = 0$ when $i \neq j$. Therefore, the information of an individual AUV with the largest communication degree is always acquired first. This kind of attack information is called priority information.

To avoid drawing out individual AUVs with a large communication degree repeatedly, that is, repeated attack, the acquisition process of the attack information is abstracted into an unequal probability sampling schedule without replacement (Ma and Lu, 2009; Schillewaert et al., 1998; Robson, 2002).

First, an individual AUV sample is drawn-out in accordance with the probability of $\eta_i = \frac{\phi_i}{\sum_{t=1}^{N} \phi_t} = \frac{r_i^{-\delta}}{\sum_{t=1}^{N} r_t^{-\delta}}$. Second, the remaining AUVs are rearranged from a large to a small communication degree. The auxiliary variable ϕ_i and the probability of being drawn-out η_i are recalculated. Third, a sample is drawn-out on the basis of the newly calculated η_i. Finally, the second and third processes are repeated until S samples are drawn-out.

A measure for determining the network collapse is (Sun et al., 2013b; Sun and Wang, 2013; Gupta et al., 2013):

$$z = \frac{\sum_{k=m}^{M} k(k-1)p(k)q(k)}{\sum_{k=m}^{M} kp(k)} \tag{3}$$

where k is the communication degree of an individual AUV, $p(k)$ is the communication degree distribution, $q(k)$ is the unaffected probability of an individual AUV with communication degree denoted as k, m is the minimum communication degree in the system and M is the maximum communication degree. If $z < 1$, then the multi-AUV cooperative system is in a state of collapse; if $z > 1$, then the system is not in a state of collapse; if $z = 1$, then the system is in a state of critical collapse.

When the portion of known information V_s is determined, the unaffected probability $q(k)$ of an individual AUV with communication degree denoted as k can be determined. As long as the communication degree distribution $p(k)$ is given, whether the multi-AUV cooperative system has collapsed or not can be determined.

Definition: System Reliable Probability (SRP) is defined as:

$$\beta = \lim_{n\to\infty} \frac{b(n)}{n} \approx \frac{b(n)}{n} \tag{4}$$

where n is the number of random experiments under certain attack condition and information. $b(n)$ is the number of experiments that will not collapse in n random experiments. If n is sufficiently large, then $\frac{b(n)}{n}$ will approach β.

3. OCEAN CURRENT INFLUENCE.

An individual AUV of a multi-AUV cooperative system will inevitably be affected by ocean currents during sailing. For a relatively slow AUV (or one with no rapid speed requirement), ocean currents will considerably affect its navigation, positioning and communication with other AUVs. For example, an individual AUV executing a task within a system is usually positioned intermittently. Between two instances of positioning, the AUV usually uses inertial navigation to sail toward the target location. In the inertial navigation process, which is influenced by ocean currents, the AUV may deviate from the established track position prior to its next positioning, and the tracks of certain AUVs may exhibit large drift. Ultimately, the entire system will suffer from unexpected effects.

In oceanography studies, the speed of ocean currents in the east–west direction is usually expressed by the symbol u, whereas the speed of ocean currents in the north–south direction is usually expressed by the symbol v (Liang, 2013); this rule is followed here. The relationship between a multi-AUV cooperative system and ocean currents is shown in Figure 1.

In Figure 1, S_1 is the maximum operating area of the multi-AUV cooperative system, the shaded part S_2 is the area where sea currents exist, u represents the velocity of currents in the east–west direction, v represents the velocity of currents in the north–south direction, and S_3 is the minimum rectangular area that contains the multi-AUV cooperative system.

When the interfering factor of ocean current is considered alone, the attack proportion is:

$$f = \frac{S_2 \cap S_3}{S_3} \tag{5}$$

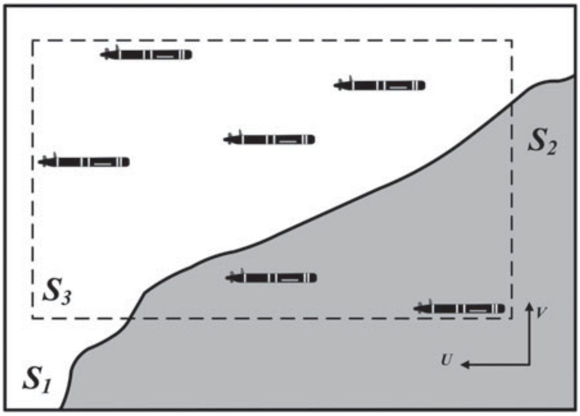

Figure 1. Relationship between Multi-AUV cooperative systems and ocean currents.

The attack information range is:

$$\alpha = \frac{S_2}{S_1} \tag{6}$$

When the interference of simple currents belongs to unconscious attacks, the attack information accuracy is $\delta = 0$.

For an AUV, the attack strength of the multi-AUV cooperative system subject to interference of ocean currents is mainly reflected by the noise interference flow. According to Blokhin Zaitsev's theory (Liu and Lei, 2010), the attack strength can be obtained by:

$$c = k\bar{v}^n \tag{7}$$

where k is a constant, n is an amount comprising AUV underwater linearity and other factors, and $\bar{v}$ represents the speed of ocean currents. Combined with the velocity u of the west–east direction and v of the north–south direction, $\bar{v}$ can be expressed as:

$$\bar{v} = \sqrt{u^2 + v^2} \tag{8}$$

Definition: $\rho = \rho_0 \cdot e^{-C}$ is the probability that the multi-AUV collaborative system is still available when a single AUV is attacked, where C is the attack strength and indicates the degree of interference from the harsh marine environment or the strength of the hostile attack. The value range of C is $(0, +\infty)$. A large value of attack strength C indicates a high interference degree of the harsh marine environment or high intensity of the attack by the hostile forces. ρ_0 is the benchmark reliability of a single AUV, that is, the probability that a single AUV is available in the ideal case of no harsh marine environment interference or hostile attack.

4. EXAMPLE.

A multi-AUV cooperative system of 13 AUVs is analysed as an example. Figure 2 shows the distribution of the 13 AUVs and ocean current. Figure 3 shows a multi-AUV cooperative system topology structure operating in a sea area of

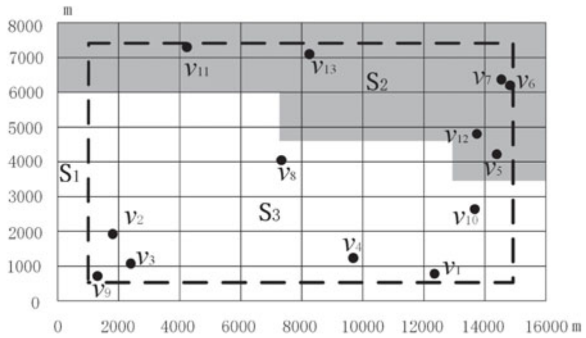

Figure 2. Distribution of AUVs and ocean current.

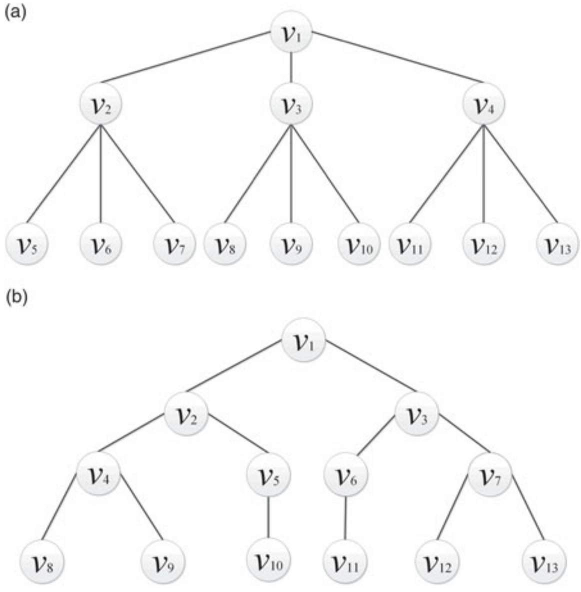

Figure 3. Two topological structure schemes.

16,000 × 8,000 m. The system comprises 13 AUVs, which will jointly perform a task. The coordinates of the 13 AUVs are presented as follows:

v_1 : (12,300, 750)
v_2 : (1,950, 1,950)
v_3 : (2,400, 1,050)
v_4 : (9,600, 1,200)
v_5 : (14,400, 4,200)
v_6 : (14,700, 6,150)
v_7 : (14,550, 6,300)
v_8 : (7,350, 4,050)
v_9 : (13,650, 2,700)
v_{10} : (12,300, 750)
v_{11} : (4,200, 7,500)
v_{12} : (13,800, 4,950)
v_{13} : (8,250, 7,050)

The speeds of ocean current in the west–east and north–south directions are $u = 5$ cm/s and $v = 2$ cm/s, respectively.

Table 1. Randomised simulation data of reliable and collapsed systems.

Number of random experiments n	Number of reliable systems $b(n)$	Number of collapsed systems $1 - b(n)$	System Reliable Probability β
10,001	8,678	1,323	0·8675
10,001	8,742	1,259	
10,001	8,661	1,340	
10,001	8,679	1,322	
10,001	8,710	1,291	
10,001	8,592	1,409	
10,001	8,657	1,344	
10,001	8,647	1,354	
10,001	8,631	1,370	
10,001	8,759	1,242	

Scheme A:

The interaction of the SRP with environmental factors centres on the attack proportion f, attack information range α, attack information accuracy δ and attack strength c. These parameters are in turn closely related to the effects of ocean currents.

The shaded area S_2 in Figure 2 is the region with ocean current. The entire area of S_1 (16,000 × 8,000 m) is the region where the multi-AUV cooperative system navigates. S_3, which is surrounded by a dotted line, is the smallest rectangle that contains all the AUVs. From the data in Figure 2, the following data can be calculated:

$$S_1 = 1{\cdot}04 \times 10^8\, m^2, \quad S_2 = 4{\cdot}864 \times 10^7\, m^2,$$
$$S_3 = 8{\cdot}118 \times 10^7\, m^2, \quad S_2 \cap S_3 = 2{\cdot}4735 \times 10^7\, m^2.$$

The attack proportion is $f = \frac{S_2 \cap S_3}{S_3} = 0{\cdot}30$. The attack information range is $\alpha = \frac{S_2}{S_1} = 0{\cdot}47$. The current attacks are unconscious ones. The attack information accuracy is $\delta = 0$. The current speed is $\bar{v} = \sqrt{u^2 + v^2} = 0{\cdot}054$ m/s. The attack strength is $c = k\bar{v}^n$, where $k = 1{\cdot}2 \times 10^5$ and $n = 2$; thus, $c = k\bar{v}^n = 349$.

For this multi-AUV cooperative system, $f = 0{\cdot}3$; thus, $Nf = 3{\cdot}9$. When rounded down, the nearest whole number of actual attacked AUVs is three. $N\alpha = 6{\cdot}11$ when $\alpha = 0{\cdot}47$. $N\alpha$ can be rounded to six, as the number of AUVs within V_s. The standard reliability of an individual AUV is taken as $\rho_0 = 0{\cdot}5$. Thus, the reliability of an individual AUV is $\rho = \rho_0{\cdot}e^{-c} \approx 0$. Therefore, an individual AUV under attack is nearly completely unreliable.

Data after a large number of randomised simulations can be obtained, as shown in Table 1, in accordance with the standards of disintegration and collapse.

The System Reliable Probability (SRP) of Scheme A is 0·8675.

Scheme B:

Similar to Scheme A, λ, α, δ, and c are defined.

Under the same ocean environment of Scheme A, the following data can be the same:

$$S_1, \quad S_2, \quad S_3, \quad S_2 \cap S_3, \quad f, \quad \alpha = \frac{S_2}{S_1}, \quad \delta, \quad \bar{v} = \sqrt{u^2 + v^2}, \quad c = k\bar{v}^n,$$
$$Nf, \quad N\alpha, \quad \rho = \rho_0 \cdot e^{-c}.$$

Table 2. Randomised simulation data of reliable and collapsed systems.

Number of random experiments n	Number of reliable systems $b(n)$	Number of collapsed systems $1 - b(n)$	System Reliable Probability β
10,001	9,121	880	0·8921
10,001	9,011	990	
10,001	8,879	1,122	
10,001	8,791	1,210	
10,001	8,893	1,108	
10,001	8,872	1,129	
10,001	8,668	1,333	
10,001	8,984	1,017	
10,001	9,007	994	
10,001	8,990	1,011	

Data after a large number of randomised trials can be obtained, as shown in Table 2, in accordance with the standards of disintegration and collapse.

The System Reliable Probability (SRP) of Scheme B is 0·8921.

The SRP of Scheme A is lower than that of Scheme B. In other words, the invulnerability of Scheme A is low when nodes are influenced by the ocean current environment, as shown in Figure 2. Under the same current environment as in Figure 2, the structure of Scheme B is more reliable than that of Scheme A.

The influence of the same current environment on different structures of the multi-AUV cooperative systems differs. This result provides a reference for the structure selection of multi-AUV systems.

5. CONCLUSION.

Multi-AUV cooperative systems operate in complex marine environments, and an inevitable interaction occurs between the systems and their surroundings. The influence of ocean current on System Reliable Probability is analysed here by assessing attack information. Such consideration is necessary for this index to approach a realistic representation of the reliability of multi-AUV systems.

This study can be further explored by determining the reason behind the higher reliability of Scheme B than that of Scheme A and by using additional structures. The different strength zones of ocean current should also be considered.

This paper focuses on the impact of currents on System Reliable Probability (SRP). Other marine environmental factors, such as temperature, depth, seawater density and salinity, shock, vibration and noise require further research.

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