Hindawi
Journal of Advanced Transportation
Volume 2019, Article ID 1323105, 10 pages
https://doi.org/10.1155/2019/1323105

Research Article

Design and Analysis of Collaborative Unmanned Surface-Aerial Vehicle Cruise Systems

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Received 8 August 2018; Revised 8 December 2018; Accepted 11 December 2018; Published 14 January 2019

Academic Editor: Yair Wiseman

With the increasing application of unmanned surface vehicle-unmanned aerial vehicles (USV-UAVs) in maritime supervision, research on their deployment and control is becoming vitally important. We investigate the application of USV-UAVs for synergistic cruising and evaluate the effectiveness of the proposed collaborative model. First, we build a collaborative model consisting of the cruise vehicles and communication, detection, and command-and-control networks for the USV-UAV. Second, based on an analysis of the problems faced by collaborative USV-UAV systems, we establish a model to evaluate the effectiveness of such synergistic cruises. Third, we propose a weighting method for each evaluation factor. Finally, a model consisting of one UAV and four USVs is employed to validate our synergistic cruise model.

1. Introduction

An unmanned surface vehicle (USV) can be used for various tasks in different application areas such as intelligence surveillance of coasts, port and border security, autonomous searching, signals transmission between air and underwater vehicles, and submarine protection. An unmanned aerial vehicle (UAV) can be utilized in many missions including search-and-rescue operations, aerial surveillance, and remote-sensing applications.

Two of the purposes of maritime safety administration are to build a modern supervision platform and to realize intelligent maritime supervision based on an electronic patrol system. In recent years, electronic patrol systems have been employed under the concept of perception ships in maritime supervision [1].

Intelligent vehicles, unmanned surface vehicle(s), and unmanned aerial vehicle(s) (UAVs and USVs) are widely used in military and civilian applications. Their flexible manipulation and mobility enable them to collect surveillance, reconnaissance, and road traffic information [2]. Due to the small size and lighter weight of UAVs and USVs, they can be deployed quickly by small teams near the mission site, without substantial physical infrastructure. Their relatively low deploy cost also permits deployment more frequently and riskier missions in challenging terrains. A single UAV or a single USV can fulfil nearly all aspects of a task, such as both searching a large area efficiently and providing high-fidelity reconnaissance data, but some data like imagery is always difficult for a single UAV or single USV. An USV can get up close to objects or targets to provide high-resolution imagery, can be fast-moving, and also can cover wide areas quickly above most obstacles or danger zones. But USVs cannot carry large accurate sensors and execute long run-time missions. In contrast, an UAV can carry large sensors and execute long run-time missions, but it can only provide low-resolution images of targets at a distance. Generally, the UAV can fly in an altitude of at least some hundreds of meters. Due to this different characteristic compared to the USV, the narrow beam demerit of LIDAR based rangefinder [3] would not be a serious obstruction to the UAV. Hence, a LIDAR based rangefinder could be much more suitable than the ultrasonic rangefinder [3] to be equipped with the UAV for objects detection. Additionally, this characteristic of the USV also impacts the selection and use of a mechanism to decode information from camera pictures. Even though RFID is the most reliable method compared to Bluetooth and OCR to conduct the information decoding task [4], its short range is a barrier for its application in UAV. Therefore, it should be advantageous to use both in a system to leverage these complementary properties. We purpose a collaborative model that combines their strengths. Through this collaboration, UAVs and USVs can cruise synergistically and provide richer information to an electronic patrol system. Such a collaborative operation may even provide more accurate, real-time navigation information for traffic organization, thus ensuring water traffic safety and greatly improving the efficiency of maritime supervision.

An USV-UAV collaborative system can accomplish several tasks such as surveillance and reconnaissance, search and rescue, mapping unknown environment, and payload transportation. Such synergetic cruise has many advantages such as the ability to handle more complex tasks, ability to tackle a task with increased robustness through redundancy, increased efficiency through task distribution, and reduced cost of operation. Therefore, collaboration among multiple vehicles should enhance the performance, adaptability, and flexibility and fault tolerance. To measure the ability of UAVs and USVs to undertake and complete such synergetic cruises, it is important to evaluate both their individual and combined effectiveness.

In this paper, we first build a model of USV-UAV(1,n) synergetic cruises and analyze its effectiveness. We then design an effectiveness evaluation model for such synergetic cruises. Finally, we propose a method to determine weight factors for this evaluation based on a cloud model and the Delphi method. Such a model may not only collaborate UAVs and USVs strengths but also provide more accurate, real-time navigation information for synergetic cruise, thus ensuring water traffic safety and greatly improving the efficiency of maritime supervision, environmental protection, better monitoring, coastal protection, and ship navigation.

The organization of this paper is as follows. Section 2 presents literature review. A description of the USV-UAV(1,n) synergetic cruises and its effectiveness issue is formulated in Section 3. Effectiveness evaluation model for the proposed collaborative model is considered in Section 4. The empowerment system to give the weight of each factor is explained in Section 5. Example conducted to explain the use of the effectiveness evaluation model is reported in Section 6. Finally, Section 7 is devoted to conclusion.

2. Literature Review

USVs have been widely used for various tasks in different application areas such as intelligence surveillance of coasts, port and border security, autonomous searching, signals transmission between air and underwater vehicles, and submarine protection [5, 6]. UAVs have been utilized extensively in many tasks including search and rescue operations, aerial surveillance, and sensing applications [7]. In recent years, the collaborative unmanned vehicles and their applications have been extensively studied.

At present, many studies of collaborative unmanned vehicles focus on UAVs, UGVs, and USVs and related technologies, ability, and mechanism of collaboration. Ryan et al. [8] implemented a UAV system that performed collaborative sensing tasks under the supervision of a single user and also applied a collaboration algorithm that combined shared and local information to minimize the global cost of the mission. To support multiple-UAV operations in tactical scenarios, Tortonesi et al. [9] studied multiple UAV coordination and communications in tactical edge networks. Jameson et al. [10] studied the autonomy and collaboration ability of a team of vehicles to relieve the burden of providing continuous oversight of UAV operations, enabling the effectiveness of teams of vehicle to be improved. Bastianelli et al. [11] studied collaborative mechanisms between unmanned vehicles. In order to close the surveillance gaps of the littoral state, Chng [12] comprehensive benefit the unmanned platforms containing UAVs and USVs and manned patrol crafts (PCs) to develop two concept of operations (CONOPS) with the purpose of detecting two key types of maritime terrorism threats including large ships (LSs) and small boasts (SBs). Furthermore, the analytical models built by incorporating both differential equations and probabilistic arguments was used to assess the CONOPS. The above studies provide a good reference for studying synergetic cruises and the effectiveness of USV-UAV systems.

Collaboration among multiple vehicles enhances the performance, adaptability, and flexibility and fault tolerance [13–15]. Therefore, this paper will focus on collaboration between UAV and USV. Such collaboration has many advantages such as the ability to handle more complex tasks, ability to tackle a task with increased robustness through redundancy, increased efficiency through task distribution, and reduced cost of operation. USV-UAV collaborative system can accomplish several tasks such as surveillance and reconnaissance, search and rescue, mapping unknown environment, and payload transportation. In this paper, USV-UAV collaborative system is used to cruise for providing information to an electronic patrol system. In addition, the effectiveness issue of such collaborative system is another core research part.

3. USV-UAV Synergetic Cruises and Their Effectiveness

3.1. Synergetic Cruises. In practical applications, UAVs and USVs will be subject to mileage constraints. Relative to USVs, UAVs are smaller and faster and have a wider detection range but can only handle smaller task loads and are less capable of carrying large equipment. Both UAVs and USVs are limited in terms of the acquisition, processing, and control of information, as well as in their ability to handle complex tasks and respond to changes in work environment. Therefore, by integrating the advantages of USVs and UAVs, a collaborative system can be proposed to overcome tasks that may be difficult for single UAVs or USVs. Such a system would exhibit strong advantages, such as parallelism and robustness. For instance, during a USV-UAV collaborative system implementing its tasks, one of other UAVs will perform the tasks of the failed UAV provided that the

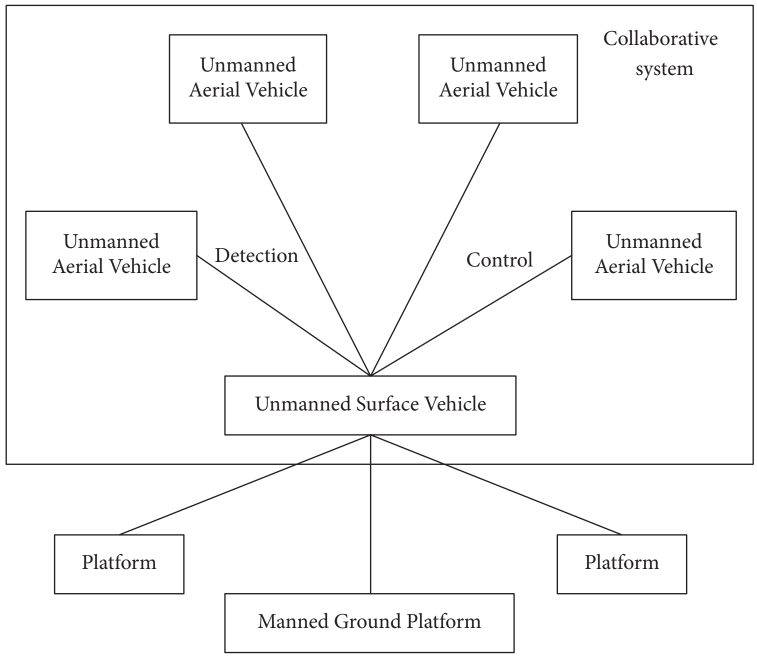

Figure 1: The model of USV-UAV(1,n) synergetic cruises.

collaborative system makes appropriate adjustments which guarantee that the system continues to complete the assigned tasks. However, for a single UAV system, the reliability of each UAV must be extremely high to ensure that the assigned tasks will be completed as scheduled.

In this paper, the USV-UAV synergetic cruise refers to a cruise model for collecting and processing water traffic information through an air-sea collaborative model. In this mode, the USV is the habitat platform and information centre for several UAVs, and the detection range has the USV as its centre and a radius equivalent to the range of the UAVs.

Depending on the number of assigned tasks, the USV-UAV synergetic cruises may include a single UAV and several USVs, a single USV and several UAVs, several USVs and several UAVs, or a single USV and a single UAV.

The USV-UAV synergetic cruise consists of multiple subsystems covering communications, navigation, detection, and command-and-control. Each subsystem has its own layers of complexity, making it difficult to build a universal mathematical model. This paper proposes the USV-UAV synergetic cruise model shown in Figure 1. The model consists of one USV and n (= 1, 2, 3,) UAVs and includes subsystems for command-and-control, communication, and detection.

The command-and-control subsystem is the nerve centre and is responsible for the control of the entire system (including the USV and UAVs) according to instructions from the manned ground platform (see Figure 1).

The communication subsystem is responsible for communication and data transfer between the manned ground platform and the USV-UAV system, as well as intrasystem communications. In this paper, the water moving target detection and tracking and static target detection are finished by multiple sensors based on infrared and visual images which are mounted on the UAVs. Then the data and video information are transmitted to the USVs via a wireless communication system. After that, the USV utilizes high-performance processor to process and integrate the information received from UAVs as well as through its own sonar, radar, and environment sensing device, which are transferred to the manned ground platform via satellite communication system. After analyzing the information, the manned ground platform transfers instructions about further cruise tasks to USV through satellite communication system. Finally, each UAV gets the instructions from USV through wireless communication system to take further actions.

The detection subsystem is a sensor network consisting of detection equipment aboard the USV and UAVs and is responsible for collecting information. The command-and-control function of the collaborative system is located on the USV.

In the collaborative system, the USV-UAVs send detection information about cruise objectives to the USV. The USV is responsible for decision-making and information integration, as well as controlling the UAVs. Upon receiving orders, the UAVs take the necessary actions.

3.2. Effectiveness Issue. The effectiveness of USV-UAV synergetic cruises directly affects the quality and quantity of information collected. If the cruise is ineffective, certain required information may be subject to intolerable delay, deletion, or omission. Hence, to improve the effectiveness of USV-UAV synergetic cruises, we analyze the major influencing factors and build a series of evaluation models.

USV-UAV synergetic cruises can be divided into three chronological stages. First, the command-and-control stage gathers cruise information and sets out the command-and-control of the entire synergy system. Second, the cruise stage detects information on the cruise objectives. Finally, the synergy stage integrates cognitive and detection synergy throughout the entire cruise. Accordingly, the overall effectiveness of USV-UAV synergetic cruises depends on (1) synergy capacity, (2) command-and-control capacity, and (3) cruise capacity.

Synergy capacity plays a key role, as it is responsible for linking the target detection system with the command-and-control system through the communication network. Hence, synergy guarantees that detected information from each platform can be shared with other platforms almost immediately and enables effective command of the USV and UAVs to complete the cruise tasks. Additionally, synergy capacity is influenced by the acquisition, distribution, and sharing of information.

The command-and-control capacity mainly relies on receiving and sending instructions, control ability, and robust performance. When cruise objectives are detected, the UAVs send detection information to the USV, which rapidly processes and integrates this data. The USV comprehensively treats this information so that UAVs can carry out further cruise tasks. The above processes involve the command-and-control.

The cruise capacity refers to the ability to acquire information on cruise objectives and complete cruise tasks. This cruise capacity directly affects the effectiveness and is impacted by changes in environment and detectivity. Detectivity is the ability of the detection platform to recognize and locate cruise objectives within the detection range. Environmental adaptability allows the synergy system to gather information by perceiving, recognizing, and understanding the natural environment.

4. Effectiveness Evaluation Model for USV-UAV Synergetic Cruises

We have identified the factors that influence the effectiveness of USV-UAV synergetic cruises systems. We can evaluate the overall effectiveness of the synergy model as

$$E = f\left(E_s, E_{cc}, E_c\right) = \omega_s E_s + \omega_{cc} E_{cc} + \omega_c E_c \tag{1}$$

where E_s, E_{cc}, and E_c denote the effectiveness of the synergy capacity, command-and-control capacity, and cruise capacity, respectively; and ω_s, ω_{cc}, and ω_c are their respective weights, respectively.

4.1. Evaluation of Synergy Capacity. Good synergy capacity will ensure that the USV-UAV system performs effectively. Factors affecting synergy capacity include the capability of information sharing, information distribution, and information acquisition. Thus, the evaluation model for the synergy capacity can be written as

$$E_s = \omega_{is} E_{is} + \omega_{id} E_{id} + \omega_{ia} E_{ia} \tag{2}$$

where E_{is}, E_{id}, and E_{ia} denote the effectiveness of information sharing, information distribution, and information acquisition, respectively; and ω_{is}, ω_{id}, and ω_{ia} are the weights of E_{is}, E_{id}, and E_{ia}, respectively.

4.1.1. Evaluation of Information Sharing. When the main control platform USV receives information from manned ground platforms, it will process and share this data across the synergetic cruises system. The whole process of information sharing is impacted by network reliability. The evaluation of information sharing is modelled as follows:

$$E_{is} = \lambda \frac{N_{is}}{\sum_{i=1}^{n} N_{iri}} \tag{3}$$

where $\lambda \in (0,1)$ is the network reliability, N_{is} is the amount of shared information from the main control USV in unit time, n is the number of ground platforms that transmit information to the main control USV in unit time, and N_{iri} is the amount of information that the main control USV receives from ground platforms in unit time.

4.1.2. Evaluation of Information Distribution. Information distribution reflects the ability of the main USV to transmit the information it receives to other platforms. This ability is heavily influenced by network reliability. The evaluation of information distribution is modelled as follows:

$$E_{id} = \lambda \frac{\sum_{i=1}^{n} N_{iai}}{N_{is}} \tag{4}$$

where $\lambda \in (0,1)$ represents network reliability, n is the number of platforms that receive information from the main control USV in unit time, N_{iai} is the amount of information received by non-main-control platforms in unit time, and N_{is} is the amount of information shared by the main control USV in unit time.

4.1.3. Evaluation of Information Acquisition. The connection status is measured by the digital communication success probability between all platforms communication systems. This plays a decisive role in the information acquisition ability of the system. The digital communication success probability is always calculated using the mistakenly believed rate P_e. The evaluation of information acquisition is therefore modelled as

$$E_{ia} = 1 - P_e \tag{5}$$

4.2. Evaluation of Command-and-Control Capacity. While the synergy capacity is in good condition, the command-and-control capacity is the key to ensuring that the USV-UAV system runs normally. The command-and-control capacity is affected by the reception and sending of instructions, control ability, and robust performance. Therefore, the evaluation of command-and-control capacity can be modelled as follows:

$$E_{cc} = \omega_{or} E_{or} + \omega_{ot} E_{ot} + \omega_{ic} E_{ic} + \omega_{rb} E_{rb} \tag{6}$$

where E_{or}, E_{ot}, E_{ic}, and E_{rb} denote the effectiveness of the instruction reception and instruction sending, control ability, and robust performance, respectively; and ω_{or}, ω_{ot}, ω_{ic}, and ω_{rb} are their respective weights, respectively.

4.2.1. Evaluation of Instruction Reception. Instructions are sent by the ground platform. The proportion of these instructions received by the main control USV determines the instruction reception ability. The evaluation model is therefore

$$E_{or} = \frac{N_r}{N_{gs}} \tag{7}$$

where N_r is the number of instructions received by the main control USV in unit time and N_{gs} is the number of instructions transmitted from manned ground platform in unit time.

4.2.2. Evaluation of Instruction Sending. After receiving instructions from the ground command-and-control platform, the main control USV may need to send commands to other platforms within the collaborative system. The evaluation of instruction sending is modelled as follows:

$$E_{ot} = \frac{\sum_{i=1}^{m} N_i}{N_{usv}} \tag{8}$$

where m stands for the number of platforms receiving instructions in unit time, N_i is the number of instructions received by each platform in unit time, and N_{usv} is the number of instructions sent by the main control USV in unit time.

4.2.3. Evaluation of Control Ability. In this paper, the control ability is represented by the efficiency with which instructions are followed by the cruise system. The command-and-control system in USV-UAV synergetic cruises has high timeliness requirements and must make decisions within a certain time. Beyond this allotted time period, the system effectively loses its command-and-control capacity. According to the process of command-and-control, this time period is determined by five components. The control efficiency is expressed as follows:

$$E_{ic} = \exp\left(\frac{-0.7T_{sum}}{T_{max}}\right) \tag{9}$$

where T_{max} is the allowed time of command-and-control and T_{sum} is actual total time of command-and-control.

$$T_{sum} = T_u + T_c + T_d + T_r + T_a \tag{10}$$

where T_u is the time from discovering a target to reporting to the main control USV; T_c is the time in which the main control USV fuses and disposes information; T_d is the time for the main control USV distributing cruise tasks; T_a is the time in which the main control USV monitors the cruise and makes adjustment.

4.2.4. Evaluation of Robust Performance. The robustness of performance is measured by the probability that the USV-UAV synergetic cruises will fail during cruise tasks. This probability is related to the mean time between failures of the USV and UAVs and the time required to perform tasks. The evaluation of robust performance is modelled as follows:

$$\begin{aligned} E_{rb} = {} & \delta\left(1-\eta_{usv}\right)\exp\left(\frac{-t_{usv}}{T_{usv}}\right) \\ & + \left(1-\delta\right)\left(1-\eta_{uav}\right)\exp\left(\frac{-t_{uav}}{T_{uav}}\right) \end{aligned} \tag{11}$$

where $\delta \in (0,1)$ is a constant; t_{usv} and t_{uav} denote the time taken by the USV and UAVs to perform tasks, respectively; and T_{usv} and T_{uav} denote the mean time between failures of the USV and UAVs, respectively; η_{usv} is the vulnerability coefficient of the USV; and η_{uav} is the average vulnerability coefficient of UAVs.

4.3. Evaluation of Cruise Capacity. The cruise capacity expresses the ability of the USV-UAV collaborative system to perform and implement cruise tasks. The two main factors influencing this capacity are environmental adaptability and detectivity. Therefore, the evaluation of cruise capacity can be modelled as follows:

$$E_c = \omega_{ea}E_{ea} + \omega_{id}E_{id} \tag{12}$$

where E_{ea} and E_{id} refer to the effectiveness of environment adaptability and detectivity, respectively; ω_{ea} and ω_{id} are their respective weights, respectively.

4.3.1. Evaluation of Environmental Adaptability. Environmental adaptability is the basis whereby the USV-UAV synergetic cruises system can realize intelligent cruising. This is affected by many factors and is therefore difficult to measure. Wang [16] analyzed environmental adaptability from the perspective of the variety of environments, time to adapt, and the scope of adapting environment. Because the USV-UAV synergetic cruises system will be applied at sea or on inland waters, there is little variety in the environment. Thus, the evaluation of environmental adaptability is modelled without considering different environments.

$$E_{ea} = \lambda\frac{\max_{i=1}^{n}\{T_i\}}{T_{max}} + (1-\lambda)\frac{\sum_{i=1}^{n} A_i}{A} \tag{13}$$

where $\lambda \in (0,1)$ is a constant; n is the total number of all USV and UAVs of the system; T_i is the time for UAV or USV to adapt to environment; T_{max} is the maximum allowed time; A_i is the scope that USV or UAV can perceive the state of environment; and A is the total scope needed to be cruised.

4.3.2. Evaluation of Detectivity. Detectivity can be measured using the detection probability. If the detection probability of each platform in the USV-UAV synergetic cruises system is $P(U)$, the detectivity can be evaluated as follows:

$$E_{id} = 1 - \left[P\left(\overline{U}\right)\right]^n \tag{14}$$

where n is the total number of all USV and UAVs of the system.

5. Empowerment Based on a Cloud Model and the Delphi Method

In this study, we use a cloud model [17–21] and the Delphi method [22] to determine the weight of each evaluation factor. First, we formulate a weight cloud model for each evaluation factor. Then, we normalize the expectation of these weight models to give the weight of each evaluation factor.

5.1. Delphi Method. The advantages of Delphi method [22] lie in its convenience, feasibility, certain scientificity, and certain practicality. The characteristics of Delphi method are anonymity, iteration, and feedback.

Anonymity. Participants (mostly refer to experts) are approached by mail or computer.

Iteration. There are several rounds. The first round can be inventory, in which participants are asked for events to be forecast or parameters to be estimated. In subsequent rounds, participants are asked to give quantitative estimates about dates of future events or values of unknown parameters. The number of rounds is fixed in advance or determined according to a criterion of consensus in the group of participants or stability in individual judgments.

Feedback. The results of an eventual first inventory round are clustered and sent back to all participants. In the first estimation round, participants give their quantitative estimates. Before the second and subsequent estimate rounds, the results of the whole group on the previous round are fed back in a statistical format to all participants. On the second and subsequent estimation rounds, participants making judgments that deviate from the first-round group score according to a fixed criterion are asked to give arguments for their deviating estimates. Before the third and subsequent estimate rounds, these arguments are along with the statistical results fed back to all participants.

The steps of application of Delphi method are as follows: firstly, one or two panels are recruited. The experts on the panels are not needed to be large in number. Secondly, each expert is sent an initial questionnaire inquiring his or her opinions. Thirdly, the completed questionnaires are returned to the monitoring team that summarise the response and circulate them back to the panel members, accompanied by a new reply form. Fourthly, in the first iteration, the panel members compare their responses with those of their peer colleagues. The iteration is repeated until the replied views converge. Fifthly, when there is no further progress towards consensus, the procedure is stopped.

5.2. Cloud Model. A cloud generator is a vital part of any cloud model, as it produces cloud droplets according to numerical characteristics, which are calculated according to the cloud distribution. As it is universally applicable, we use a normal cloud algorithm and an improved reverse cloud algorithm.

The normal cloud algorithm proceeds as follows:

Input: (E_x, E_n, H_e), the required number of cloud droplets p.

Output: $drop(x_i, y_i),\ i = 1, 2, 3, \ldots, p$.

(1) Generate a normal random number E_n' with expectation E_x and standard deviation H_e.

(2) Generate a normal random number x_i with expectation E_n and standard deviation E_n', in which x_i is a cloud droplet belonging to the domain space.

(3) $\mu_i = \exp[-(x_i - E_x)^2 / 2(E_n')^2]$ in which μ_i is the membership degree of x_i with respect to some qualitative concept.

Repeat steps 123 until p cloud droplets have been generated.

The improved reverse algorithm can be described as follows:

Input: $x_i (i = 1, 2, 3, \ldots, p)$

Output: (E_x, E_n, H_e)

$$\begin{aligned}
\overline{x} &= \frac{1}{p}\sum_{i=1}^{p} x_i; \\
B &= \frac{1}{p}\sum_{i=1}^{p} \left|x_i - \overline{x}\right|; \\
S^2 &= \frac{1}{p-1}\sum_{i=1}^{p} \left(x_i - \overline{x}\right)^2; \\
E_x &= \overline{x}; \\
E_n &= \sqrt{\frac{\pi}{2}} \times B; \\
\text{and } H_e &= \sqrt{S^2 - E_n^2}.
\end{aligned} \tag{15}$$

5.3. Empowerment Method. We determine the weight of each evaluation factor as follows.

First, select q experts that are familiar with and fully understand the meaning of the evaluation factors. We assume that each evaluation factor is influenced by m subfactors $\{U_{i1}, U_{i2}, \ldots, U_{im}\}$.

Second, if the q experts consider evaluation factor $U_{ij}(j = 1, 2, \ldots, m)$ and give a score set of $\{V_1, V_2, \ldots, V_q\}$, then we use the improved reverse cloud generator to obtain the numerical weight characteristics $(E_{xij}, E_{nij}, H_{eij})$ for U_{ij}.

Third, based on $(E_{xij}, E_{nij}, H_{eij})$, the cloud atlas of U_{ij} is obtained from the forward cloud generator.

Fourth, the condensation of cloud droplets in the cloud atlas is examined. If the distribution of cloud droplets produces a mist (i.e., the cohesion of cloud droplets is poor), then the experts have not provided unified evaluation comments. In this case, we must reconsolidate the evaluation comments.

The above operation is repeated until the experts' evaluation comments are unified to give a cohesive cloud atlas, which is the final weight cloud of the evaluation factor.

Finally, the above steps are repeated for all m evaluation factors.

The weight of U_{ij} is then $\omega_{ij} = E_{xij} / \sum_{j=1}^{m} E_{xij}$.

Table 1: The relative parameters and effectiveness of each evaluation factor.

Evaluation factor	Parameters	Effectiveness
Information sharing (IS)	$\lambda = 0.8$; the percent of information that comes from USV shared with UAV is 90%.	0.7200
Information distribution (ID)	$\lambda = 0.8$; the percent of information that UAVs receive from sharing information from USV is 95%.	0.7600
Information acquisition (IA)	Mistakenly believed rate is 5%.	0.9500
Instruction reception (OR)	The percent of instruction that comes from ground command-and-control centre received by USV is about 98%.	0.9800
Instruction sending (OT)	All of the 3 UAVs can receive instruction coming from USV, and the acceptance percent is 90%.	0.9000
Control (IC)	The allowed time for command-and-control is fifth as long as the actual total time.	0.8694
Robust performance (RB)	$\eta_{usv} = 5\%; \eta_{uav} = 10\%; t_{usv}/T_{usv} = 0.001; t_{uav}/T_{uav} = 0.002; \delta = 0.6$	0.9287
Environment adaptability (EA)	$\lambda = 0.8; \max_{i=1}^{n} T_i/T_{max} = 0.9; \sum_{i=1}^{n} A_i/A = 0.0001$	0.7200
Detectivity (ID)	$P(U) = 0.75; n = 4$	0.9961

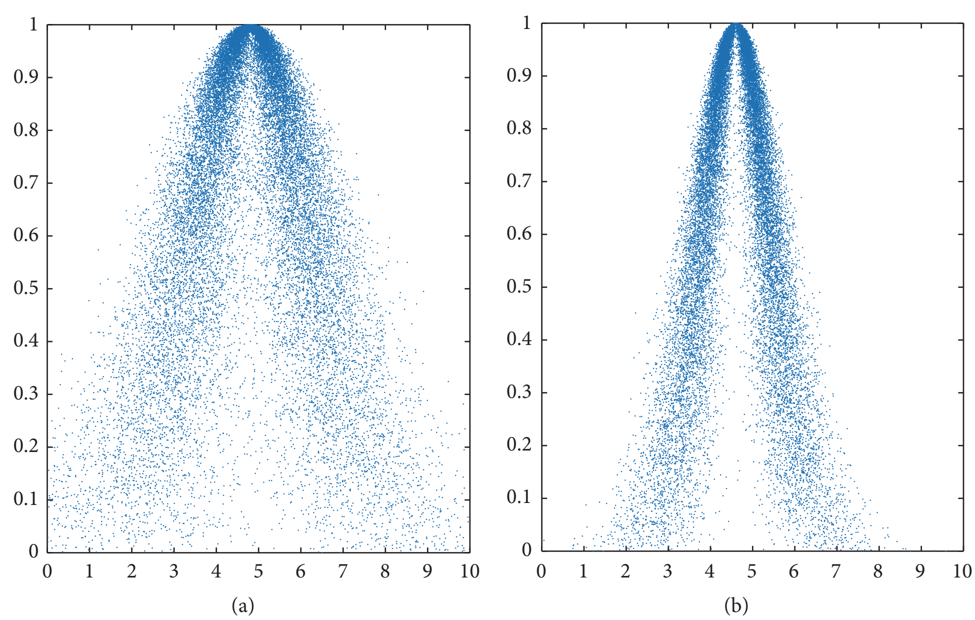

Figure 2: The weight of "information sharing": (a) represents the first cloud weight, and (b) indicates the final best cloud weight.

6. Numerical Example and Analysis

In this section, a synergetic cruises system consisting of one USV and three UAVs, that is, USV-UAV(1,3), is chosen to verify the effectiveness evaluation model proposed. Without loss of generality, we assume that the three UAVs belong to the same type and have the same performance. The weather conditions of cruise area are good. The instruments and equipment of the collaborative system have stable performance and can be normally used. In addition, the network is stable and bandwidth is enough to meet the use. The relative parameters of each evaluation factor are listed in Table 1. The effectiveness of the collaborative system is calculated after the weight of each evaluation factor is determined.

According to the empowerment based on cloud model and Delphi method, the weight of each evaluation factor of USV-UAV synergetic cruises can be ensured. In order to well understand the application of the empowerment method, the evaluation factor named "information sharing" is taken as an example.

Firstly, there are ten experts scoring for "information sharing" marked as (3, 5, 5, 7, 5, 3, 7, 5, 3, 5). We can get numerical characteristics value which is (4.800, 1.3536, 0.5879). Then we get the cloud atlas shown in Figure 2(a) based on forward cloud generator. From Figure 2(a), we can see that the dispersion of cloud droplets is relatively large and the cloud atlas is shown as mist. So we should collate experts' scores for feedback to experts and prepare

Table 2: The weights of the evaluation factors of USV-UAV synergetic cruises.

Upper level	Evaluation factor	Subscript	Weight
Overall	Synergy capacity	S	0.2352
	Command-and-control capacity	CC	0.3208
	Cruise capacity	C	0.4442
Synergy capacity	Information sharing	IS	0.2949
	Information distribution	ID	0.3462
	Information acquisition	IA	0.3590
Command-and-control capacity	Instruction reception	OR	0.2619
	Instruction sending	OT	0.2619
	Control ability	IC	0.2937
	Robust performance	RB	0.1825
Cruise capacity	Environment adaptability	EA	0.4625
	Detectivity	ID	0.5375

next round of experts' scoring. Repeat above operation until unifying experts cognition and get final numerical characteristics signed as (4.6000, 0.8021, 0.2602) of "information sharing" whose cloud atlas is shown in Figure 2(b). So do the remaining three evaluation factors. The final weight of "information sharing" is 0.2949 through normalizing the above three expectations. The weights of all evaluation factors of USV-UAV synergetic cruises are listed in Table 2.

From the weight of each evaluation factor of USV-UAV synergetic cruises, we can see that the weight of "cruise capacity" is 0.4442, which is the biggest compared with the other two evaluation factors in the same layer index and has the most prominent effect on the effectiveness of USV-UAV synergetic cruises. "Information acquisition" whose weight is 0.3590 is a much important factor to "synergy capacity." In terms of "command-and-control capacity," "control ability" makes major contribution to it. It is "detectivity" that produces more influence on "cruise capacity" compared with "environment adaptability." Therefore, "cruise capacity," "information acquisition," "command-and-control capacity," and "control ability" should be improved so that the total effectiveness of USV-UAV collaborative system could be enhanced.

According to the effectiveness evaluation model proposed in this paper, the effectiveness values of synergy capacity, command-and-control capacity, and cruise capacity are 0.8165, 0.9172, and 0.8684, respectively. At the same time, the total effectiveness value of USV-UAV system is 0.8720. Thus, the USV-UAV system is in good effectiveness, which can well finish given cruise tasks and provide a wealth of information for electronic patrol system.

7. Conclusion

This paper has considered a USV-UAV collaborative system. We have focused on the application of synergistic cruise of USV-UAV system to electronic patrol systems and have established a collaborative model and a method for evaluating its effectiveness. Furthermore, we have quantitatively evaluated and verified the proposed system using a numerical example.

Both unmanned surface vehicle (USV) and unmanned aerial vehicle (UAV) are valuable in ocean and coastal management. USV can be used for intelligence surveillance of coasts, port and border security, autonomous searching, signals transmission between air and underwater vehicles, and submarine protection. UAV can be used for search and rescue operations, aerial surveillance, and sensing applications. They are often used separately and independently. Remote sensing (or sea search and rescue or armed attacks of maritime pirates) operations of UAV are often limited by the viability and sea conditions. For remote sensing in foggy sea conditions, it will be better to have USV and UAV collaboratively. For example, in Bohai Sea in the spring season, the fog is very thick, and it is impossible for any practical operation of UAV alone, because an UAV alone cannot carry large heavy sensors and carry out long run-time tasks. But it is possible for USV-UAV(1,n) collaborative system to carry out some tasks. In this system, the USV carries large sensors such as sonar, radar, and environment sensing device and executes long run-time tasks. The UAV gets up close to objects or targets to provide high-resolution imagery, is fast-moving, and also can cover wide areas quickly above most obstacles or danger zones in the case of fog on the basis of command-and-control of the USV.

In a USV-UAV(1,n) system, the USV can be used to be served as a mobile control station of the UAVs. The advantages of this command-and-control system are that USV can be used as energy supply and landing platform for UAVs to enhance implementation and adaptability of UAVs. It can share databases and communicate with the on-shore (fixed) command-and-control station. It can monitor, analyze, and process the real-time information on spot. It can load long-distance call and analyze information quickly and combine with the information collected by UAVs and instructions from ground control station to do situation analysis and forecasting.

Future potential applications of collaborative operations include surveillance and reconnaissance, search and rescue, mapping unknown environment, and payload transportation. Surveillance and reconnaissance are quoted as example. A collaborative system can conduct real-time monitoring to sand-mining operations in the inland waters so that the overharvesting and illegal operations can be avoided. In the coastal waters, a collaborative system is able to supervise fishing areas and fishing vessels operations to avoid the harm caused by overfishing to marine ecological balance.

The major challenges of collaboration between USV and UAVs are to build a collaborative system, to develop collaborative mechanisms, and to evaluate collaborative performance. This paper has attempted to address these challenges by analyzing USV-UAV system and its subsystems, proposing definition of USV-UAV synergetic cruise, building USV-UAV system, and establishing effectiveness evaluation model for USV-UAV collaborative system.

Our research on synergetic cruises and their effectiveness has laid the foundations for further study on the application of USV-UAV systems in electronic patrol scenarios. However, changing application requirements and environments means that our USV-UAV synergetic cruises model must be continually improved.

Data Availability

The simulated data by Matlab used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

The work described in this presentation was supported by the National Natural Science Foundation of China (NSFC) through Grant No. 51579204 and Double First-Rate Project of WUT, the National Key R&D Program of China through Grant No. 2018YFC1407405, and the Ministry of Science and Culture of Lower Saxony for funding the Graduate School of Safe Automation of Maritime Systems (SAMS).

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