Research on Simulation Experiment of Underwater Cluster Multi-source Information Fusion

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Abstract. Intelligent cluster information fusion technology is one of the key technologies to solve systematic cooperative operations in underwater manned and unmanned cooperative operations clusters. In this study, aiming at the multi-node hybrid multi-level hierarchical information fusion architecture and global optimization association algorithm based on cluster formation detection, the test scheme and evaluation method of multi-level information fusion are proposed, and the cluster information fusion simulation test system including sonar system, simulation deduction and evaluation system and multi-source information fusion system is constructed. For the first time, the system comprehensively verified the ability of multi-platform from orientation to positioning in the grouping of fusion algorithm, and proved the correctness and effectiveness of the fusion algorithm, which could greatly improve the accuracy of orientation and distance, and formed a highly credible simulation test evaluation ability. The system is extensible at the same time, and can also be applied to other simulation experiments.

Keywords: Human and unmanned cooperation, multi-source information fusion, simulation test.

1. Introduction
Under the sea battlefield environment of future system of systems (SOS) confrontation, the coordinated operation mode of underwater manned and unmanned systems (UAS) is one of the main modes of underwater SOS operation. In the process of combat, unmanned system cluster undertakes the tasks of long-term underwater battlefield perception and accurate fire strike. Although the submarine does not directly participate in the battle, it takes on the key role of formation commander.

Intelligent cluster integrated command and control technology is one of the key technologies to solve the systematic cooperative operation in the underwater manned unmanned cooperative operation cluster. According to the characteristics of unmanned equipment cluster in deep-sea combat, this study establishes the overall framework of command and information fusion with submarine as the center, and conducts simulation test research on the multi-source information fusion criterion model of cluster cooperative detection.
In this paper, based on underwater cluster confrontation, combined with simulation deduction, the dynamic confrontation process between the enemy and the enemy is constructed. With the tactical and technical indicators such as cluster underwater communication and detection as constraints, and the target characteristic simulation and multi-source detection model as inputs, the multi-source information fusion criterion model methods such as cluster distributed information fusion framework and joint optimization association are simulated and verified. The index performance of information fusion is evaluated, which provides a basis for the implementation of underwater cluster cooperative detection.

2. Cluster information fusion method

2.1. Problem analysis

The main detection information of UUV sonar is azimuth, lack of range information, lack of information, poor observability and difficult positioning, resulting in poor measurement accuracy and low resolution. Due to the non-uniformity of ocean acoustic field, the specificity of target noise source radiation field, the nonlinearity of underwater acoustic propagation and the time-varying of ocean hydrological environment, the tracking measurement accuracy is time-varying due to the influence of relative movement situation of enemy and us, sea area conditions and hydrological environment. With the participation of artificial information, the pulse signal of underwater acoustic reconnaissance sonar depends on the detection accuracy of target active sonar It has randomness and discontinuity. Some characteristics bring many disadvantages to the classification and fusion of measurement information, such as the observability of bearings-only system, a large number of false targets in multi-platform information fusion (when P observation platforms observe M targets, the number of false targets is at least AA), the problem of target crossing in azimuth measurement, the problem of "combination explosion" of computation, the limitation of traditional methods, and the resulting contradiction between multi-platform information association and target estimation, etc., the problem of target crossing in azimuth measurement, the problem of "combination explosion" of computation, the limitation of traditional methods, and the resulting contradiction between multi-platform information association and target estimation, etc.

According to the characteristics of sensor distribution and detection information in this study, the information correlation and target estimation of multi-platform passive sonar detection is the key problem of cluster formation information fusion, and the traditional "combined explosion" phenomenon is another key problem in this study.

2.2. Information fusion method

In this study, a hybrid ordered multi-level and multi-layer information fusion structure is applied, as shown in Figure 1, to avoid the problem of combined explosion of multi-sensor information, and a joint optimization model of information association and target estimation based on two sensors is established. An optimized neural network algorithm is adopted to avoid combination calculation in association, thus improving the performance of information fusion.

In this information fusion structure, firstly, the priority of UUV sensors is sorted in a certain order. According to m sensors and n targets, m-1 ordered fusion nodes are constructed in the fusion processing center, and the fusion results are finally output.
The first Level of Integration
The second Level of Integration
The $m-1$ Level of Integration

Figure 1. Hybrid multi-level hierarchical information fusion structure.

This processing structure solves the problem of unobservable single source. In terms of calculation amount, the number of possible targets for hierarchical information fusion processing is $(m - 1)n!$. The ratio of the number of possible targets to multi-sensor information fusion is $(m - 1)n! / (n!)^{m-1}$, so the calculation amount of hierarchical information fusion is reduced by a factor of $(n!)^{m-2} / (m - 1)$. It shows that when there are more than two sensors, the amount of fusion calculation is greatly reduced.

However, when the sensor information is correlated, the total number of feasible correlation targets reaches $n!$, and the computation still has NP complexity. Therefore, an optimized Hopfield neural network is applied to establish association algorithm. The process of global optimization association solving algorithm based on Hopfield neural network is shown in Figure 2.

Figure 2. Neural network global optimization correlation solving process.

The focus is to solve the global correlation optimization problem (1) and solve the parameter optimization problem (2).

$$\min_{C \in C^{(n)}} \sum_{ij} d_{ij} C_{ij} \quad (1)$$

$$d_{ij} = \min_x \left[ -\ln p(Z_i^{(1)}, Z_j^{(2)} | X) \right] \quad (2)$$

In the formula: $d_{ij}$ is called the cross-correlation index; $C = (C_{ij})_{n \times n}$ is a feasible incidence matrix, and its elements are only 0 or 1; $p(Z|C_i X)$ is the conditional probability density function of azimuth measurement, and $Z^{(s)}$ is the fusion output matrix of 2 detectors [2].
3. Cluster Information Fusion Modeling
The multi-source information fusion criterion model of underwater cluster includes three parts: framework, association and fusion algorithm. Among them, the multi-source information fusion framework includes information fusion level, priority, differentiated use strategy, mobility strategy within the group and cooperation strategy between groups; the Association criteria include the criteria to determine whether it is the same target; the fusion criteria include the fusion algorithm of different detection sources for the same target.

Build a simulation deduction and evaluation system to edit the forces and models of both sides, carry out simulation deduction of both sides, and simulate the characteristics and movement information of enemy targets. Sonar target detection enters the simulation deduction system after transforming the relationship, and carries out target detection of our underwater cluster at the same time. The multi-source information fusion system takes our detection information as input, according to the information fusion criterion model, uses multi-source information fusion framework, association and fusion methods to obtain target fusion information, displays panoramic situation, and transmits it to the simulation deduction and evaluation system to comprehensively verify the indicators of the information fusion criterion model.

3.1. System composition
The underwater cluster information three-level fusion test system mainly includes three parts: simulation deduction and evaluation system, multi-source information fusion system and sonar system.

3.1.1. Sonar system. The sonar system is mainly used to verify the information fusion framework, association and fusion algorithm in the marshalling. It consists of more than two sonar and data processing modules and is deployed in the pool. The detection information is transmitted to the simulation deduction and evaluation system as an external detection information source and integrated with the detection simulation data of the simulation deduction and evaluation system to participate in the test and evaluation of cluster multi-source information fusion.

3.1.2. Simulation deduction and evaluation system. The simulation deduction and evaluation system creates the situation scene of both sides for the multi-source information fusion system. It consists of simulation and evaluation host, simulation and evaluation software and director display screen. Scenario editing and simulation deduction are carried out, sonar target detection information is comprehensively output to the multi-source information fusion system, and the target fusion information of the multi-source information fusion system is received, and man-machine interaction is carried out by the director's display screen, thereby realizing the index evaluation of information fusion.

3.1.3. Multi source information fusion system. Multi source information fusion system loading information fusion criterion model is the core of integrated simulation test system. Multi source information fusion system mainly includes multi-source information fusion host, multi-source information fusion simulation software and situation display screen. The target detection information of the simulation deduction and evaluation system is received through the network interface, and the multi-target fusion information is solved, which is fed back to the simulation deduction and evaluation system for comprehensive evaluation, and man-machine interaction is performed by the situation display screen to display the target situation.

The information flow among the components of the test system is shown in Figure 3.
Simulation deduction and evaluation system

Multi source information fusion system

Director screen
Editing interface
Deduction interface
Evaluation interface

Model development
Scenario editor
Simulation deduction
Analysis and evaluation

Simulation engine
Data interaction
Geographic information System

Model Base
Database
Scenario Base

Situation screen
Fusion view (core)
Fusion view (major)
Fusion view (common)

Hierarchical structure
Information Association
Fusion algorithm

Multi source information fusion criterion model

Sonar System
Detection Information

Figure 3. Information flow diagram of multi-source information fusion simulation test system.

3.2. Three-level convergence architecture

With the deduction, the enemy target enters the UUV detection circle, and the UUV sends the detection information to the fusion software, which performs three-level fusion. The flow of information interaction between simulation deduction system and fusion system is shown in Figure 4. The process involves three levels of fusion, including platform level, grouping level and cluster level fusion.

Platform level fusion: the sensor of UUV that detects the information sends the detection information to the platform-level fusion module of fusion software, and the platform-level fusion module returns the platform fusion result. UUV sends the platform fusion results to marshalling center, and the communication process must consider communication rate, communication delay and bit error rate.

Figure 4. Schematic diagram of fusion information interaction process.
Group-level fusion: the group-level fusion module performs group-level fusion according to the fusion results of UUV platforms in the same group, and sends the fusion results to the UUV platform of the group center. The UUV platform of the marshalling center sends the fusion results to the mother boat, and the communication rate, communication delay and bit error rate must be considered in the communication process.

Cluster-level fusion: the cluster-level fusion module performs cluster-level fusion according to the fusion results of each group, and sends the fusion results to the cluster center.

3.3. Evaluation method
The simulation deduction and evaluation system takes the objective relative position data of red and blue as the benchmark, evaluates the three-level fusion results for the multi-source information fusion performance indicators in the deduction process, and gives the performance index evaluation results. See table 1 for specific test methods of key technical indicators.

| Serial number | Test content                          | Test method                                                                 | Eligibility criterion                                      |
|---------------|---------------------------------------|-----------------------------------------------------------------------------|------------------------------------------------------------|
| 1             | Number of information sources detected | Simulation deduction and evaluation system interface, set up multiple UUVs to form formation information source. In the simulation process, the number of information sources in the multi-source information fusion system is counted in real time. | Multi-source information fusion system can interconnect, process and comprehensively display multiple batches of information sources. |
| 2             | Leakage rate                          | In the red alert area of the simulation deduction and evaluation system interface, a large number of large ship targets and their maneuvering modes are set. In the simulation, the ratio of the number of missed targets to the total number of targets after multi-source information fusion is counted. | The number of missed targets is less than 10% of the total number of targets. |
| 3             | False feeling rate                    | In the red alert area of the simulation deduction and evaluation system interface, a large number of large ship targets and their maneuvering modes are set. In the simulation, count the proportion of false targets to the total number of targets after multi-source information fusion. | The number of false targets is less than 10% of the total number of targets. |
| 4             | Positioning accuracy                  | In the red alert area of the simulation deduction and evaluation system interface, a large number of large ship targets and their maneuvering modes are set. In the simulation, the positioning deviation of multi-source information fusion for all targets is counted, and the maximum positioning deviation is taken. | The maximum positioning deviation is less than 1km. |

In the course of the experiment, statistics related data were made according to the index system. First, the number of objective targets is N, the number of real targets after the fusion of objective target position \((x_i, y_i)\) is \(N_c\), the number of false targets after fusion is \(N_f\), and the target position of fusion is \((\bar{x}, \bar{y})\). The analysis methods for establishing some relevant indicators are shown in Table 2.

| Serial number | Name                  | Analytical method                                      |
|---------------|-----------------------|--------------------------------------------------------|
| 1             | Tracking capability    | \(N_{\text{max}} \geq N_c + N_f\)                      |
| 2             | Probability of discovery |\(Pr \geq N_c/N\)                           |
| 3             | False alarm probability |\(Pr \geq N_f/N\)                                 |
| 4             | Fusion accuracy        | \(F = \left(\left(x - \bar{x}\right)^2 + \left(y - \bar{y}\right)^2\right)^{1/2}\) |
4. Experimental design

In order to verify the multi-source information fusion criterion model of underwater cluster, this study adopts Monte Carlo method, and designs the following two levels of test contents for the verification of fusion architecture and algorithm and information fusion performance index:

Verification of information fusion framework, association and fusion algorithm in group. More than two sonar are added to the pool, and the position information of the target is obtained through different sonar automatic differential use strategies, target association and fusion algorithms. Combined with the actual target, the index improvement of information fusion framework is analyzed, and the ability of multi-source information association and fusion in marshalling is verified.

Verification of multi-source information fusion performance index of underwater cluster. According to the index requirements, design the operational process of both sides, and carry out dynamic deduction. Combined with the underwater cluster multi-source information fusion criterion model, the target fusion information is solved, and the objective information of the target is synthesized. The false information rate, leakage rate and positioning accuracy are analyzed to verify the performance index of underwater cluster multi-source information fusion.

4.1. Information fusion architecture and algorithm verification

Through the demonstration of sonar group detection example, it shows the ability of information fusion from azimuth to positioning, from rough to accurate, from misjudgment to accuracy.

More than two sonars are arranged in the pool through sonar fixing devices, and the sonar distance between groups is determined by the detection range, thus forming an inverted triangle "long stream" group. The vertex of the lower triangle is "long machine", which realizes grouping management and detection information fusion. As a "wingman", the front vertex is responsible for battlefield alert and cooperative detection, as shown in Figure 5.

![Figure 5](image)

**Figure 5.** Multi-source information fusion test sonar deployment diagram in the group.

Several obstacles have been placed to simulate underwater targets, which reflect the characteristics of target occlusion, detection overlap and detection range, and stimulate different sonar automatic differential use strategies. Each sonar detects the orientation of the target, and obtains the position information of the target through the target association and fusion algorithm.

This paper analyzes the number of detection targets, accuracy of information elements (azimuth/position), false probability, etc. of each sonar and the whole group before and after information fusion, and shows the characteristics of cluster information fusion by an example.
4.2. Verification of multi-source information fusion performance index

Through the design of combat forces and actions of both sides, a large number of targets are created to enter the warning zone of underwater cluster by means of simulation deduction, and the upper limit of performance index of multi-source information sources of underwater cluster is verified. The specific design is as follows:

The enemy's surface ships and submarines formed a joint fleet to conduct exercises, and our side sent underwater clusters to carry out real-time underwater patrol, search and alert covering the whole sea area.

Three enemy ship formations invaded from three directions at the same time. Each formation consisted of several submarines and surface ships, and cruised according to the set route. Our underwater cluster consists of several unmanned submersibles to form a "honeycomb" formation array. Each unmanned submersible is equipped with sensors such as side array sonar, towed linear array sonar, bow active and passive sonar, etc. Through multi-source information fusion, the target is tracked and approached for reconnaissance, and underwater acoustic countermeasures are used for confrontation, forcing hostile forces to stop their actions and leave our defense zone.

The initial position, heading and speed of enemy ship formation and our underwater cluster are designed respectively, and the movement situation diagram is formed, so as to achieve the goal that three enemy ship formations and our underwater cluster encounter at the same time. At this time, all three enemy ship formations entered our detection range. After many simulations, the number, accuracy, false information probability and discovery probability of detection targets of the whole cluster before and after the cluster information fusion are analyzed.

4.3. Experimental procedure

The following describes the test steps in detail.

4.3.1. Place sonar. In turn, three sonar are fixed in the pool, one as the marshalling center, with the marshalling center as the origin of the coordinate system, and the other two as the marshalling members, and the relative positions between the sonar are measured with a meter ruler. Initialize and set the position and data channel of each sonar system, and the sonar uploads the processed detection data through cables.

4.3.2. Force allocation. In the simulation deduction and evaluation system, the positions, formations, routes and regions of enemy and enemy formations are set by using scenario editing tools. Including the type, quantity, initial position, formation, acoustic radiation characteristic parameters, motion characteristics and so on.

Force data preparation. In the simulation deduction and evaluation system, the force scale, load, maneuverability, acoustic radiation characteristics and so on are set by data preparation tools. Furthermore, force-borne sensors (UUV includes side array sonar, towed linear array sonar and bow active and passive sonar) and their detection indicators (detection range, detection accuracy, detection probability, etc.) are set up, thus creating the problem elements of "three lows and one high" underwater.

4.3.3. Edit the battle plan. By designing editing tools, we set up the movement plan, communication relationship, detection plan and strike plan of both sides, so that the detection areas of both sides form overlapping areas. At the same time, customize the relevant indicators to be evaluated statistically (the number, location, time and distance of targets before and after fusion in each time period, etc.).

4.3.4. Simulation deduction. When the scenario is started, the forces of both sides move dynamically according to the set track, and the detection sensors of submarine formation acquire the target information and transmit it to the multi-source information fusion system. Through the framework of information fusion, association and fusion algorithm, the target information is obtained, and the situation of both sides is displayed through the situation display screen, which is fed back to the simulation
deduction and evaluation system, and the objective combat situation is displayed by the director display screen.

After the deduction, the Red submarine gradually released UUV formation and gradually became a honeycomb cluster, and the enemy formation approached the cluster, as shown in Figure 6.

![Director's station combat situation interface](image)

**Figure 6.** Director’s station combat situation interface.

Select UUV-07-1 on the situation map, as shown in figure 9. You can see the fusion results at the formation level in the fusion situation of the force information bar, and display the fusion targets received by UUV-07-1. After the image display is selected, the fusion target position is displayed on the image, marked as UUV-07-1 (fusion_20701).

4.3.5. **Index statistics.** The simulation deduction and evaluation system can obtain the pre-fusion detection, fusion target and tracking fusion process information in real time. After the simulation, the information fusion indexes of the multi-source information fusion system are evaluated, including the number of information sources, false information rate, missing information rate, positioning accuracy and so on.

After the deduction, the data of false situation rate, missing situation rate and fusion accuracy are recorded and described graphically. On the left side, the cluster level, group level and platform level are listed in a tree view. You can click to select them. On the right side, the results of each index of the selected group level uuv-02-1 changing with time are displayed.

4.3.6. **Data analysis.** Repeat the above steps, carry out more than 1000 different simulation deduction (the detection error, detection probability and false alarm probability of the detection sensor are all generated by random values), and obtain the average fusion index value statistically.

5. **Test results and evaluation**

The multi-source information fusion software takes the criterion model of multi-source information fusion as the core, and obtains the target detection information under different scenarios by sonar system, simulation deduction and evaluation system, realizes three-level information fusion of platform, grouping and cluster, and realizes the ability from bearing-only to real-time target positioning. The farthest detection distance is XX kilometers, and the detection area is XX million square kilometers.

The following figure shows the statistical results of cluster-level false information rate and missing information rate, as shown in Figure 7 and Figure 8. The false information rate was unstable at first, but
reached a low point in about 340 seconds, which was the time when UUV detected the target at most. After that, as the blue forces moved away, they gradually stabilized.

Figure 7. Cluster-level false love rate curve.

Figure 8. Cluster-level leakage rate curve display diagram.

The information fusion architecture, association and fusion algorithm in the marshalling verify the overlapping coverage of detection ranges among multiple platforms in the test, and start different sonar successively, through the association and weighted fusion of multiple platforms with different addresses and bearings. Calculate the distance information of the target to obtain the track information of the target, demonstrate the integration and processing ability of multi-source information fusion algorithm for sonar data, verify the ability of multi-platform in marshalling from bearing to positioning, greatly improve the accuracy of bearing and distance, meet the design requirements of performance index, and achieve the simulation expectation.
6. Conclusions
System confrontation is an important development direction of underwater three-dimensional offensive and defensive operations in the future. In underwater manned and unmanned cooperative combat cluster, intelligent cluster integrated command and control technology is one of the key technologies to solve systematic cooperative combat. According to the verification requirements of underwater cluster multi-source information fusion model, a simulation test system including sonar system, simulation deduction and evaluation system and multi-source information fusion system is constructed. By designing the test content, principle, evaluation method and process, the test results are output, which solves the performance verification problem of fusion criterion model. It has the hardware-in-the-loop simulation test capability of multi-platform from orientation to positioning in the marshalling, which greatly improves the target positioning accuracy and meets the design requirements, and proves the correctness and effectiveness of the fusion algorithm. This research carries out experimental practice for the simulation verification of underwater cluster intelligent command and control research. The test system and method can be applied in the field of demonstration, design and test of underwater weapons and equipment under the condition of system confrontation, which is of great significance for improving the intelligent level of cluster under the condition of system confrontation.

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