Multi-source heterogeneous data model for marine biological monitoring at intake of nuclear power plant

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Abstract. The reliability of the cold source is an important guarantee for the safe operation of the nuclear power plant, and the life of the sea threatens the safety of the cold source of the nuclear power plant. The threat of cold source in nuclear power plant is studied and analysed. Several methods of marine biological detection are proposed, including multi-source heterogeneous ontology extraction method based on sonar, underwater camera, water quality sensor and flow sensor. We suggest that a nuclear power plant in the biological monitoring and early warning procedures of cold source, and establish and monitoring model of sonar-optic composite monitoring model, and marine biological monitoring model, including spatial domain, these models are all consistent with the sea creatures that threaten the safety of nuclear power sources.

1. Summary

Cooling water supply from the coastal nuclear power plant which adopts direct cooling mode of seawater circulation directly affects nuclear power safety. With the change of marine ecological environment, explosion of alga and other planktons, jellyfish, fish and shrimps, which block water intake, frequently occurs. Capacities of existing protective measures in coping with cooling water in the nuclear power plant are presenting a declining tendency. A report from World Association of Nuclear Operators (WANO) analyzed 44 major incidents regarding water intake blocking by cooling water, where 20% of these events had a direct bearing on safety-related systems, and over 80% of the events affected power generation of units, including unit shutdown or power reduction, etc.

Sound wave is the best form of underwater detection and communication energy. Sonar plays a significant role in the field of hydrographic surveying and charting through detection, positioning, tracking and analysis of underwater targets using underwater sound techniques. Water intake of the nuclear power plant has a wide distribution depth, marine organisms pervade the whole shallow sea area in the explosion season and usually this is accompanied by bad water quality under the tidal action, and active high-resolution sonar can be used as the main detection equipment in the biomass evaluation [1]. However, restricted by sonar working principles, fineness of sonar detection will be sacrificed if a wide detection interval of the sonar is required, and consequently, some echoes will be disturbed and imaging is not clear enough. When it’s necessary to judge target types, the underwater camera should be used as an auxiliary detection means, which mainly exerts the effects of quantity estimation and verification of target types [2]. Sonar and video image-based detection can reach the goal of quantity estimation in the detected zone, but the detected marine organism development tendency and whether it is enough to pose a threat to cold sources of the nuclear power plant needs a
comprehensive judgment according to ocean current and tidal activities and siphon action at the water intake. Therefore, sonar, underwater camera and water flow sensor should be used as core detectors in the marine biological monitoring model together with forecasting and anticipation of monitored water quality data in order to carry out a forecasting model study of intrusion tendency based on monitoring data.

2. Data ontology and reconstruction models

2.1. Establishment of the ontology model

Equipment used in the specific demand-based marine biological monitoring at the water intake of the nuclear power plant mainly include sonar, underwater camera, water quality sensor and water flow sensor, etc. Monitoring equipment and monitoring information can be seen in table 1. Four sensors include features of four different application fields. Domain ontology should be firstly established in the process of multi-source heterogeneous data fusion [3].

| Monitoring equipment   | Monitoring information                                      |
|------------------------|-------------------------------------------------------------|
| Sonar                  | Time, position, measuring slant distance, measuring range and sampling points |
| Camera                 | Grayscale and morphology                                    |
| Water quality sensor   | Water temperature, salinity and eutrophic index             |
| Water flow sensor      | Flow velocity and flow direction                            |

Table 1. Equipment & effects of marine biomonitoring.

Domain ontology is a word and term definition expressing object-oriented knowledge which can be used by multiple platforms. It includes object features, inference rules, limitations, etc. The most famous seven-step method among its implementation methods is proposed by Stanford University for the first time. Different from the general data mining, marine biological monitoring at the water intake of the nuclear power plant is target-based data screening and reconstruction, so the extraction process of the domain ontology has its specific method, and its logic relation and ontology model are shown in figures 1 and 2 [4].

Figure 1. Logic diagram of marine biomonitoring.
2.2. Original data and their preprocessing

Entities (detectors) of different functions are used in the marine biological monitoring system at the water intake of the nuclear power plant. These entities are under distributed arrangement and respectively acquire and process data. Different detectors have different data types and elements. During the marine biological monitoring process of the nuclear power plant, which requires real-time online monitoring and early warning, if original data-level fusion is adopted to establish the heterogeneous ontology model of multi-source data, the excessively enormous data size will inevitably affect the overall operating rate of the system, so the priority should be given to preprocessing to screen out key elements of the entities in order to constitute a local entity database as the input of the next data reconstruction and integration [5].

2.3. Data reconstruction and integration

Sonar data reconstruction taken as an example, sonar data in *.XTF format contains many data packets. Each Pin of data packet contains multiple information, where the information of significance to the system establishment includes position, time, strength, etc. Extracting and analyzing sonar data and sub-packing corresponding local ontology database is the key of data reconstruction.

After the local ontology database is reconstructed, relational parameters are set. Data images are compared and preliminarily integrated based on time relation, data are integrated for a second time based on spatial elements, and then multi-source heterogeneous model of marine biological monitoring in the whole nuclear power plant is established.

3. Marine biological acoustic monitoring model

It’s necessary to conduct qualitative and quantitative analysis and measurement of marine organisms in order to transform acoustic data into corresponding biological information (organism type, abundance, etc.). Echoes of marine organisms depend on many factors including incident wave frequency, target size, whether there is any swim bladder, the included angle between target and incident wave, and even stomach contents, fat content and reproduction state of animals, etc. It’s assumed that each organism has its own unique acoustic features and its scattering mechanism can be identified, measured and modeled, and in this way echo information is associated with size, shape and material characteristics of the scattering object, etc [6].

The acoustic technique is used to monitor the marine organism having a severe influence on the
nuclear power plant namely jellyfish. According to sonar test and detection results, jellyfish echo data are processed to further obtain acoustic images of a single jellyfish and recheck jellyfish parameters like diameter (De) and height (He). Relative echo strength (RES) can be calculated so as to extract echo features of jellyfish individuals.

The sonar equation is used to calculate the parameters:

\[ EL = SL - 2TL + TS \]  
\[ TL = 20 \log R \]

Where EL is combinational sonar parameter namely echo signal level of and SL is sonar sound source level; TL is one-way acoustic transmission loss, spherical wave damping is taken, and seawater absorption loss is neglected; R is target distance; TS is target strength. Relative echo strength (RES) is used to describe jellyfish ability in reflecting acoustic waves, and relative echo strength (RES) is directly related to parameters such as sound source level (SL), target strength (TS), etc.

A frame of acoustic images containing jellyfish is selected in the image processing process as shown in the figure 3. Figure 3(a) is the detected jellyfish acoustic image, including a jellyfish individual with clear image and jellyfish community acoustic image with fuzzy edge; figure 3(b) is the jellyfish acoustic image through normalization processing, which only contains the acoustic image of a jellyfish individual with clear image. Processing of individual jellyfish data refers to calculation using normalized acoustic features.

![Figure 3. Sonar image for jellyfish.](image)

Statistical results of relative echo strength RES of multiple jellyfish individuals are shown in the figure 4. According to measured and statistical results, maximum RES value of jellyfish individuals is 59.9 db and minimum value is 47.6 db.

Based on acquired data of acoustic features of jellyfish individuals, jellyfish community distribution density conforming to RES features within the sonar coverage scope is evaluated. Detected sonar wave beam is divided into N sections by distance to the sound source, and each section is a 50° × 50° spatial angle as shown in the figure 5. It is totally divided into N spherical sections from minimum radius to maximum radius and from horizontal opening angle and longitudinal opening angle, recorded as A1, A2…An, and number of sectioned water bodies they enclose is M and these water bodies are recorded as V1, V2…Vm. M and V values are determined according to the Max (De and He) of the detection object. 10Max (De and He) should be properly selected according to test results [7].

During the statistical process of target number in the seawater, number of targets on each section is firstly calculated, and then statistical values of targets within the detection scope are obtained as follows:
Figure 4. RES statistics of the relative echo intensity of jellyfish individual.

Figure 5. A schematic diagram of the segmentation method for sonar detection results.

\[ \sigma = \frac{\sum_{i=1}^{M} V_i \cdot C_i}{\sum_{i=1}^{M} V_i} = \sum_{i=1}^{M} \frac{V_i}{V} \cdot C_i \]  

(3)

where \( \sum_{i=1}^{M} V_i = 1 \) and \( C_i = \sum_{i=1}^{M} A_i \). \( A_i \) is the grayscale image value projected by marine biomass on each spherical section onto each spherical surface, and the obtained the quantitative evaluation model of marine biomass through the high-frequency 3D sonar is as follow, and unit is ind./m³:

\[ \sigma = C_i = \sum_{i=1}^{M} A_i \]  

(4)

Jellyfish and Acete Chinensis are analyzed and processed based on the target strength, the local
sonar data ontology of marine organisms which have important influences on the water intake of the nuclear power plant is formed, and sonar data analysis and processing flow is shown in figure 6 [8].

4. Acousto-optical composite marine biological monitoring model

As the calculated particle size is large in the sonar-based resource quantity estimation and it is greatly influenced by reflection of other clutters, the underwater camera is used for secondary verification and information comparison in order to further verify the detection result and improve detection precision. As the camera acquired image is of planarity with a small scope, intelligent linkage-type underwater robot visual detection system should be used for the camera, and when it is installed in a fixed way, the installation angle should be consistent with sonar angle so that information can have the same properties, and visual detection ontology weight can be introduced to realize automatic comparison of local sonar data ontologies and reconstruct monitored resource quantity [9]. Logic diagram of acousto-optical combination is shown in the following figure 7.

![Figure 7. Logic diagram of sonar-optic data reconstruction.](image)

Acousto-optical composite data reconstruction is expressed by the following formula:

$$ \rho = p \sigma $$

where p is acousto-optical fusion weight, and p value is defined in the following table 2.

| P value | Rules                                                                 | Definition               |
|---------|------------------------------------------------------------------------|--------------------------|
| 2       | Optical detection value absolutely exceeds the threshold value, namely marine organisms exceeding the 1/2 detection scope can’t be identified by sonar due to factors like resolution | Absolutely strengthened  |
| 1.4     | Optical detection value exceeds the threshold value, namely sonar fails to identify all target marine organisms due to factors like resolution and exceeds the 1/2 detection scope | Strengthened             |
| 1       | Optical detection value doesn’t exceed the threshold value, namely monitoring sample is basically identical with sonar identified one after optical detection | Consistent               |
| C0.6    | Acoustic detection value exceeds the threshold value, namely optical detection identifies non-automatic motion-type marine organisms (like aquatic plants) including target marine organisms | Weakened                 |
| 0.2     | Acoustic detection value absolutely exceeds the threshold               | Absolutely               |
5. Marine biological monitoring model containing space-time domains

In consideration of clustering behaviors of some marine organisms, the biomass density is considerably large, but the overall scale is not enough to reach the degree to block the water intake, and when these clustering organisms will generate a large quantity signals and cause system alarm when passing wave beams. In order to avoid false alarm, the moving average method is used for recursive migration of density value phase by phase so as to solve the average value as true alarm value. Moving average method refers to averaging the k nearest monitoring values and taking the average value as the final value of alarm judgment. Moving interval is k (1<k<t), and then moving average monitoring value of t density values is:

\[ n = \frac{\rho_1 + \rho_2 + \ldots + \rho_k}{k} \quad (5) \]

Disaster-inducing marine organisms in the nuclear power plant in this study are mainly jellyfish which have low movement speed and usually go with the current. Hydrodynamic model method is used to evaluate marine biomasses at the water intake. Water flow monitoring station is set around the water intake to conduct real-time recording of water flow velocities \(v_1, v_2, v_3, \ldots v_k\) at measuring points, \(\theta\) is direction angle of water flow at the water intake and \(L\) is the distance from monitoring point to the nearest pump station. After moving average density values \(n_1, n_2, n_3, \ldots n_k\) of target marine organisms in the seawater, total marine biomass \(N\) which can reach the water inlet within the monitoring time is calculated according to static flux flowing towards the water intake, and the farther the monitoring point, the longer the time, and the greater the biomass, and the calculation formula is shown as follow:

\[ N = n_1 \frac{L_1}{v_1} \cos \theta_1 + n_2 \frac{L_2}{v_2} \cos \theta_2 + n_3 \frac{L_3}{v_3} \cos \theta_3 + \ldots \quad (6) \]

6. Evaluation of detected density of a marine organism sample

A monitoring station is arranged outside the water intake of one nuclear power plant in this experiment as shown in figure 8. Water flow velocity at this station towards the water intake is 1.82 m/s and it is 280 m from the nearest pump station, so monitoring time is set as 120 s and monitoring time setting is related to arrangement of monitoring points in order to ensure that the reaction time from finding a large scale of marine organisms to the time point when they pose a threat is effective, and sampling period is 10 s/time.
Color rendering of suspected jellyfish targets detected in this test process is conducted according to echo strength. Color difference means different jellyfish echo signal strengths, which is mainly caused by differences of jellyfish size and pose as shown in the figure 9.

According to test results, effective identification distance of the sonar detector for target jellyfish is 1~10 m, and this type of adult jellyfish has diameter of De≥0.10 and height of He≥0.07. In order to ensure objectivity of projection data, section interval is set as 10Max (De and He), namely M=10 and N=11. Table 3 shows identification results of spherical sections Ai based on relative echo strength RES of jellyfish individuals.

| Number | Quantity | Number | Quantity | Number | Quantity | Number | Quantity | Number | Quantity |
|--------|----------|--------|----------|--------|----------|--------|----------|--------|----------|
| A1     | 15       | A3     | 475      | A5     | 625      | A7     | 37       | A9     | 28       |

**Table 3.** Projection number of jellyfish in each sphere.
Quantity of initially sampled jellyfish in the water body is calculated according to the statistical results as follow:

\[ \sigma = \sum_{i=1}^{M} A_i = 1654 \]

The image of the detected region is rechecked through fixation and the underwater robot-carried camera. It’s identified that schools of fish move in regions A3, A4 and A5 at this detection time, which causes a great disturbance. No obvious disturbing organisms except for jellyfish are seen in other regions, and P is taken as 0.2. The corrected quantity of jellyfish initially sampled in this region after acousto-optical combination.

\[ \rho = p\sigma = 0.2 \times 1654 = 330.8 \approx 331 \]

Within this monitoring period, continuous monitoring data of this system are shown in the figure 10.

**Figure 10.** The data of jellyfish monitoring.

Moving average monitoring value within this monitoring period is:

\[ n = (\rho_1 + \rho_2 + \ldots + \rho_{11} + \rho_{12})/12 = 2219/12 = 185 \]

There is only one experimental sample in this monitoring period and \( \cos\theta = 1 \). From the first time when marine organisms are monitored till they can generate harm, the marine biomass which can enter the cold-source system of the nuclear power plant within this interval is estimated as:

\[ N = 185 \times 280/1.82 = 28462 \]

It’s noteworthy that both n and N present real-time changes with dynamic change of monitoring value \( \rho \). If marine organisms are continuously monitored, this value will continue to superpose, indicating that the risk of marine organisms entering the cold-source system of the nuclear power plant is aggravated, or otherwise the risk is weakened.

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