

Ship Navigation System Based on Wireless Sensor

<https://doi.org/10.3991/ijoe.v14i06.8701>

Baofeng Xie[✉], Rong Ge
Jiangsu Maritime institute, Jiangsu, China
baofengxie2047@163.com

Qinyou Hu
Shanghai Maritime University, Shanghai, China

Abstract—To study the application of wireless sensor in the ship dynamic positioning system, the distributed fusion function model and structure model of wireless sensor network were set up. Using the DJC model-based SVM prediction algorithm, the quadratic optimal performance index in ship dynamic positioning MPC control was solved and the optimal control thrust was obtained. According to the classic cluster routing protocol, a data fusion structure based on residual energy and dormancy scheduling mechanism was proposed. The results showed that the proposed routing protocol based on the residual energy and sleep scheduling mechanism data fusion structure was superior to the Leach protocol. It improved the real-time performance of data transmission. Thus, the network data fusion structure achieves the goal of energy balance. The energy consumption is reduced to a certain extent and the design is reasonable.

Keywords—wireless sensor, ship navigation, model, system

1 Introduction

The wireless sensor network is used in the ship positioning system. Ship position information, heading information and environmental information are monitored. The system requires each sensor node to transfer the measured information to the control system, so that the controller can calculate, analyze and process information. Here, the controller is not realized by the traditional computer, but by the convergence node of the wireless sensor network. It has good flexibility and reliability. In the ship positioning control system, the control object mainly includes three aspects: position control, heading control and track control. Combined with data fusion model of ship dynamic positioning system, the application of decision control method based on sink node fusion structure in optimal control thrust prediction is studied. Based on the cluster data fusion structure, the network transmission protocol of the ship dynamic positioning system is designed.

2 State of the art

There were many researches on ship navigation system and fruitful results were obtained. Perera, L. P. et al. [1] conducted on an experimental setup that consists of a navigation and control platform and a vessel model. They used navigation and control platform to control the vessel model and further divided under two sections: hardware structure and software architecture. Therefore, the physical system was used to conduct ship maneuvers in autonomous navigation and collision avoidance experiments. Ravichandran, R. and Meena, N [2] explored the ship detection methods with wireless sensor network. They differentiated the ocean and ship generated waves by signal processing and cooperative signal processing techniques and discussed traditional ship detection methods that could monitor a large area but cost more. Deng [3] developed a set of on-line navigation safety monitoring system for liquefied natural gas (LNG) fuelled ship by combining an update Automatic Identification System (AIS) device, some sensors and a software monitoring platform. Perera, L. P. [4] proposed a methodology for overcoming Mamdani-type inference failures on a fuzzy-logic-based decision-making process applied to collision avoidance in ship navigation.

Liu and others [5] designed a stable attitude estimator method through the calibration of IMU's components - accelerometer, gyroscopes and magnetometers. Meanwhile, they carried out experiments in simulative ship environment and proved that the proposed scheme could fulfill the demand of pedestrian positioning in nautical situation. Perera and Mo [6] also proposed data analysis techniques to understand marine engine operating regions as a part of the ship energy efficiency management plan (SEEMP) and used Principal Component Analysis (PCA) in the ship energy efficiency management plan (SEEMP) to monitor ship navigation with respect to marine engine operating regions. Zaniewicz, G. et al. [7] discussed the possibilities of external sensors using in mobile navigation system for inland shipping. The analysis of data and sensors availability in this filed was followed with data model definition. Then, they presented various possibilities of integration of spatial data in the system, including typical for GIS, geo-informatic web services approach. Chang and others [8] designed new software-defined wireless network architecture to enable high performance in the next generation of ship area networks and proposed a new network architecture, which combines SOTDMA and SDWN advantages to reduce end-to-end transmission delay to achieve high performance in ship area networks. Du, J. L. et al. [9] analyzed the control problem of dynamic positioning for surface ship and combined the dynamic surface control technology with the vectorial back-stepping method, based on which, an adaptive robust nonlinear control law of dynamic positioning was proposed. Tomera [10] presented the designs of two observers, which were: the extended Kalman filter and the nonlinear passive observer. Based on the measured values of ship position and heading, the observers estimate the surge, sway and yaw velocities of the ship motion.

In conclusion, ship navigation system is discussed from the perspectives of ship detection, navigation and control platform, on-line navigation safety monitoring system and so on, but wireless sensor is not combined with the navigation system. To study the application of wireless sensor in the ship dynamic positioning system, the

distributed fusion function model and structure model of wireless sensor network are set up. The quadratic optimal performance index in ship dynamic positioning MPC control is solved and the optimal control thrust is obtained. As a result, the proposed routing protocol based on the residual energy and sleep scheduling mechanism data fusion structure is superior to the Leach protocol and it has the advantages of effectively improving the real-time performance of data transmission.

3 Methodology

In ship dynamic positioning control system, data fusion is adopted. The main purpose is to enhance monitoring redundancy and improve data transmission reliability, accuracy and real-time. Fusion information comes from a number of different sensors. The data types, sampling frequency, location and angle of the multi-sensor are different. It has the characteristics of inaccuracy, incompleteness, unreliability, fuzziness, and reporting conflict. In order to operate the data in real time, a large knowledge base is needed, which makes the data fusion very complicated. The whole data fusion model is divided into functional model and structure model. The function model mainly describes the function of data fusion in the process of data fusion, and the interaction process between the database and the data fusion system. The structure model consists of the hardware and software of the data fusion system, the processing mode of data information, and the human-computer interface of the system and the external environment.

3.1 Functional model

According to the degree of abstraction of the sensed data, it is divided into data level, feature level and decision level. Data level fusion directly integrates raw data collected by the underlying sensors, rather than synthesizing and analyzing all kinds of data before the original prediction data of the sensor is not processed. This is the minimum level of fusion, which can provide as much as possible other field data that cannot be provided by other fusion levels. However, it needs to deal with a large amount of sensor data, so the layer fusion has poor real-time performance, high cost and long processing time. This fusion is carried out in the lowest data fusion layer. Because the information of the original sensor has the characteristics of large amount of data and poor anti-interference ability, data fusion needs a good error correction processing capability.

Feature level fusion is used to analyze and deal with the feature information extracted from the original information of the sensor. In general, the extracted feature information represents sufficient pixel information or sufficient statistics. Then, the data of multi-sensor are classified, converged and integrated according to the characteristics of information. The advantage of feature fusion is that massive data compression is conducive to real-time processing, and can provide reliable feature information for decision analysis, so as to maximize its fusion function and give information analysis. The feature level data fusion is divided into the fusion of target state data and the

fusion of target characteristics. The state data fusion is used to preprocess the sensor data and verify the data. Then, the main parameters and the related state vectors are estimated. Feature fusion is based on pattern recognition technology, and the feature is processed by correlation. The feature vectors are divided into meaningful combinations. Decision level fusion is the result of three level fusions. The layer fusion must start from the actual problem and make full use of the feature extraction results. The final fusion results directly affect the specific level of decision-making. The layer fusion can effectively reflect the different types of information on the various sides of the environment or target. The results of the fusion will not affect the decision result because of the error of individual sensor measurement. Therefore, it has good flexibility, fault tolerance and anti-interference ability. According to the three levels data fusion structure of the multi-sensor, the specific function model of the ship dynamic positioning system can be designed, as shown in Figure 1.

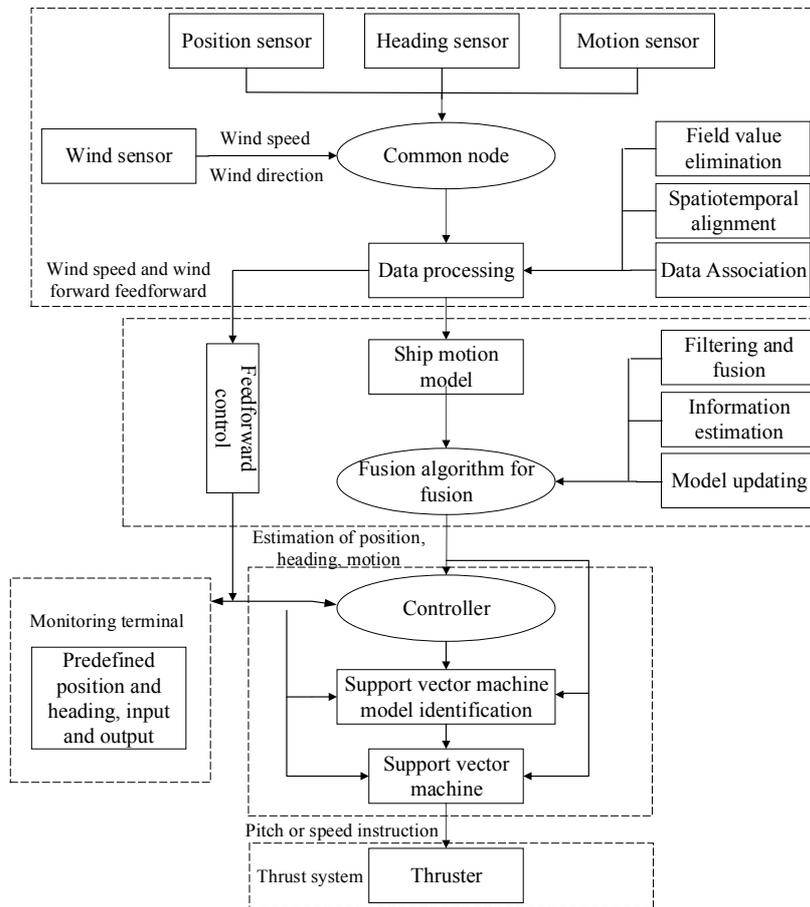


Fig. 1. General flow chart of ship dynamic positioning control system

3.2 Structural model

The system structure consists of the lowest sensor nodes, transmission networks, converging nodes and management terminals. A number of sensor nodes are distributed in a number of non-adjacent monitoring areas, to form a number of clusters. It guarantees the accuracy of the data and the robustness of the system. The cluster head node is responsible for the fusion of the data transmitted by the sensor nodes. Then, it is transmitted to the aggregation node for decision fusion. The common nodes, especially the nodes on the edge of the network, are responsible for data acquisition and data preprocessing. Each node in the transmission network has strong computing power and storage capacity. In order to ensure the reliable communication between the local converging nodes and the converged nodes, the uninterrupted power supply can be used.

The convergence node and the management terminal are connected through the bus network. The result of decision fusion at the aggregation node is sent to the management terminal. The data records are stored in the local database. According to the reliability requirements of data, in practical applications, data collected by sensor nodes can be sent to a central database through the client, to provide remote data services. Each sensor node is equivalent to the traditional network terminal and routing functions in terms of network functions. It also works with other sensor nodes to complete data acquisition, data processing, data storage, fusion and forwarding. Compared with the common sensor nodes, the data processing and communication ability of the converged node is strong. It needs to communicate with the external network, such as the connection of the sensor network and the bus transmission network, to achieve the transformation between the search for both protocols. At the same time the terminal is monitored, the task is released, and the collected data is forwarded on the external network.

4 Result Analysis and Discussion

4.1 The application of strong converging node fusion structure in MPC control

The processing ability, storage capacity and communication ability of the converging node are strong. The data of the head nodes of each cluster are fused. Through the sensor network and the external network, the fusion results are transmitted to the control center. It has the function of controlling the decision. In order to ensure the efficient working ability of the aggregation node, the ARM9 series of AT91RM9200 is selected as its processor. It supports a large number of systems and provides rich application peripherals, including serial port, CAN bus interface and Ethernet interface. At the same time, good reliability and excellent real-time Vxworks operating system are selected. The BP neural network hard fusion module based on FPGA is a very important part of the strong converging nodes. It is mainly used in the MPC control of the support vector machine model. The structure of the convergence node of the ship dynamic positioning system is shown in Figure 2.

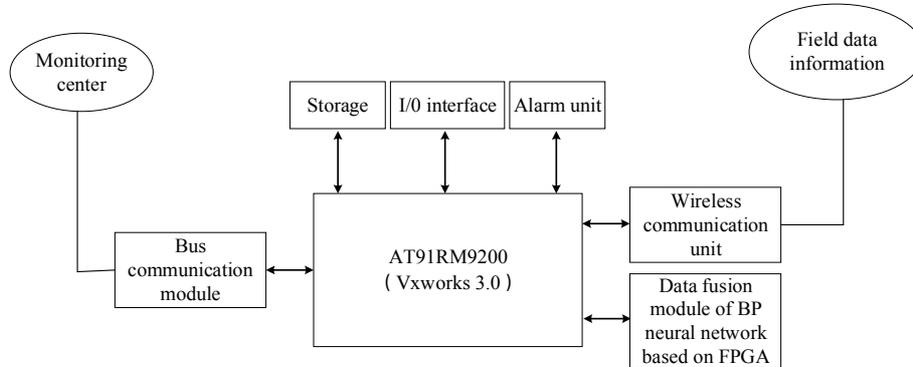


Fig. 2. The structure of the convergence node of the ship dynamic positioning system

In the ship dynamic positioning system, MPC (model predictive control) has the function of prediction. Using its robustness to changes in the environment and system parameters, the deviation between the measured and estimated values is corrected before it is produced. Compared with the traditional PID control method, MPC control can better deal with the constraints of the dynamic positioning system. It has strong security and robustness. In addition, the MPC control is used in the constraint processing of the dynamic positioning system. MPC control can be applied to SISO and MIMO systems, linear and nonlinear systems. It is handled by a simple method of constraint. The input and output constraints are included in the expression. At each sampling time, the controller is updated. It has a strong self-adaptive ability.

Most of the control applications need to meet two types of constraints, input (state volume) constraints and output (control) constraints. The input constraint is caused by the actuator physical restriction, that is, the so-called "actuator saturation". The output constraint is caused by security reasons or other operating reasons of the controlled object. The input limit cannot be violated in any case, which is called a hard constraint. The output constraint can be violated in a certain range, which is called a soft constraint.

Constraints in ship dynamic positioning system can be roughly divided into power consumption constraints (hard input constraints), thruster loads (hard input constraints), operating areas and work areas (hard and soft output constraints). The thrust linear quadratic optimal control of ship power system transforms the performance measure of thrust distribution into a quadratic function of state variables and control variables. Then, the optimal solution of the quadratic function containing these quadratic performance indices is found, and some constraints can be transformed into linear inequality constraints. Therefore, the optimal control of quadratic performance index becomes a dynamic programming problem. There are input and output constraints in the dynamic positioning system. It includes propulsion restraint, work area, operating area constraints. The operating area is represented by a weighted linear inequality. The work area is represented by a weighted quadratic inequality, that is $u_{min} \leq u_k \leq u_{max}, k = 0, 1, \dots, N - 1$, $y_{min} \leq y_k \leq y_{max}, k = 0, 1, \dots, N - 1$. Among them, % is the control vector of the time. It only represents the observed val-

ues of the A time position and the heading. The inequality constraints mentioned above can be described as $LU \leq M$.

The support vector machine prediction algorithm based on DJC model is used to transform the input sample vector into a high dimensional space. The linear relationship between input and output vectors is obtained in high-dimensional space. The optimal regression function is obtained, which corresponds to the nonlinear optimal regression function in low dimensional space. Then, by choosing the appropriate kernel function to replace the inner product of the optimal regression function, a linear fit of the nonlinear optimal regression function can be achieved. Through this linear optimal regression function, the global optimal solution is obtained. Therefore, the SVM can solve the nonlinear problem of quadratic optimal performance index. The parameters of the support vector machine model can be realized through the hardware-in-the-loop structure of the FPGA-based BP neural network of sink nodes in the network. In order to reduce the computational load of aggregation nodes, this DJC structure model can disperse the thrust prediction process of MPC controller to some cluster head nodes. The sink node only needs to perform an optimal weighted fusion on the thrust prediction uploaded by the cluster head node. The optimal control thrust result is obtained. The schematic diagram of the support vector MPC controller is shown in Figure 3.

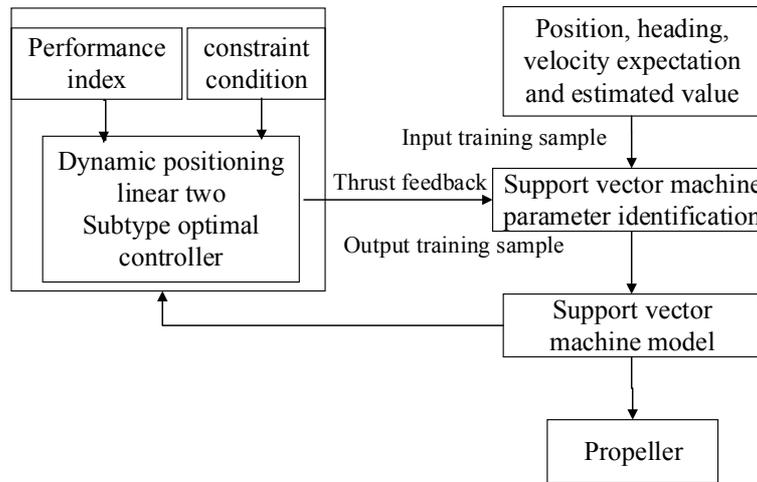


Fig. 3. The schematic diagram of the support vector MPC controller

The MPC control of support vector machine is simulated. First of all, it is clear that the linear quadratic form control of ship dynamic positioning system is achieved by minimizing the performance index. The linear constant system is given:

$$\dot{x}(t) = Ax(t) + Bu(t) \tag{1}$$

In the formula, $\hat{x}(t)$ is the state estimator after Calman filtering.

The quadratic performance index function is:

$$J(u) = \min \left\{ \frac{1}{T} \int_0^T [e^T Q e + u_{LQ}^T R u_{LQ}] dt \right\} \quad (2)$$

In the formula, e is the error variable of the state estimation and the expected value. $\int e^T Q e dt$ represents the requirements for dynamic performance. Q is a positive semi-definite symmetric weighted matrix. $\int u_{LQ}^T R u_{LQ} dt$ represents the requirements for the control of energy. R is a positive definite weighted matrix. For linear time invariant systems, according to the linear two order optimal control law, the system can be obtained.

$$u_{LQ} = R^{-1} B^T P e \quad (3)$$

It can be seen from the optimal performance index function that the first integral item is the requirement for the dynamic performance of the system, that is, the trajectory and time requirements of the expected state from the initial state. The second item indicates the requirement of the system to control the energy. The elements of the weighted matrix represent the relative importance of the state variables and the components of the control variables. The experimental ship model parameters are as shown in Table 1.

Table 1. Ship model parameters used in simulation experiments

Total ship length / m	116	Displacement / t	Item4
Vertical length / m	86.0	Rudder area /m ²	7.2
Ship width / m	15.2	Rudder height /m	3
Deep /m	7.4	Rudder aspect ratio λ	1.2
Designed draft /m	5.6	Number of sheets	4
Square coefficient	0.54	Propeller diameter /m	3.6~4.0
Diamond coefficient	0.56	Pitch /m	Adjustable

For the problem of optimal control of linear quadratic performance index, the constraint condition described above is transformed into a dynamic two - time programming problem. The DJC-SVM model is used to solve the problem. The radial basis function is selected as the kernel function. The BP neural network model based on the systolic array fusion structure is used to optimize the online parameters of support vector machine's accuracy parameter S , penalty factor C and kernel function parameter a . Initial value is $0=5$, $C=50$, $8=0.02$. Based on the DJC-SVM model, the control force of the three degrees of freedom of the ship's longitudinal, transverse and heading are predicted. The prediction error of the lateral control force of the ship is shown in Figure 4. The prediction error of the longitudinal control force of the ship is shown in Figure 5.

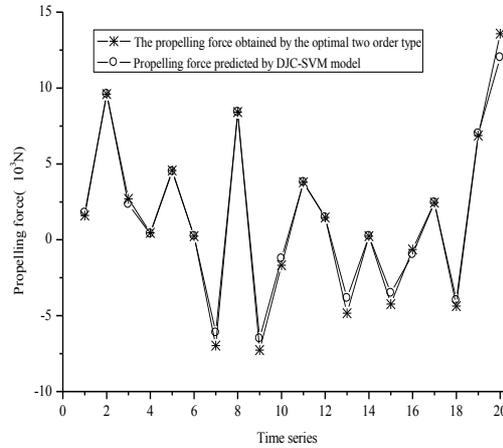


Fig. 4. The prediction error of the lateral control force of the ship

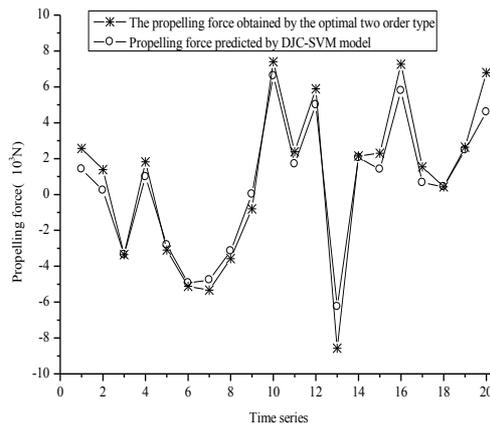


Fig. 5. The prediction error of the longitudinal control force of the ship

As can be seen from Figure 4 and Figure 5, the propulsive force predicted by the DJC-SVM model is basically consistent with the propulsive force obtained from the optimal quadratic calculation. It shows that DJC-SVM model prediction can really solve the nonlinear problem of quadratic optimal performance index. In the DJC-SVM model, the parameter identification based on the pulsating array fusion structure of convergence nodes is further proved. The rationality and validity of the SVM model method are updated in real time.

For the whole wireless sensor network, based on DJC structure model, SVM prediction model can disperse the thrust prediction process of MPC controller to some cluster heads. The sink node only needs to perform an optimal weighted fusion on the thrust prediction uploaded by the cluster head node. The optimal control thrust result is obtained. This avoids the complex optimization process at the aggregation node and greatly reduces the energy consumption of the aggregation node.

4.2 Design and analysis of routing protocol for dynamic positioning system based on data fusion

In the ship dynamic positioning system, the basic function of WSN is to collect data in real time, and immediately upload the monitoring information of each sensor node. This will cause the node to start frequently, and the amount of communication and energy will increase. Therefore, it is necessary to adopt a certain data fusion algorithm in the network layer routing protocol design and application layer of the sensor network. Based on the residual energy and dormancy scheduling mechanism, the network layer data fusion structure and the network layer data fusion mechanism are adopted. The MAC layer sleep scheduling mechanism is applied to routing layer protocol, which can not only improve the real-time performance of data transmission, but also save energy. When the cluster head is selected, the residual energy of the node is considered, and the equilibrium principle is used to solve the problem of the uneven distribution of nodes in each cluster. The strategy of hierarchical forwarding and delay retransmission is adopted to prevent congestion when a large number of data are transmitted. It reduces the delay of data transmission and enhances the real time.

For traditional network layer data fusion mechanism, data centric routing algorithm must be used to identify data and realize data exchange at cross protocol level. The different data types of the same sensor nodes cannot be fused. The agreements of each layer are independent and complete. It lacks mutual transparency. The ability of adaptive network load is insufficient.

The traditional network layer data fusion mechanism is overly dependent on the application. Aiming at this shortage, the network layer data fusion mechanism independent of application is designed. It is not concerned with the content of data transmission. The core idea is to merge multiple data units based on the next hop address. Data transmission is used to transmit data and extend the path. The MAC layer transmission conflict is reduced to achieve the energy saving effect. The data fusion mechanism independent of the application is shown in Figure 6.

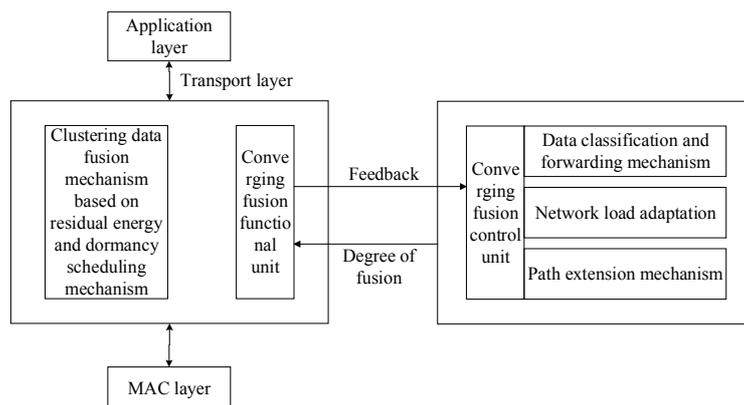


Fig. 6. The data fusion mechanism independent of the application

Convergence and fusion function unit mainly converges the network packet data and cancels the fusion operation. The convergence and fusion control unit is mainly responsible for adjusting the degree of fusion based on the idle state of the link and the state control of the state of the load. The data packet sent by the network layer enters the converging fusion function unit. The next hop address of the same data unit is fused and sent to the MAC layer for transmission. The call time and fusion degree of the fusion functional unit are determined by the fusion control unit. The data uploaded by the MAC layer is decomposed into the original network layer data unit and transmitted to the network layer, to allow the network layer to reconstruct the routing of each data packet. In converged fusion functional units, a data fusion structure based on residual energy and dormancy scheduling mechanism is used.

The formation of clusters has a great influence on the life cycle and other performance of the network, so it plays an important role in the network protocol. Aiming at the problem of unstable cluster heads, uneven distribution of cluster heads and uneven distribution of cluster members in most classical clustering protocols in wireless sensor networks, the following cluster head selection mechanism is proposed. Based on the minimum network energy, the optimal cluster head formula is:

$$K_{opt} = a \sqrt{\frac{N \cdot \mu_{fs}}{2\pi}} \sqrt{\frac{1}{E_{eRX} + E_{eTX} - \mu_{mp} a^4 \left[\frac{28}{45} + C(r) + C(q) + B(r, q) \right]}} \quad (4)$$

The number of the optimal cluster heads is only related to the area a of the wireless sensor network. The number of nodes is N . The communication parameters between the cluster members and the cluster heads are μ_{fs} . The data transfer between the cluster head and the aggregation node is μ_{mp} . The base station coordinate is (r, q) . The energy consumed by the cluster head to receive the unit bit data of the member nodes in the cluster is E_{eRX} . The cluster head sends the energy E_{eTX} of the unit bit data to the member nodes in the cluster. Formation process of cluster data fusion based on residual energy dormancy scheduling is shown in Figure 7.

In order to solve the problem of uneven distribution of cluster heads, the whole wireless sensor network (WSN) is divided into regions. The whole network topology is divided into a number of sector areas because the sensor node's perception range itself is round. The aggregation node can be more effectively monitored in each area of the sensor network. The structure is well balanced. The sector division is convenient for the establishment of multi hop routing mechanism between cluster heads. In addition, the topology control of the network can be optimized. The traditional rectangular partition does not have such advantages in the distribution of energy balance.

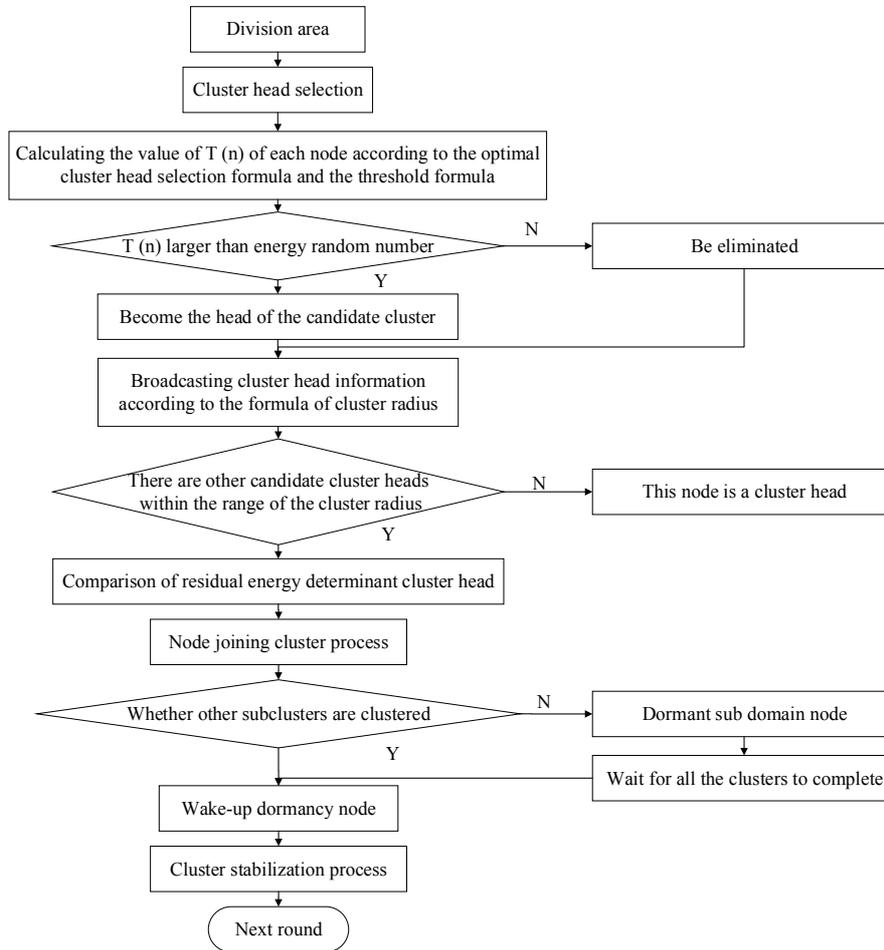


Fig. 7. Formation process of cluster data fusion based on residual energy dormancy scheduling

The cluster head selection mechanism used in this paper can adjust the energy adaptively. In the new round of cluster formation, the residual energy is an important requirement for the head of the node election cluster. If the energy is sufficient, the node can run for the head of the cluster. Therefore, the average energy of the network and the residual energy factors of the node are considered when choosing the cluster head. The new threshold formula is:

$$T(n) = \frac{K_{opt}}{N - K_{opt} \times [rmod(N/K_{opt})]} \frac{E_{res} - E_{ave} \theta}{|E_{res} - E_{ave} \theta|} \frac{E_{res}}{E_{ave}} \quad (5)$$

In the formula, E_{res} represents the current residual energy of a node. E_{ave} represents the average energy of the network.

The cluster heads in all subdomains are selected. The cluster head sends a broadcast notifies the other domain nodes to be cluster heads. The rest of the nodes decide to join the cluster according to the principle of equilibrium and send messages to the cluster head. When a sub domain is formed, if other sub domains have not yet completed the formation of clusters, all nodes in the subdomain will go to sleep and wait for the formation of other sub domain clusters. The innermost subdomains first complete the formation of the cluster, and the outer subdomain is finally completed. In this way, the problem of the ownership of cluster heads and other nodes in each sector is solved. The following nodes transfer ID, location and residual energy information to their cluster heads. According to the residual energy value of all nodes, the cluster head node obtains the average residual energy E_m in the cluster and assigns the control time slot to each node. Two important performance indicators for measuring the network layer data fusion structure of wireless sensor networks are network survival time and average energy consumption. These two performance indicators are simulated. The data fusion structure based on the classical Leach protocol and the data fusion structure based on the residual energy and the dormancy scheduling mechanism proposed in this paper are compared.

It is assumed that 200 nodes are randomly distributed in the range of 100x100, and Matlab is used to simulate. The experimental parameter setting is: The initial energy of the node is 4J, and the generation probability of the cluster head is 0.05. The two parameters involved in the principle of equilibrium are: The intensity ratio of the cluster head signal is $\beta=1.5$. The difference between the number of cluster heads is $\lambda=5$. Each packet size is 50bit. The energy E_{eRX} and E_{eTX} consumed by each node to receive or send data is 50Ni/bit. The comparison of network lifetime is shown in Figure 8. The comparison of the average energy consumption is shown in Figure 9.

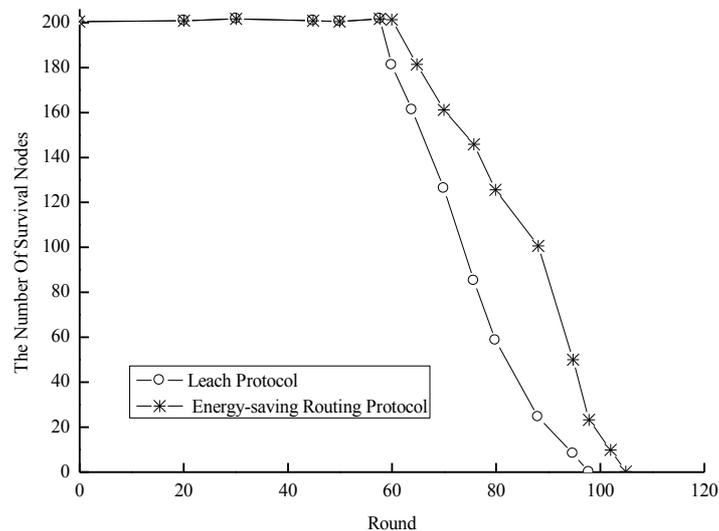


Fig. 8. The comparison of network lifetime

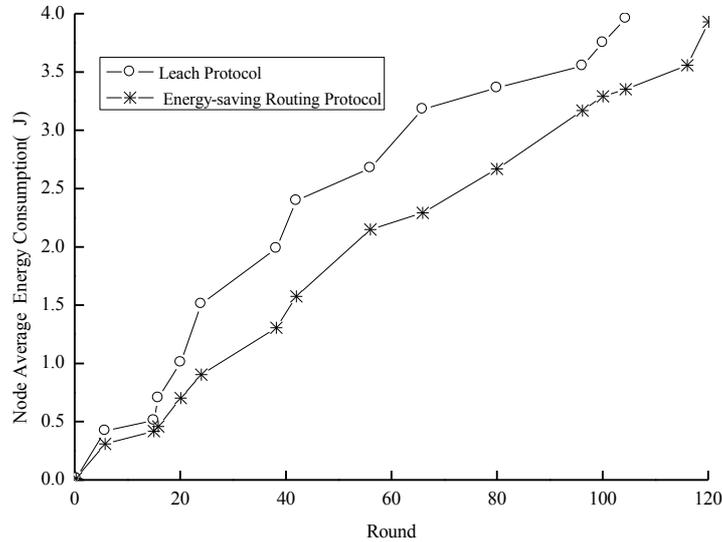


Fig. 9. The comparison of the average energy consumption

From the simulation results in Figure 8 and Figure 9, in terms of network life cycle and average energy consumption, the proposed routing protocol based on the residual energy and sleep scheduling mechanism data fusion structure is superior to the Leach protocol. This shows that the network data fusion structure achieves the goal of energy balance and reduces the energy consumption to a certain extent. The design is reasonable.

5 Conclusions

The data fusion of network transmission function was applied to the ship dynamic positioning system. According to the classic cluster routing protocol, a data fusion structure based on residual energy and dormancy scheduling mechanism was proposed. The data fusion method of common sensor nodes and converging nodes was based on a reasonable and reliable data fusion structure and data transmission mode. At last, the following conclusions are drawn:

- (1) The first integral item is the requirement for the dynamic performance of the system, that is, the trajectory and time requirements of the expected state from the initial state.
- (2) The proposed routing protocol based on the residual energy and sleep scheduling mechanism data fusion structure is superior to the Leach protocol and it improves the real-time performance of data transmission.
- (3) The network data fusion structure achieves the goal of energy balance, enhances the ability of the whole network to avoid congestion, and improves the real-time performance of data transmission.

6 Reference

- [1] Perera, L. P., Ferrari, V., Santos, F. P., Hinostroza, M. A., & Soares, C. G. Experimental evaluations on ship autonomous navigation and collision avoidance by intelligent guidance. *IEEE Journal of Oceanic Engineering*, 2015, vol. 40(2), pp. 374-387. <https://doi.org/10.1109/JOE.2014.2304793>
- [2] Ravichandran, R., & Meena, N. An Instantaneous Power Saving Method in Ship Detection with Wireless Sensor Network. *Networking and Communication Engineering*, 2014, vol. 6(3), pp. 97-102.
- [3] Deng, J. Real-time Navigation Monitoring System Research for LNG-Fuelled Ship in Inland Water. *Journal of Maritime Research*, 2017, vol. 12(2), pp. 95-102.
- [4] Perera, L. P., Carvalho, J. P., & Soares, C. G. Solutions to the failures and limitations of Mamdani fuzzy inference in ship navigation. *IEEE Transactions on Vehicular Technology*, 2014, vol. 63(4), pp. 1539-1554.
- [5] Liu, K., Xie, Y., Chen, M., & Ma, J., October. Ship-board pedestrian positioning method by integrating Dead Reckoning and Wireless Sensor Networks. In *Navigation World Congress (IAIN), International Association of Institutes of*, 2015, pp. 1-7
- [6] Perera, L. P., & Mo, B. Data analysis on marine engine operating regions in relation to ship navigation. *Ocean Engineering*, 2016, vol. 128, pp. 163-172. <https://doi.org/10.1016/j.oceaneng.2016.10.029>
- [7] Zaniewicz, G., Kazimierski, W., & Bodus-Olkowska, I., June. Integration of spatial data from external sensors in the mobile navigation system for inland shipping. In *Geodetic Congress (Geomatics), Baltic 2016*, pp. 165-170.
- [8] Chang, S. H., & Mao-Sheng, H. A novel software-defined wireless network architecture to improve ship area network performance. *The Journal of Supercomputing*, 2017, vol. 73(7), pp. 3149-3160. <https://doi.org/10.1007/s11227-016-1930-5>
- [9] Du, J. L., Yang, Y., Hu, X., & Chen, H. Q. Control law design of dynamic positioning for ship based on dynamic surface control. *Journal of Traffic and Transportation Engineering*, 2014, vol. 14(5), pp. 36-50.
- [10] Tomera, M. Nonlinear observers design for multivariable ship motion control. *Polish Maritime Research*, 2012, vol. 19, pp. 50-56. <https://doi.org/10.2478/v10012-012-0023-5>

7 Authors

Baofeng Xie and **Rong Ge** are with Jiangsu Maritime Institute, Jiangsu, China.
Qinyou Hu is with Shanghai Maritime University, Shanghai, China.

Article submitted 13 January 2018. Resubmitted 25 February 2018. Final acceptance 28 March 2018.
Final version published as submitted by the authors.