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Research Article

A Two-Level Iterative Node Importance Evaluation of Aircraft Function Modules Based on Influence Matrix

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Accurate evaluation of the critical nodes in the system is essential work for a multiplatform avionics system (MPAS) for resource allocation and other works. However, current evaluation methods are either limited to the aircraft level or the function module level. There is a lack of research on the evaluation using the information of these two levels. In view of this situation, this paper researches the two-level iterative method of evaluating the importance of aircraft function modules. The influence matrix was constructed by using the node access probability calculated by the PageRank algorithm and the function module weight calculated based on centrality. In addition, the importance of aircraft nodes was used to carry out two-level iteration, and finally, the importance of aircraft function modules was obtained. The experimental results show that this method can comprehensively utilize the information on aircraft cooperative network and function module cooperative network, solve the key problems of two-level iterative evaluation, and meet the requirement of evaluating critical nodes in a system.

1. Introduction

Modern avionics system has broken through the concept of traditional avionics systems. The most typical one is the multiplatform avionics system (MPAS, Figure 1(a)), based on networks, with different types of aircraft avionics systems [1]. For an aircraft, its internal avionics system has gradually developed from integrated modular avionics (IMA) system to distributed integrated modular avionics (DIMA) system (Figure 1(b)) [2]. Inside the DIMA, the functions are no longer bound to the hardware, and the accouterments are no longer centralized. Instead, the network connects multiple devices, and the MPAS integrates and manages the resources of each aircraft's avionics system. Therefore, the realization of the vehicle functions becomes a matter of requesting the available hardware resources. The functional application software issues an application for hardware resources according to its requirements, and the MPAS responds to the application based on the existing resources of each device to ensure that the functional application software completes its task on the appropriate device. Accurately assessing the critical nodes in the system is an essential task for the multiplatform avionics system when it comes to resource allocation and other related work.

Although manned aerial vehicle (MAV) can carry a variety of equipment and cooperate easily, they have problems such as high cost and long maintenance cycle, and the safety of the pilot must also be considered. The unmanned aerial vehicle (UAV) has the characteristics of low complexity and low cost, but there are problems with autonomous intelligence, communication delay, situation awareness, and so on. The MAV/UAV mixed formation can complement the advantages and disadvantages of MAV and UAV in function and performance [3], which is also a typical application of MPAS. Existing research on multiplatform avionics systems often uses MAV/UAV mixed formations as examples. [4] proposes a collaborative combat effectiveness evaluation method of MAV/UAV based on the Hopfield neural network. They use a discrete Hopfield neural network to train data and make simulation verification. However, this method

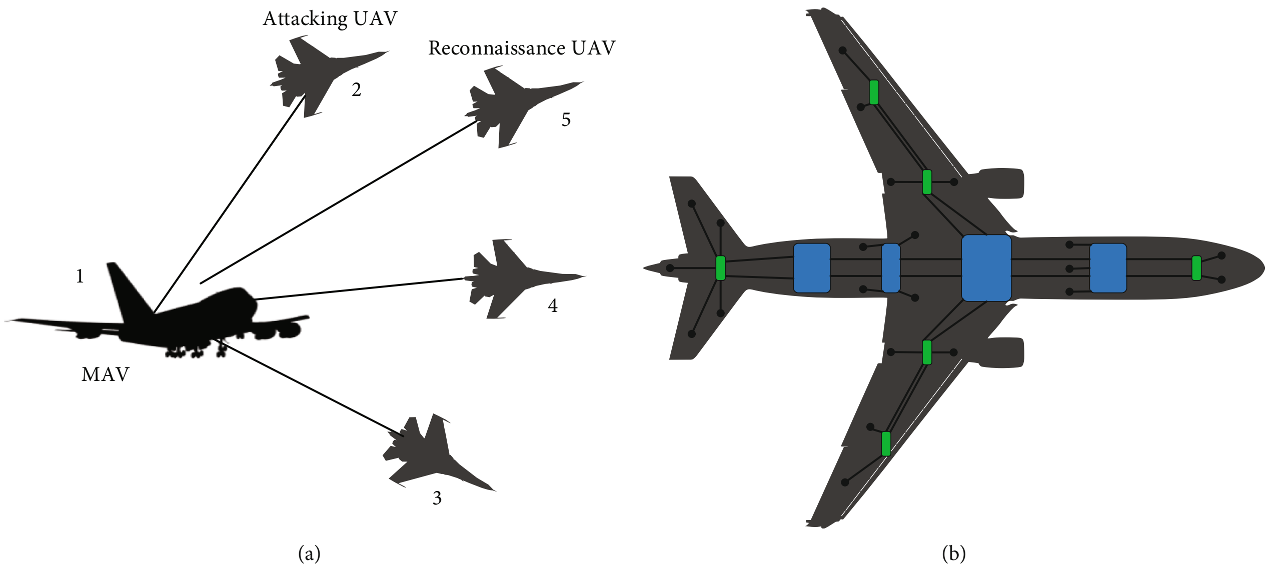

Figure 1: Schematic diagrams of different avionics systems: (a) schematic diagram of MPAS; (b) schematic diagram of DIMA.

requires a period of training to face different datasets, and the real-time performance is poor. [5] proposes an evaluation method of MAV/UAV collaborative combat effectiveness based on information entropy. They establish the node and edge models for targets, equipment, and information interaction between them in a collaborative combat network. However, membership functions of information entropy and combat capability are calculated based on expert experience and are not objective and accurate enough.

Some scholars have also undertaken research focused on evaluating function modules. [6] modeled the multiplatform avionics system as a network structure composed of switches and processing modules at different levels. They evaluated the system by simulating the task reception process and using the task reception rate as the evaluation metric. However, this method resulted in significant delays in the evaluation results. [7] proposed a three-layer designed DIMA architecture and presented the mathematical formulation of its constraints and quality metrics. However, a specific evaluation method for optimizing the DIMA architecture was not provided. [8] proposed a framework for monitoring integrated modular avionics equipment. This framework utilizes time-triggered Ethernet to analyze the synchronization information in the DIMA system.

Overall, the main issue in the research on the evaluation of critical nodes in multiplatform avionics systems is that most studies focus on either the aircraft level or function module level, and there is a lack of comprehensive research that utilizes information from both aircraft level and module level for evaluation. This study adopts a two-level iterative approach, utilizing both aircraft level and function module level, to explore evaluation methods for functional modules in collaborative systems. When evaluating from the perspective of two-level iteration, the key issue that has to be considered is how to further use the information of the function module level based on the aircraft evaluation. This paper proposes a two-level iterative importance evaluation method for aircraft function modules. Based on the influence matrix, it uses the importance of aircraft nodes and the information on the function module cooperative network to evaluate the importance of function modules and solves the key problem of two-level iterative evaluation.

2. Two-Level Iterative Importance Evaluation Model

[6] discusses the construction method of the aircraft-level MAV/UAV cooperative network (hereafter referred to as "cooperative network"), and [9] discusses the design method of the aircraft function module structure. This study focuses on the decomposition method of aircraft cooperative networks and the evaluation method of function module importance in two-level iteration.

Two-level iterative important degree evaluation methods can be divided into the following several points:

(1) Decomposing aircraft collaborative network into function module collaborative network. Moreover, the node weight of the function module cooperation network is obtained by using the centrality method

(2) Using the PageRank algorithm to evaluate the function module collaborative network. The evaluation value is used as the node access probability

(3) Using the importance of aircraft, node weight, and node access probability to calculate the influence matrix of the function module collaborative network

(4) Obtaining the importance of function modules by two-level iterative calculation with aircraft importance and influence matrix

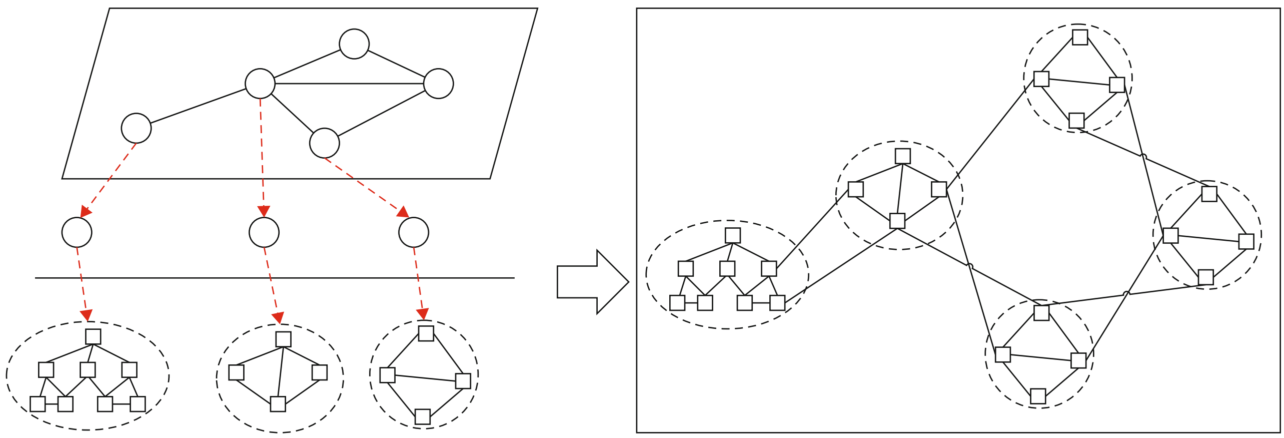

Figure 2: Aircraft cooperative network decomposition processing.

Besides, in the following paragraphs, the concepts of importance and weight will be repeated, which may cause some confusion for the reader. To avoid this situation, these concepts are clearly defined here.

Definition 1 (aircraft importance). In a cooperative network, the degree to which the failure of an aircraft node may affect the ability of the whole network to complete the mission is called aircraft importance.

Definition 2 (domain importance). In the process of collaborative network decomposition, each aircraft node is regarded as a domain containing a series of function modules. The aircraft importance of the aircraft node where the function module resides is called the domain importance of the function module.

Definition 3 (function module weight). In a decomposed function module cooperative network, the function module weight is the importance of each function module node that is only calculated by using the information provided by this network.

Definition 4 (integrative importance). The integrative importance of a function module is defined as the reflection of the impact of a function module on a mission, which takes domain importance and function module weight as input and uses collaborative network information for iterative calculation.

2.1. Cooperative Network Decomposition. The collaborative construction and embedding method of the aviation information network service function chain proposed by [10] have certain reference significance for the decomposition process of aircraft collaborative networks. However, this approach applies to scenarios where tasks are mapped to links between several modules, rather than to the decomposition of the entire collaborative network. This paper intends to adopt a top-down decomposition method, which is based on the ideas in [10] and guides the manual decomposition of the whole collaborative network.

The main operations are as follows:

(1) Each aircraft node in the aircraft cooperative network is regarded as a domain

(2) Adding different types of function module architectures to the corresponding domain

(3) Mapping edges between aircraft to edges between function modules

Figure 2 shows a simplified process. This process directly reuses the nodes and edges of the aircraft cooperative network and decomposes them into nodes and edges in the function module cooperative network. At the same time, because of regarding the aircraft node as a domain, its internal state is separated from the external state, so the mapping of function modules can be directly carried out without considering the specific state of function modules.

Then, it is necessary to simply quantify the information of the decomposed function module cooperative network. The centrality measure can identify the key nodes in the function module cooperative network by using the structure information of the cooperative network. The commonly used centrality measures in research are as follows [11–16]: degree centrality and eigenvector centrality, which are based on node degree, and closeness centrality, betweenness centrality, and delta centrality, which are based on shortest paths. Use FC to denote the weight of function modules.

After the establishment of the function module cooperative network, the aircraft node importance is mapped to a diagonal matrix PC.

$$\exists\left(F_i \in \mathrm{domain}\left(A_j\right) \wedge \langle F_i, c_i\rangle \wedge \langle A_j, W_j\rangle\right) \longrightarrow \left(c_i = W_j\right), \tag{1}$$

$$\mathrm{PC} = \begin{bmatrix} c_1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & c_n \end{bmatrix}. \tag{2}$$

Equation (1) uses a logical expression to show how the c_i expression of function module domain importance is determined. And the $<\text{subject, its importance}>$ is what the symbol $<,>$ means. Therefore, the meaning is if there is function module F_i in the domain of aircraft A_j, and the aircraft importance of aircraft A_j is W_j, and the domain importance of function module F_i is c_i, then the value of c_i is W_j. Equation (2) composes c_i into the aircraft importance matrix PC.

2.2. Node Access Probability Based on PageRank. PageRank was proposed and applied to webpage ranking by Page et al. [17], one of the founders of Google. It has now been widely used in various scenarios that datasets can be represented as graphs [18]. The basic idea is to obtain an importance ranking of web pages by analyzing the link structure of a network. The calculation process of PageRank is like an aimless netizen who opens a web page at random. The PageRank value (for short, PR value) represents the probability of the netizen staying on the web page. The higher the PR value of a webpage, the higher the probability of randomly jumping to the webpage. Therefore, when the PageRank algorithm is applied to the function module cooperative network, the PR value can be used to represent the access probability of the function modules. PageRank mathematical model is as follows:

$$\mathrm{PR}_u = \frac{(1-d)}{N} + d\sum_{i=1}^{n}\frac{\mathrm{PR}_{T_i}}{C_{T_i}}, \tag{3}$$

$$\mathrm{pr}_i = \frac{\mathrm{PR}_i}{\min(\mathrm{PR}) + \max(\mathrm{PR})}. \tag{4}$$

In Equation (3), the meanings of each symbol are as follows: PR_u represents the PR value of the node u; d is the damping coefficient (usually set to 0.85), which can prevent the node access probability from being 0; T is a set of nodes that point to node u; and C is the out-degree of a node. To ensure numerical rationality, the obtained node PR values need to be linearly normalized using Equation (4). pr is the PR value after normalization, which denotes the access probability of the function modules.

2.3. Influence Matrix. Any network is made up of nodes and links (or edges). Nodes are connected through links. Each node in the network is not isolated and is affected and limited by its neighbors. Nodes and links form a unified whole and play their roles [19]. The influence matrix is used to describe the relationship between nodes.

[20] uses the node deletion method to demonstrate that the influence of a node is not limited to its adjacent nodes. When the reachability between nodes is strong, deleting a node will not only affect the adjacent nodes but also affect the nonadjacent nodes. At the same time, [21] finds that when considering nonadjacent nodes of second order or more, the running efficiency of the algorithm decreased sharply without significant accuracy improvement. Therefore, in order to balance the accuracy and efficiency of the algorithm, this only considers the neighbor nodes within the second order.

Define the internode influence probability p to express the possibility of mutual influence between nodes:

$$p_{ij} = \frac{\mathrm{PP}_{ij}/\mathrm{FC}_j}{\sum_{k\in\tau}(\mathrm{PP}_{ik}/\mathrm{FC}_k)}, \tag{5}$$

$$\mathrm{PP}_{ij} = \begin{cases} \mathrm{pr}_j, & j\in\tau_1(i), \\ \mathrm{pr}_k\cdot p, k\in\tau_1(i), j\in\tau_2(i)\wedge & j\in\tau_1(k), \\ 0, & \text{others}. \end{cases} \tag{6}$$

In Equation (5), $\tau(i)$ denotes the set of nodes within second-order adjacent nodes of node i; τ_1 is the set of first-order adjacent nodes; τ_2 is the set of second-order adjacent nodes. The PP of Equation (6) is an intermediate variable and denotes the probability of accessing the nodes within second-order adjacent nodes.

Through such a processing procedure, it obtains the influence probability between a node and its adjacent nodes within the second order. Then, use p to construct the influence probability matrix P:

$$P = \begin{bmatrix} 0 & p_{12} & \cdots & p_{1n} \\ p_{21} & 0 & \cdots & p_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ p_{n1} & p_{n2} & \cdots & 0 \end{bmatrix}. \tag{7}$$

According to the aircraft importance matrix PC and the influence probability matrix P of the function module cooperative network, the influence matrix H can be obtained as follows:

$$H = \mathrm{PC}\cdot P = \begin{bmatrix} c_1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & c_n \end{bmatrix} \cdot \begin{bmatrix} 0 & p_{12} & \cdots & p_{1n} \\ p_{21} & 0 & \cdots & p_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ p_{n1} & p_{n2} & \cdots & 0 \end{bmatrix}. \tag{8}$$

In the influence matrix H, each row reflects the degree of influence a node has on other nodes in the network, and each column reflects the degree to which a node is influenced by other nodes in the network. The influence matrix quantifies the degree of mutual influence of nodes in the function module cooperative network.

2.4. Integrative Importance of Function Modules. This section presents a method to calculate the integrative importance of function modules by using the aircraft importance matrix PC and influence matrix H. This method considers the importance of the aircraft to which the function module belongs and the influence of the function module node. The

Input: G: function modules cooperative network;
W: a set of aircraft importance;
FC: a set of function module weights
Output: I: the integrative importance set of function modules collaborative network
for i in $G.nodes$ ***do*** $//C_i$ is the importance of the aircraft
  $C_i := W[G.nodes_i.aircraft\_id]$
$PC :=$ *diagonal matrix* of C
//step 1: Calculate access probabilities
$PR =$ ***PageRank***(G)
for pr in PR ***do***
  $pr := PR/(PR_{\min} + PR_{\max})$
for v in $G.nodes$ ***do***
  if v in $\tau_1(v_1)$ ***then*** $PP(v_1, v) := \max\ (PP(v_1, v), pr_v)$
   if v in $\tau_2(v_1)$ and ***exist*** $(edge(v_2, v_1)$ and $edge(v_1, v))$ ***then***
     $PP(v_2, v) := \max\ (PP(v_2, v), pr_{v_1} * pr_v)$
// step 2: Calculate the impact matrix H
for $edge(i, j)$ in $G.edges$ ***do***
  for k in $\tau(i)$ ***do***
    $P_{ij} = PP(i, k)/FC(k) + P_{ij}$
  $P_{ij} = PP(i, j)/FC_j/P_{ij}$
$H := PC \cdot P$
// step 3: calculate the importance
for $j := 1$ to *size* of $G.nodes$ ***do***
  for $i := 1$ to *size* of $G.nodes$ and $i \neq j$ ***do***
    $I_j := I_j + PC_j \times H_{ij}$

ALGORITHM 1: Two-level iterative evaluation algorithm.

integrative importance I of the function modules is defined as follows:

$$I_j = \mathrm{PC}_j \times \sum_{i=1, i\neq j}^{n} h_{ij} = \mathrm{PC}_j \times \sum_{i=1, i\neq j}^{n} p_{ij} \cdot \mathrm{PC}_i. \quad (9)$$

The intuitive meaning of the process of calculating the node importance of a function module is as follows: at the beginning, the importance of function modules is equal to that of aircraft; then, adjust the importance of function modules according to the degree of influence of other nodes; finally, the two-level iterative integrated importance of function modules is obtained.

2.5. Evaluation Algorithm. Algorithm 1 is the two-level iterative node importance evaluation algorithm of aircraft function modules. The input G is a graph model of function module collaborative network. The input W is a set of aircraft importance. The input FC is a set of the function module weights that are obtained by centrality. Algorithm output I is a set of integrative importance of function modules obtained by two-level iteration.

This algorithm first calculates the access probability between adjacent nodes based on PageRank. Then, the influence between any two nodes in the function module cooperative network is calculated by using aircraft importance, function module weights, and access probability between adjacent nodes. Finally, based on aircraft importance and the influence of the function modules, the two-level iterative integrated importance of the function modules is obtained.

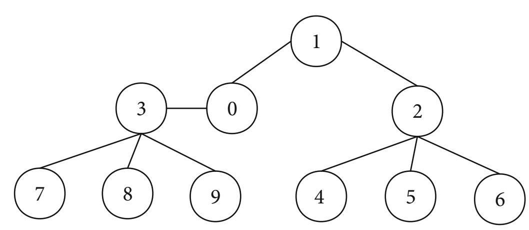

FIGURE 3: Aircraft cooperative network.

It is assumed that a function module cooperative network, the number of nodes is V and the number of edges is E, is represented by an adjacency list. The complexity of the PageRank compute node access probability is $O(V^2)$. The complexity of the process finding all nodes within the second-order adjacency of each node is $O(V * E)$. And the complexity of the process calculating the integrative importance of each node is $O(V^2)$. Therefore, the complexity of Algorithm 1 is $O(V * (V + E))$.

3. Experiment

3.1. Design of a Cooperative Network. The example in the experiments is an idealized model, which is simplified from a real cooperative network. In the cooperative network of the Figure 3 example, we only consider 10 aircraft nodes. Each node denotes only one MAV or UAV, and each edge denotes the interaction between two aircraft. This example assumes that nodes 0 and 1 of 1 are MAV nodes and the other nodes are UAV nodes.

Table 1: Aircraft importance and ranking.

Node	Node weight	Ranking
0	0.11337	3
1	0.12636	1
2	0.10419	4
3	0.1143	2
4	0.06996	8
5	0.07052	7
6	0.06875	9
7	0.07436	6
8	0.06388	10
9	0.07461	5

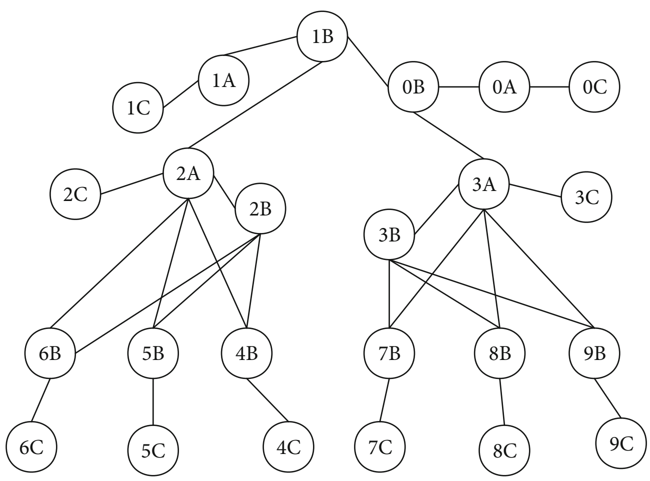

Figure 4: Decomposed function module cooperative network.

Aircraft importance is considered in several dimensions. In the command and control relationship, the closer a node is to the decision center, the higher its importance. At the same time, considering the value of the aircraft itself, the importance of an MAV is generally higher than that of a UAV. Then, the task level undertaken in the mission scenario will also affect the aircraft's importance. Of course, the topology of the cooperative network is also a part that has to be considered. Table 1 shows the importance of aircraft given by experts according to the above-mentioned factors.

The function module cooperative network in Figure 4 is decomposed by the cooperative network in Figure 3 according to a specified collaborative mission.

This example assumes that there are three function module types: A, command module; B, cooperative module; and C, execution module. Different aircraft have different function modules due to different aircraft functions. The edges between function module nodes are determined based on function module architecture and aircraft interaction information.

3.2. Experiment. In order to measure the relationship between the evaluation results of function modules and aircraft importance, Spearman's rank correlation coefficient is used to measure the similarity between two ranking lists. Spearman's rank correlation coefficient is defined as follows [16]:

$$\rho = \frac{\sum_i \left(r_{x_i} - \overline{r_x}\right)\left(r_{y_i} - \overline{r_y}\right)}{\sqrt{\sum_i \left(r_{x_i} - \overline{r_x}\right)^2 \sum_i \left(r_{y_i} - \overline{r_y}\right)^2}}. \tag{10}$$

In Equation (10), index $i \in \{1, \cdots, V\}$; r_x is the ranking of function modules; r_y is the ranking of aircraft nodes corresponding to function modules. $\rho > 0$ denotes positive correlation, and $\rho < 0$ denotes negative correlation. The closer the absolute value of ρ approximates to 1, the stronger the correlation. Regarding the relation between correlation coefficient and correlation intensity, there is no unified standard. The absolute value of ρ is defined as uncorrelated at 0.0-0.1, weakly correlated at 0.1-0.4, moderately correlated at 0.4-0.8, and strongly correlated at 0.8-1.0.

The example cooperative network will be used for the experiments below. The first experiment discusses the influence of different methods to calculate function module weights on the evaluation result. In the second experiment, the evaluation result of the method is compared with those of other evaluation methods in terms of the utilization of information at the aircraft level and the function module level.

3.2.1. Experiment 1: Influence of Function Module Weight on Evaluation. This experiment explored the influence of different function module weights on the final evaluation results.

In the experiment, degree centrality, betweenness centrality, closeness centrality, and eigenvector centrality were used to calculate the function module weight FC as the input of the algorithm. The experimental results are shown in Figure 5 using a line chart, and the values can be obtained from the left y-axis. At the same time, it drew the aircraft importance in the figure, which is represented by the area chart, and the corresponding value can be obtained from the right left y-axis. With two different y-axis orders of magnitude, two kinds of data can be scaled to the same dimension, which intuitively shows the correlation between function modules and aircraft importance. The same process was used to visualize the results of experiment 2.

The results show that the proposed method can identify the more important function modules and the less important function modules in the aircraft node. However, there are some differences in the results obtained by different methods in the evaluation. When input FC is the weights calculated by the delta centrality, the results show that the importance of all nodes is not different except the two most important nodes and the two least important nodes. In the evaluation results obtained from other centrality weights, the importance of different nodes differs significantly. Function module nodes with low domain importance are of low importance in the whole network. Function module nodes with low aircraft importance are of low importance to the whole network, while the function module nodes with high

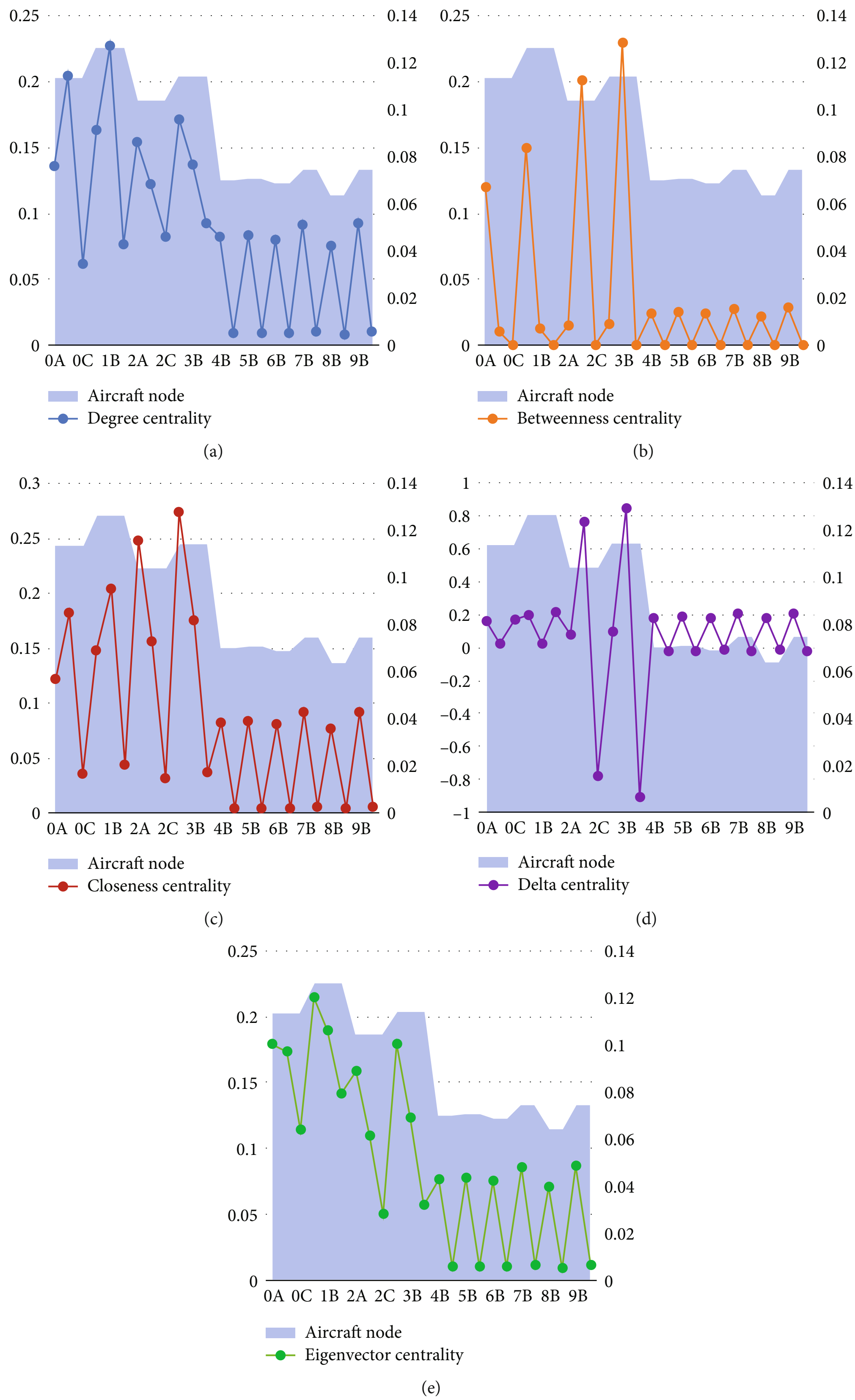

Figure 5: Node importance evaluation result: (a) using degree centrality; (b) using betweenness centrality; (c) using closeness centrality; (d) using delta centrality; (e) using eigenvector centrality.

Table 2: Spearman's rank correlation coefficient between evaluation results and aircraft importance.

Centrality method	Degree centrality	Betweenness centrality	Closeness centrality	Eigenvector centrality	Delta centrality
ρ	0.71	0.40	0.58	0.76	0.16

Table 3: Spearman's rank correlation coefficient before and after the method in this paper was used.

Centrality method	Degree centrality	Betweenness centrality	Closeness centrality	Eigenvector centrality	Delta centrality
Before	0.32	0.36	0.47	-0.11	0.15
After	0.71	0.40	0.58	0.76	0.16

aircraft importance show that some function module nodes are still of high importance to the network, but other function module nodes in the network are not as important as those function module nodes with low aircraft importance.

Spearman's rank correlation coefficient is used to specifically quantify the correlation intensity. Table 2 shows the results. The evaluation results using eigenvector centrality as input have the strongest correlation with aircraft importance (0.76), while the evaluation results using delta centrality as input have the weakest correlation with aircraft importance (0.16). It is believed that a good evaluation result should have a moderate correlation with aircraft importance. In this case, function module nodes with high aircraft importance can be selected while avoiding the situation that all function modules with high aircraft importance are judged as important nodes.

Since the function module cooperative network is decomposed based on the aircraft cooperative network, it naturally has a certain correlation. Compared with the correlation between the centrality of network nodes and aircraft importance, is the correlation between the function module importance using the method in this paper and aircraft importance improved? This problem will be analyzed next.

Table 3 compares Spearman's rank correlation coefficient of function module weights obtained by different centrality methods before and after processing in this paper. It can be found that the correlation between the function module importance obtained by using the method in this paper and aircraft importance is higher than the correlation between the function module weight and aircraft importance; that is, the information utilization of the aircraft cooperative network is more adequate.

3.2.2. Experiment 2: Comparison between the Method in This Paper and Other Methods. In this experiment, the evaluation results of the method in this paper were compared with those of other common evaluation methods. Focus on the utilization of aircraft cooperative network and function module cooperative network in the evaluation process.

Methods compared with the method in this paper are betweenness centrality method, closeness centrality method, eigenvector centrality method, PageRank, and delta centrality. The method used to calculate the weight of function modules in this paper is degree centrality.

Figure 6 shows the results of node importance obtained by the method in this paper and other methods. At the same time, it draws the aircraft importance in the figure to preliminarily estimate the correlation between function modules and aircraft importance. In the selection of high-importance nodes, the method in this paper has many similarities with the closeness centrality, the betweenness centrality, and the delta centrality.

The similarity of evaluation results between the method in this paper and other methods that only use the function module cooperative network information indicates that the method in this paper also makes effective use of the information of the function module cooperative network. The top 5 importance of function module nodes of each method is selected for a detailed analysis.

Analyzing the experimental data in Table 4, among the top 5 of eigenvector centrality and delta centrality, function module nodes ranking 8 and 6 in aircraft importance are presented, and in the top 5 of PageRank, there is no node with aircraft importance ranking of 1. The evaluation results of these methods are not well correlated with aircraft importance. Among the top 5 results of the method in this paper, betweenness centrality, and closeness centrality, the aircraft importance of the selected function module nodes ranks between 1 and 4. However, the method in this paper selects two function modules with an aircraft importance of 1, which is higher than the other two methods.

Table 5 shows the results of using Spearman's correlation coefficient to quantify the correlation intensity of the evaluation results. The evaluation result obtained by the method in this paper has the highest correlation with the aircraft importance, which is 0.71, and the result obtained by the eigenvector centrality has the lowest correlation with the aircraft significance, which is -0.11. The evaluation results of the method in this paper have the highest correlation with aircraft importance, which makes more full use of aircraft cooperative network information.

3.3. Result and Analysis. Through the above examples and experiments, the following can be obtained:

(1) Using different centrality methods to calculate the function module weight FC will have an impact on the correlation between the function module integrative importance and the aircraft importance. But it is at a moderate level of correlation in general

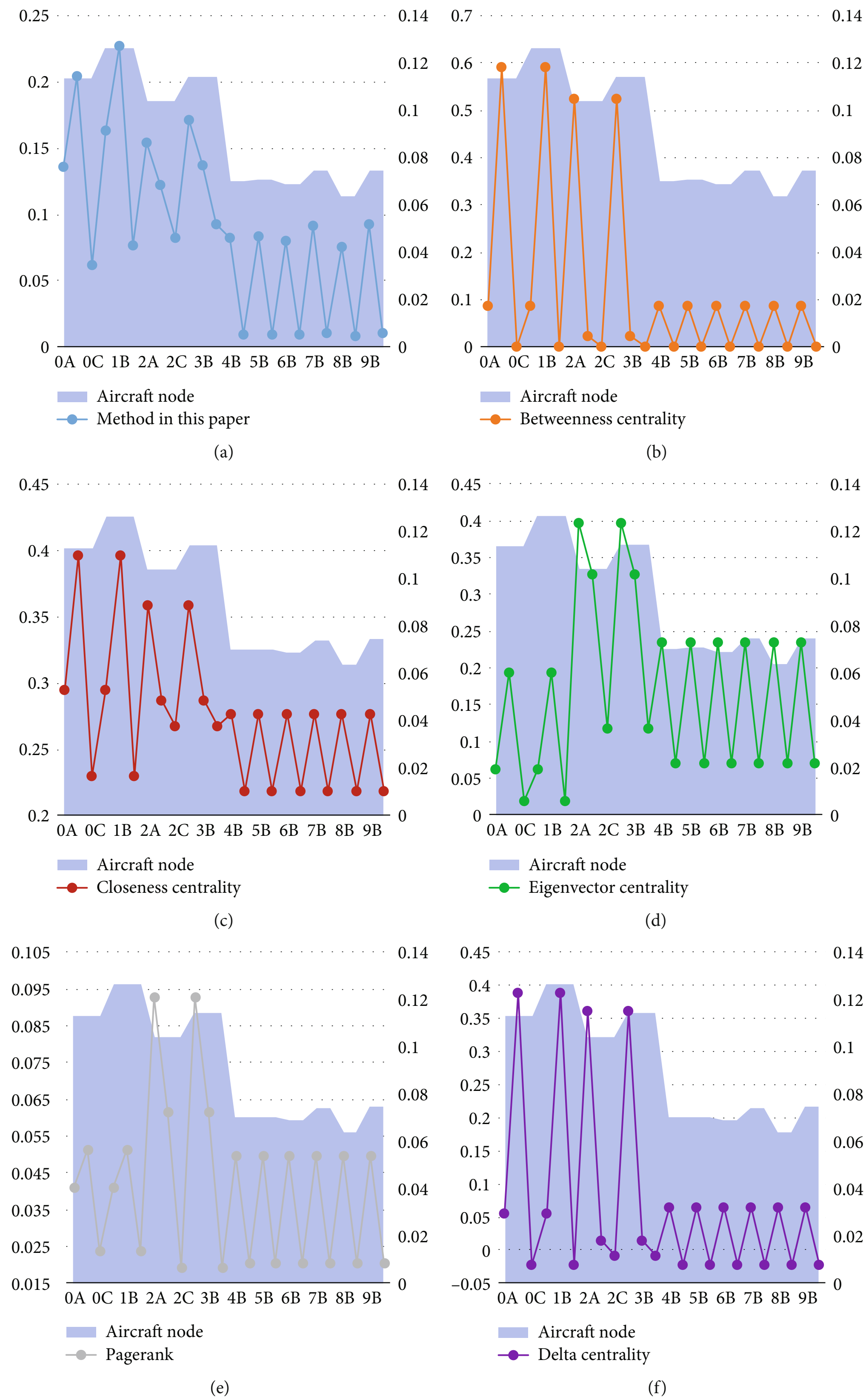

Figure 6: Evaluation result: (a) method in this paper; (b) betweenness centrality; (c) closeness centrality; (d) eigenvector centrality; (e) PageRank; (f) delta centrality.

Table 4: Top 5 node importance.

Ranking		1	2	3	4	5
Method in this paper	Node	1B	0B	3A	1A	2A
	Importance	0.227611	0.205076	0.171831	0.163777	0.154073
	Aircraft ranking	1	3	2	1	4
Betweenness centrality	Node	0B	1B	2A	3A	0A
	Importance	0.592885	0.592885	0.525692	0.525692	0.086957
	Aircraft ranking	3	1	4	2	3
Closeness centrality	Node	0B	1B	2A	3A	0A
	Importance	0.396552	0.396552	0.359375	0.359375	0.294872
	Aircraft ranking	3	1	4	2	3
Eigenvector centrality	Node	2A	3A	2B	3B	4B
	Importance	0.397396	0.397396	0.326289	0.326289	0.234866
	Aircraft ranking	4	2	4	2	8
PageRank	Node	2A	3A	2B	3B	0B
	Importance	0.092696	0.092696	0.061714	0.061714	0.051266
	Aircraft ranking	4	2	4	2	3
Delta centrality	Node	0B	1B	2A	3A	7B
	Importance	0.389910	0.389910	0.3619295	0.3619295	0.0643043
	Aircraft ranking	3	1	4	2	6

Table 5: Spearman's rank correlation coefficient between the results of each method evaluation and aircraft importance.

Evaluation method	Method in this paper	Betweenness centrality	Closeness centrality	Eigenvector centrality	PageRank	Delta centrality
ρ	0.71	0.36	0.47	-0.11	0.21	0.15

(2) The correlation between the function module importance and the aircraft importance will be improved after being processed by the method in this paper. This shows that the method makes effective use of the information of the aircraft cooperative network

(3) Compared with other methods that only use the information in the function module cooperative network, the method in this paper not only retains the information of the function module cooperative network but also makes use of the information of the aircraft cooperative network

4. Conclusions

Accurate evaluation of the critical nodes in the system can help the MPAS for efficient resource allocation. Our study adopts a two-level iterative approach, utilizing both aircraft level and function module level, to explore evaluation methods for functional modules in collaborative systems. The experiments showed that the method in this paper made use of both the information of the function module cooperative network and the information of the aircraft cooperative network, which solved the key problem of two-level iterative evaluation. Currently, this study only incorporates the topological structure of the cooperative system's different hierarchical networks into the evaluation model, without fully utilizing other aspects of data such as node attributes and edge connectivity information. Considering these factors in future research will further improve the accuracy of the evaluation.

Data Availability

The datasets used and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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