CONVERTER MAGAZINE
Volume 2021, No. 6

Formation Feature Analysis with Heterogeneous Unmanned Vehicles for Ocean Monitoring Based on Complex Network

Peng Xie *, Zhuonong Xu
School of Computer and Information Engineering, Central South University of Forestry and Technology, Changsha, China
** Correspondence*

Abstract

Complex network is a new type of analysis method in recent years, which has been widely applied in various fields. As a heterogeneous network, the joint formation of three specific types of UAV, UGV and USV has a certain mapping relationship with the characteristic parameters of the complex network. In this paper, for the complexity and networked structure characteristics of different types of unmanned vehicle formations, we propose a joint formation model of unmanned vehicles based on complex network by analyzing the dynamics of individuals in the formation system and extracting the important factors of network construction in the formation system. On this basis, we conducted a simulation experiment of joint formation ocean monitoring, constructed a formation that is conducive to ocean monitoring and realized formation transformation, analyzing and verifying the performance of the joint formation network in three aspects: average path length, clustering coefficient and degree distribution. We expect to provide theoretical guidance and foundation for practical applications such as sea resource exploration and ocean monitoring.

Keywords*: complex networks; joint formation; unmanned systems; ocean monitoring.*

I. Introduction

In recent years, with the rapid development of information and network technology, complex network science with disciplinary intersectionality and complexity has gradually emerged and is increasingly applied to many disciplines, such as system science, social science, computer and information science, etc. Along with the in-depth research of experts from different fields in the field of complex networks, network science has become a new way to explore complexity. And modern warfare is becoming more prominent as a complex network-based confrontation, more and more emphasis on the multi-service joint warfare, the seizure of the right to control the sea while immediately seizing the right to control the air and finally send ground troops, modern warfare has turned to how to control the joint control of the sea, land and air and the joint formation of the sea, land and air forces rather than a single service combat.

Air, sea, and land formation operations are a typical complex system that consists of complex relationships among many unmanned aerial vehicles (UAVs), unmanned ground vehicles (UGVs), unmanned surface vehicles (USVs), and various types of unmanned vehicles with autonomous characteristics. In formation operations, each side of the operation is a dynamical network of internal units coupled in a specific way, and the mode of operation is network-based, thus modeling air, land, and sea formation operations based on complex network science can more rationally describe the operational countermeasures.

In terms of UAV formations, Zhao et al. [1] proposed a dynamical generation algorithm with different types of node connections in 2017 to conduct research on complex network-based UAV operations, and constructed a network description model reflecting real combat scenarios, which better presents many properties such as emergence and fuzziness in UAV operations; Wang et al. [2] proposed a cluster system robustness assessment method based on complex network theory in 2020 to conduct research on UAV cluster robustness based on complex network theory, and summarized comprehensive evaluation indexes, assessment strategies and relevant algorithms for system robustness.

In terms of USV formations, numerous scholars have also conducted research. Bian et al. [3] proposed a method of networked abstraction of USV formation air defense operations with complex networks in 2015, and conducted a study of a complex network-based USV formation air defense operations model, revealing the relationship between the main parameters of the operational network and the real characteristics of the operational system; Liu et al. [4] proposed a repair model of USV formation complex networks in 2012, and conducted a study of the reliability of USV formation complex network systems based on repair strategies In 2012, Liu and other scholars proposed a repair model of USV formation complex network and conducted a study on the reliability of ship formation complex network system based on repair strategy, which significantly improved the reliability of scale-free network and concluded that the reliability of scale-free network with smaller degree index is improved more.

In terms of UGV formations, Zhang et al. [5] proposed a sliding mode control algorithm with fixed structure and less susceptible to perturbation in 2018 for the study of UGV following control method based on the pilot-following method, and achieved the UGV formation effect of following the pilot vehicle with time-varying desired relative distance and angle; Li et al. [6] proposed a pilot-following algorithm based on Liapunov's method in 2019 for the study of low-speed UGV formation based on vehicle kinematic model, and achieved accurate formation and obstacle avoidance of low-speed UGV.

All the above studies have conducted in-depth research on formation systems and achieved remarkable results. However, these studies only study the formation control of the same kind of unmanned vehicles, and the application scope has certain limitations, which is not applicable to ocean monitoring in joint formations of UAVs, UGVs and USVs, or maritime emergency search and rescue, resource exploration and other situations. Therefore, this paper uses a complex network approach to scientifically and rationally conduct a joint formation of three types of unmanned vehicles on land, sea and air, just as showed in Figure 1.

Figure 1*：*Diagram of joint formation of UAVs, UGVs and USVs.

ISSN: 0010-8189

II. Materials and Methods

Dynamics Modeling for Unmanned Vehicles' Formation

Parameter Introduction

This paper focuses on the joint formation of UAVs, USVs and UGVs using a complex network approach. In order to facilitate the analysis of the dynamics model of these three unmanned vehicles and the formation situation, the study selects the specific UAV, UGV and USV, which are widely used in practice and of the same medium model, as the research objects, and analyzes their motion and force situation by combining their own relevant parameter indexes (as shown in Table 1).

UAVs have been widely used in military, resource exploration, search and rescue and other fields because of their small size, low cost, ease of use, low operational environment requirements, and high battlefield survivability. The AZ-90 UAV weighs 90 kg, has a speed range of 0-150 km/h, a communication range of 0-500 km, and an endurance of 4 h. It is a standard medium-sized UAV, which is used here It is a standard medium-sized UAV, and it is used here as a specific object of study for the dynamic analysis of UAVs [7].

USVs are widely used for collecting maritime intelligence, detecting mines, exploring marine resources, etc. because of their ease of deployment and recovery, as well as their ability to work stealthily for long periods of time in shallow waters with high danger and changing environments. The "Yunzhou" fully automatic sampling and inspection USV weighs 57 kg, has a speed range of 0-10.8 km/h, a communication range of 0-10 km, and a duration of 6 h. It is a typical medium-sized USV, and is used here as a specific object of study for the dynamic analysis of USVs [8].

UGVs have begun to be used in public transportation, military operations, mining, emergency search and rescue, etc. because of their safety and stability, flexibility and convenience, battlefield adaptability, and ability to efficiently perform tasks in remote areas. The Zhong Yun 2.0 UGV, with an overall weight of 800 kg, a speed range of 0-80 km/h, a communication range of 0-10 km, and an endurance of 4 h, is a typical medium-sized UGV, which is used here as a specific object of study in the dynamic analysis of UGVs [9].

Table 1 Relevant parameters of three types of unmanned equipment

Unmanned vehicle	Specific study target	Weight (kg)	Speed range (km/h)	Communication range (km)	Endurance (h)
UAV	AZ90 UAV	90	0-150	0-500	4
USV	"Yunzhou" fully automatic sampling and testing USV	57	0-10.8	0-10	6
UGV	Zhong Yun 2.0 UGV	800	0-80	0-10	4

Dynamics analysis

(1) Three movement rules

The motions and forces of the three kinds of unmanned vehicles are analyzed and the dynamics model is established. The kinetic model satisfies the following three rules:

① Proximity rule

When an unmanned device deviates from the unmanned cluster, it can automatically close to the cluster, as shown in Figure 2:

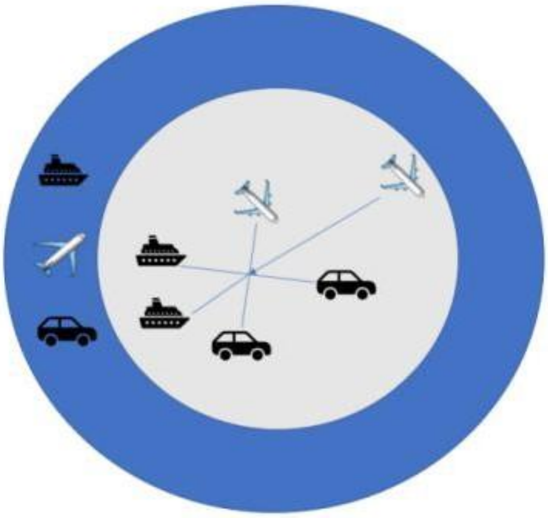


Figure 2: Diagram of proximity rule

② Alignment rule

The direction of motion of an unmanned device depends on the average vector of the direction of motion of the surrounding unmanned vehicles, as shown in Figure 3:

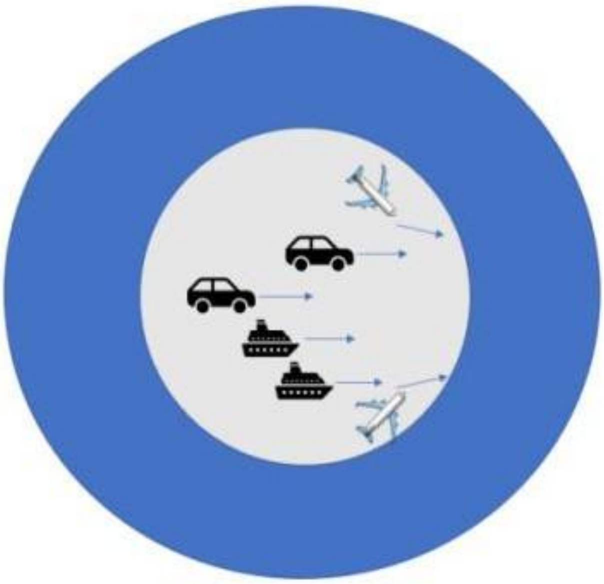


Figure 3: Diagram of alignment rule

③ Separation rule

When an unmanned device comes too close to another unmanned device, it will automatically move away, as shown in Figure 4:

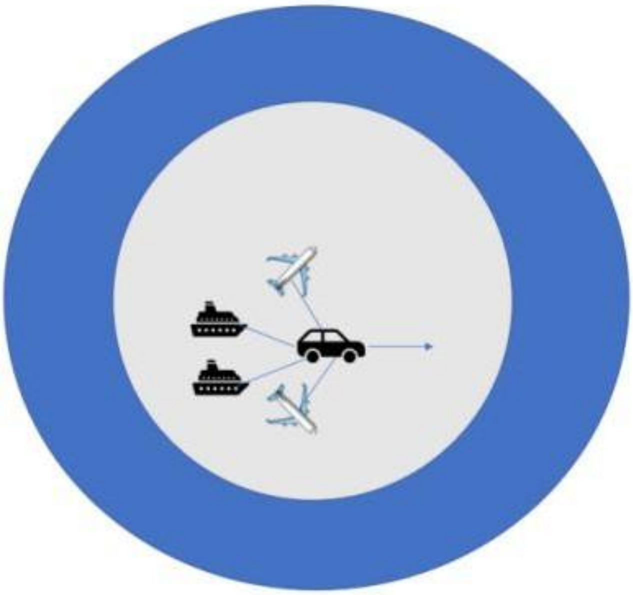


Figure 4: Diagram of separation rule

The three rules take effect in different scopes: in the larger proximity area, the proximity rule and the alignment rule take effect; in the smaller separation area, the separation rule takes effect.

(2) Analysis of forces

① Realization of the idea

Step1: The model of unmanned cluster motion is transformed into a mechanical model with multiple masses interacting with each other (subjected to forces).

Step2: Construct three partial forces, the proximity force F_1, the alignment force F_2, and the separation force F_3.

Step3: By combining the three forces F_1, F_2, and F_3. into one force F, and combining Euler's method to update the velocity v and position P of the motion, the motion of the unmanned cluster is simulated.

② Construction of the parameters related to the partial force.

The average position vector of all neighboring nodes in the proximity region (center of gravity)

$$\bar{P}=\sum_{i=1}^{n1} P_i / n_1 \tag{1}$$

P_i refers to the position vector of neighboring nodes close to the region, and n_1 refers to the number of neighboring nodes close to the region.

The average velocity vector of all neighboring nodes in the proximity region

$$\bar{V}=\sum_{i=1}^{n1} V_i / n_1 \tag{2}$$

ISSN: 0010-8189

v_i refers to the velocity vector close to neighboring nodes in the region.

The average position vector of all collision nodes in the separation region

$$\bar{C} = \sum_{i=1}^{n_2} P_i / n_2 \tag{3}$$

P_i refers to the position vector of collision nodes in the separation region, and n_2 refers to the number of collision nodes in the separation region.

③ Construction of partial and combined forces

Proximity force F_1:

$$F_1 = \bar{P} - P \tag{4}$$

P is the position vector of the selected object node, and the direction of F_1 points from the object node to the neighboring nodes.

Alignment force F_2:

$$F_2 = \bar{v} \tag{5}$$

The direction of F_2 is the same as the mean velocity vector $\bar{v}$

Separation force F_3:

$$F_3 = \frac{P-\bar{C}}{|P-\bar{C}|^2+\varepsilon} \tag{6}$$

The direction of F_3 points from the collision node to the study object node, and a very small factor ε is added to the denominator in order to avoid that the center of gravity of this collision node coincides with this node, resulting in a denominator of 0.

④ Synthesis of forces

The final weighted composite force F is composed of the close pulling force F_1, the aligned pulling force F_2 and the separated repulsive force F_3, are as shown in Figure 5. And the weight parameters w_1, w_2 and w_3 of these three forces are adjusted in the model.

$$F = w_1 F_1 + w_2 F_2 + w_3 F_3 \tag{7}$$

ISSN: 0010-8189

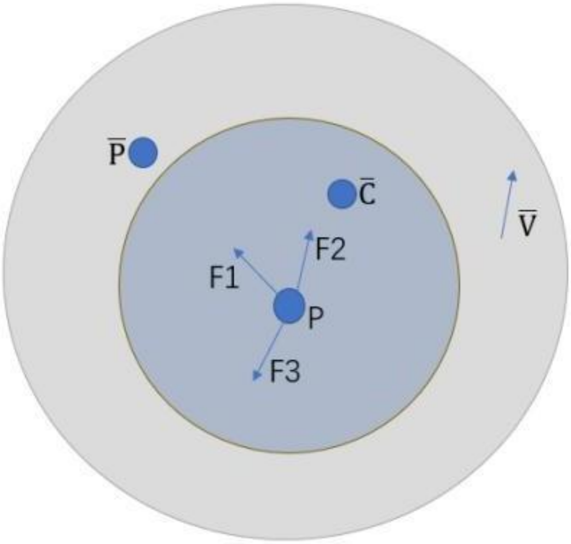


Figure 5**：**Diagram of force analysis of the node

(3) Dynamics analysis

Through the combined force F, Updating the direction and magnitude of the motion velocity v of the unmanned device.

According to Newton's second law:

$$\frac{dv}{dt} = a = \frac{F}{m} = F \tag{8}$$

According to the differential equation:

$$\frac{dv}{dt} \approx \frac{v(t+\Delta t) - v(t)}{\Delta t} = v(t+\Delta t) - v(t) \tag{9}$$

From (8) (9) it follows that F→v：

$$v(t+\Delta t) = v(t) + F(t) \tag{10}$$

According to the definition of the derivative and Euler's method, it follows that：

$$v(t) \approx \frac{P(t+\Delta t) - P(t)}{\Delta t} \approx P(t+1) - P(t) \tag{11}$$

Then the velocity v at the next moment can be updated by the current velocity v of the unmanned device and the combined force F applied to it：

$$v(t+1)=v(t)+F(t) \tag{12}$$

The current velocity v and the current position P of the unmanned device can be used to update the position P at the next moment：

$$P(t+1)=P(t)+v(t) \tag{13}$$

Complex network modeling

Modeling process of complex networks involving mapping of formation networks, parameter analysis, and construction of small-world networks. The overall modeling architecture for complex network modeling is shown in Figure 6:

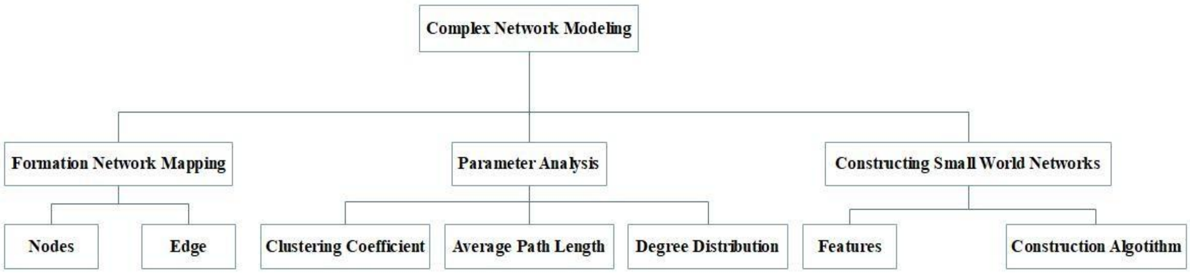


Figure 6: Diagram of complex network modeling architecture

Mapping complex networks to unmanned communication networks

Complex networks are networks with some or all of the properties of self-organization, small world, scale-free in nature, and clustering, a typical complex network is composed of many nodes and connected edges between nodes, where nodes represent different individuals in the real system and edges represent relationships between individuals, and two nodes connected with edges are regarded as adjacent images in the network [10].

Compared to the work of a single device, the cooperation of multiple individuals has better efficiency and robustness, and formation control and formation maintenance of multiple unmanned vehicles can be studied using the complex network approach. Since complex networks are abstractions of complex systems, nodes in complex networks correspond to entities in complex systems [11], specifically in this paper, nodes are abstractions of three types of entities unmanned vehicles, and each unmanned vehicle is considered as a node in the network. And the perception and mutual communication relationship between each individual unmanned vehicle is used as the edge of the complex network, and the edge length of the complex network corresponds to the distance between two unmanned vehicles, so that the unmanned formation system can be treated as a network.

Relevant parameters of complex network models

When using complex network theory to control three types of unmanned vehicles, namely UAVs, unmanned vehicles, and unmanned ships, in formation and to analyze the connected edge approach [10-17], three basic concepts are involved: mean path length, clustering coefficient, and degree distribution.

(1) Average path length

ISSN: 0010-8189

The average path length is the average of the distance between two nodes in the network and is used to describe the degree of connectivity of the network. In this paper, the average path length refers to the average distance between two of all unmanned vehicles in the unmanned formation network. The distance d_{ij} between two nodes i and j in the network is defined as the number of edges on the shortest path connecting the two nodes, and the maximum value of the distance between any two nodes in the network is called the diameter of the network, denoted as D.

$$D = \max d_{ij} \tag{14}$$

The average path length L of a network is defined as the average of the distances between any two nodes and is expressed as follows:

$$L = \frac{1}{\frac{1}{2}N(N+1)} \sum_{i \geq j} d_{ij} \tag{15}$$

Here N is the number of network nodes.

In war, the average path length can reflect the efficiency of a complex network formation to perform the task, and the situation of war is always changing, highly efficient communication becomes the key to achieving victory in formation operations. The shorter the average path length, the shorter the delay in sending and receiving information, and the higher the overall communication efficiency of the system.

(2) Clustering coefficient

The clustering factor means: the density of a closed loop formed by each node and the points around it in the whole complex network. Suppose there is a node i in the network with k_i edges connecting it to other nodes, these k_i nodes are called neighbors of node i. Obviously, there can be at most $k_i(k_i - 1)/2$ edges between these k_i nodes. And the ratio of the actual number of edges E_i of these k_i nodes to the total possible number of edges $k_i(k_i - 1)/2$ is defined as the clustering coefficient C_i of node i.

$$C_i = 2E_i / (k_i(k_i - 1)) \tag{16}$$

The clustering coefficient C of the whole network is the average of the clustering coefficients C_i of all nodes i.

$$C = \frac{1}{n} \sum_{i=1}^{n} C_i \tag{17}$$

(3) Degree distribution

The degree distribution is the number of connected edges around a node, and the degree k_i of node i is defined as the number of other nodes connected to that node. The greater the degree of a node, the more "important" the node is in some sense. The average of the degree k_i of all nodes in the network is called the (node) average degree of the network, denoted as <k>. The distribution of degrees of nodes in a network is often described by the cumulative distribution function P(k), which represents the probability that the degree of a randomly selected node is exactly k [18].

$$P(k)=\sum_{k'=k}^{\infty} p_{k'} \tag{18}$$

It represents the sum of the probabilities that the degree is greater than or equal to k. This approach ensures that all data are presented and eliminate the problem of different data points falling into the same interval.

Small world network

Most real networks are neither completely regular nor completely random and cannot reproduce some important features of real networks. In order to achieve the transition from completely regular networks to completely random graphs, Watts and Strogtz introduced a small-world network model [19] in 1998, called the WS small-world model, is as shown in Figure 7. The algorithm for constructing the WS small-world model is as following:

Starting from a fully regular graph: consider a nearest neighbor coupled network containing N points that enclose a ring, where each node is connected to each of its left and right neighboring K/2 nodes. And k is an even number.
Randomized reconnection: reconnects each edge in the network randomly with probability p, i.e., one endpoint of the edge remains unchanged while the other endpoint is a random node in the network, and there can be at most one edge between any two different nodes that are not connected to themselves.

In the above model, p=0 corresponds to a completely regular network and p=1 corresponds to a completely random network, and the transition from a completely regular network to a completely random network can be controlled by adjusting the value of p.

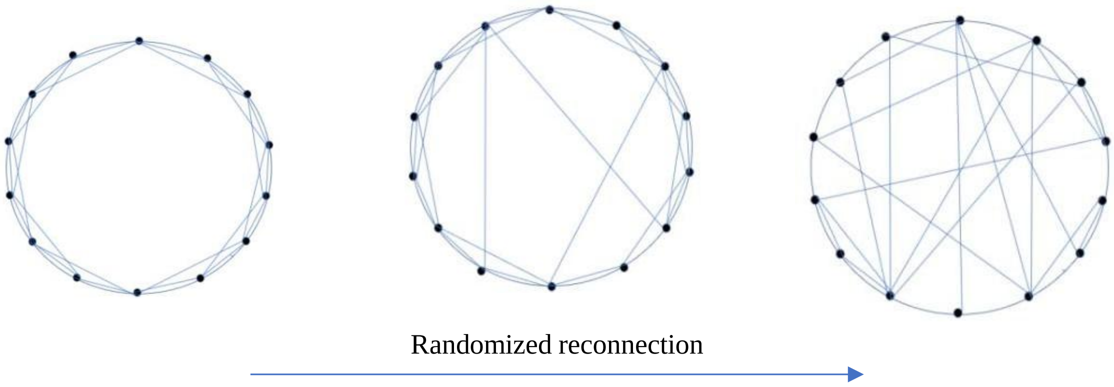


Figure 7: Diagram of small world network

Most of the networks in the real world are not completely random networks, and the degree distribution has a serious inhomogeneous distribution, and small-world networks can reproduce the real-world situation better [20], so small-world networks are chosen for the study of complex networks.

III. Results

In this paper, three experiments are done to model the dynamics of unmanned cluster networks and the study of complex network formations. Simulations are performed using Netlogo and Matlab software to verify the applicability of the complex network approach in joint formation of unmanned vehicles by analyzing the motion of the unmanned vehicles in the cluster and the formation transformation.

Experiment 1: Unmanned cluster motion based on dynamics model

The joint simulation of the three unmanned vehicles is conducted during the experiment, and the three kinds of unmanned vehicles are allowed to move at the same speed to achieve the effect of speed matching. From the relevant parameters of the three specific unmanned vehicles selected for this experiment in Table 1, it is known that the maximum movement speed of the UAV is 150 km/h, the maximum movement speed of the UGV is 80 km/h, and the maximum movement speed of the USV is 10.8 km/h. The number of UAVs is set to 22, the number of UGVs to 15, and the number of USVs to 13 at the beginning of the simulation, and the initial formation of the formation is circle (as shown in Figure 8). The simulation is carried out by continuously adjusting the initial motion speed v of the cluster, the radius d_1 of the approach area, the radius d_2 of the separation area, and the weights w_1 for the approach pull F_1 , w_2 for the alignment pull F_2 and w_3 for the separation repulsion F_3 , and the control variable method is used here for the experimental analysis.

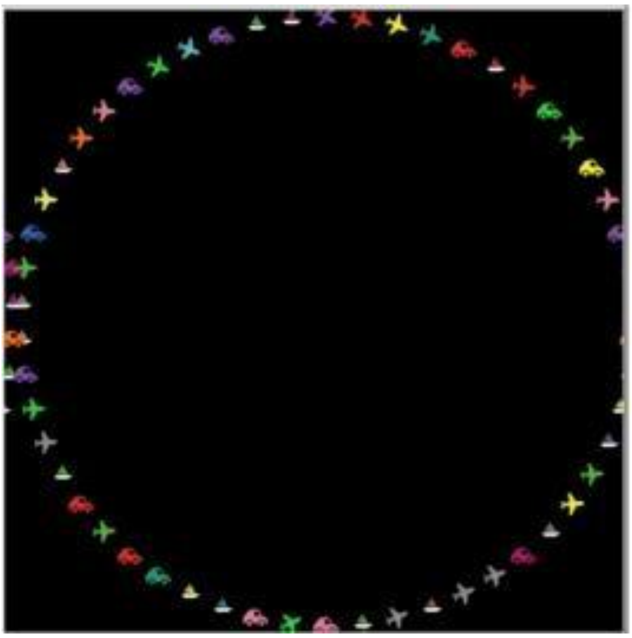


Figure 8: Unmanned cluster initial formation

In the course of the simulation, it was found that when d_1 , d_2 , w_1 , w_2 , w_3 were constant and the initial motion speed v was 10.8 km/h-80 km/h, the initial formation of the unmanned vehicle formation changed to another formation under the action of the combined external force F, but the formation didn't disperse in general, as shown in Figure 9.

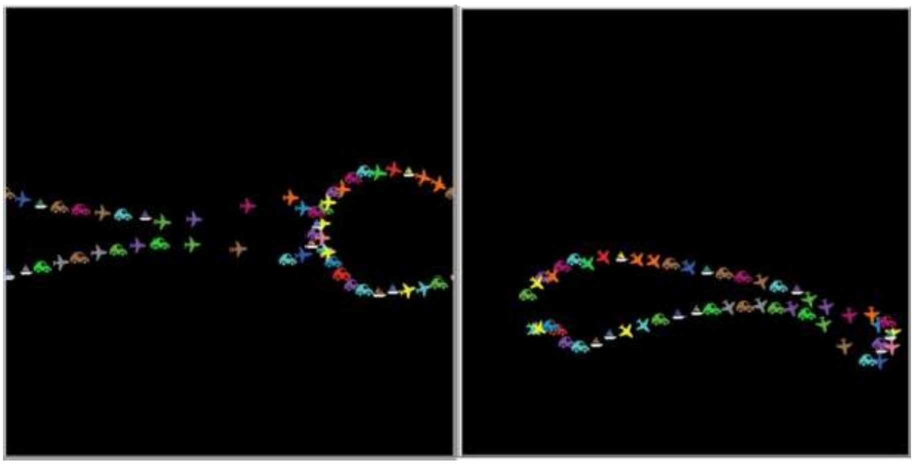


Figure 9: Formation at an initial speed greater than 10.8 km/h and less than 80 km/h

And when the initial movement speed of the formation is greater than 80 km/h or less than 10.8 km/h, the formation disperses, but under the combined external forces, the unmanned clusters still close up and move in the same direction with the guarantee of no collision. As shown in Figure 10.

Figure 10: Formation at an initial speed greater than 80 km/h or less than 10.8 km/h

From experiment 1, we can see that when unmanned vehicles' speed is between 10.8km/h and 80km/h, the formation didn't disperse based on dynamics model.Therefore, in order to ensure the stability of cluster formation, it is suggested that the initial speed range is 10.8 -80 km/h. Adjusting other parameters at a certain speed, it is found through several experiments that the best formation effect is achieved when the radius of the approach area d_1 is 80, the radius of the separation area d_2 is 41, and the weight parameters w_1 , w_2 , w_3 are: 0.06, 7.07, and 10, respectively.

Experiment 2: Formation of three unmanned vehicles in a small world network

Mesoscale eddy, a common type of eddy in the ocean, usually rotate at a high speed and move forward as they rotate. It moves like a typhoon and has a lot of kinetic energy. The kinetic energy of these mesoscale eddies accounts for more than 90% of the large and mid-ocean flow energy in the whole ocean, which is of great research value. The complex network is used to control the formation of UAVs, UGVs and USVs to keep the formation unchanged and move to eight directions such as east, south, west, north and southeast to keep the formation circular [21]. In the actual three-dimensional space, this circular formation is circular in shape from the perspective of top view, but from other perspectives, this formation is messy and cannot be seen as regular. This formation has unique advantages, seemingly messy stereoscopic three-dimentional structure, actually assumes the circular configuration. In this way, the key nodes in formation network can be adjusted easily and the mesoscale eddy can be dynamically monitored. At the same time, the formation can easily send signals to the center node when conducting joint marine monitoring by UGVs, USVs and UAVs, so as to realize more accurate monitoring of ocean eddy currents. When a node in the formation fails to act according to the given instructions due to failure, the stability of the circular structure makes it convenient for other nodes to be substituted to form a new formation, which can better support long-term ocean eddy current dynamic monitor.

ISSN: 0010-8189

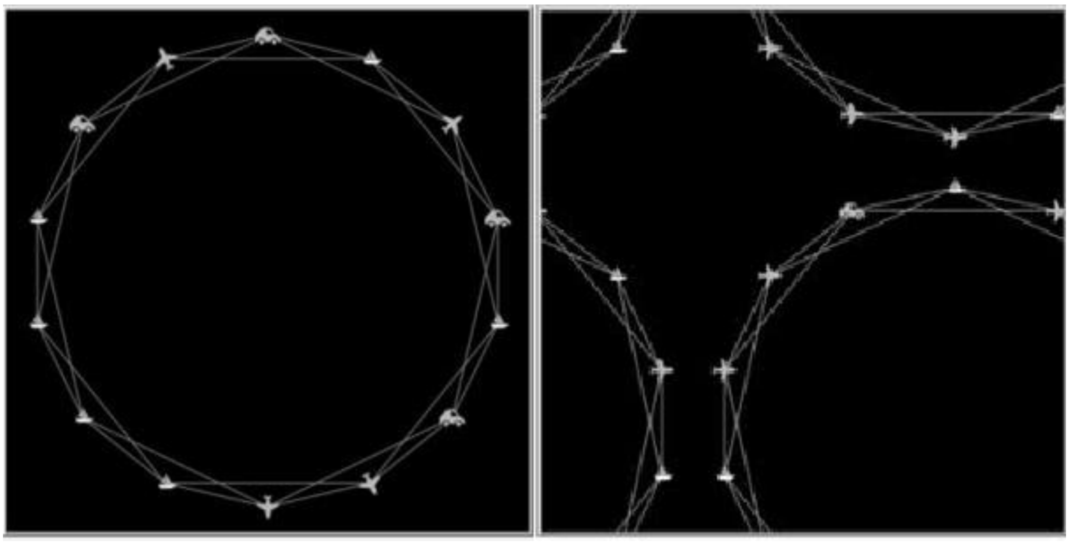


Figure 11: Circular formation and movement of the formation

When the basic formation is always kept constant, different ways of connecting edges will lead to changes in the average path length, clustering coefficient, and degree distribution, are as shown in Figure 12. As the number of reconnected edges increases, both the average path length and the aggregation coefficient of the complex network will start to undergo a significant decrease and later level off, are as shown in Figures 13 and 14. After many times of reconnecting edges, the degree distribution is found to be approximately normally distributed, which verifies that the complex network is applicable to the formation [22-23], is as shown in Figure 15.

From experiment 2, we can see that when the joint formation of UAVs, UGVs and USVs is a circle from the perspective of top view, the formation is very stable during the movement, and during the process of reconnection of sides, the important parameters of complex network: average path length, clustering coefficient, and degree distribution are also smooth and conform to the reconnection law of heterogeneous networks. So circular joint formations based on complex networks are well suited for ocean monitoring.

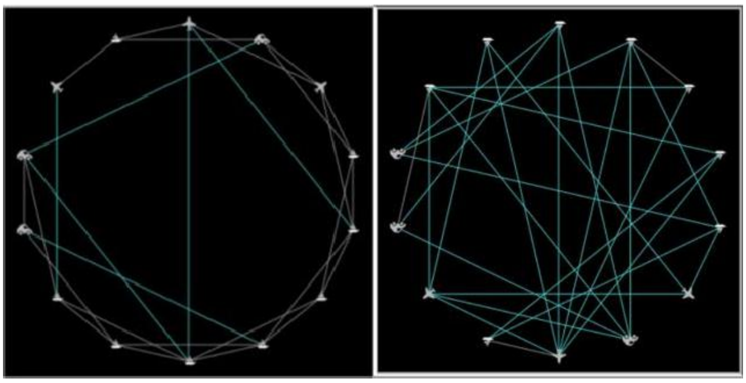
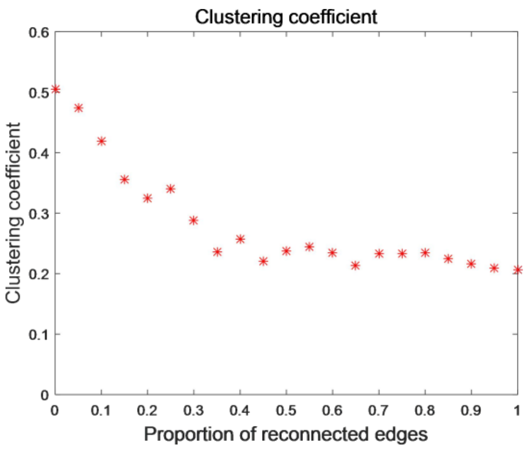


Figure 12: Circular formation after reconnection of sides



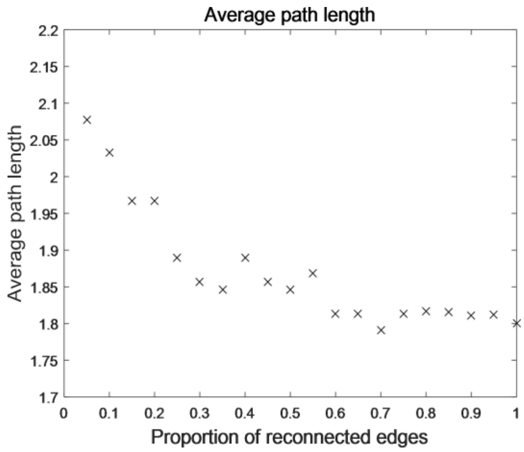


Figure 13: Clustering coefficient of the re-edge process   ***Figure 14: Average path length of the re-edge process***

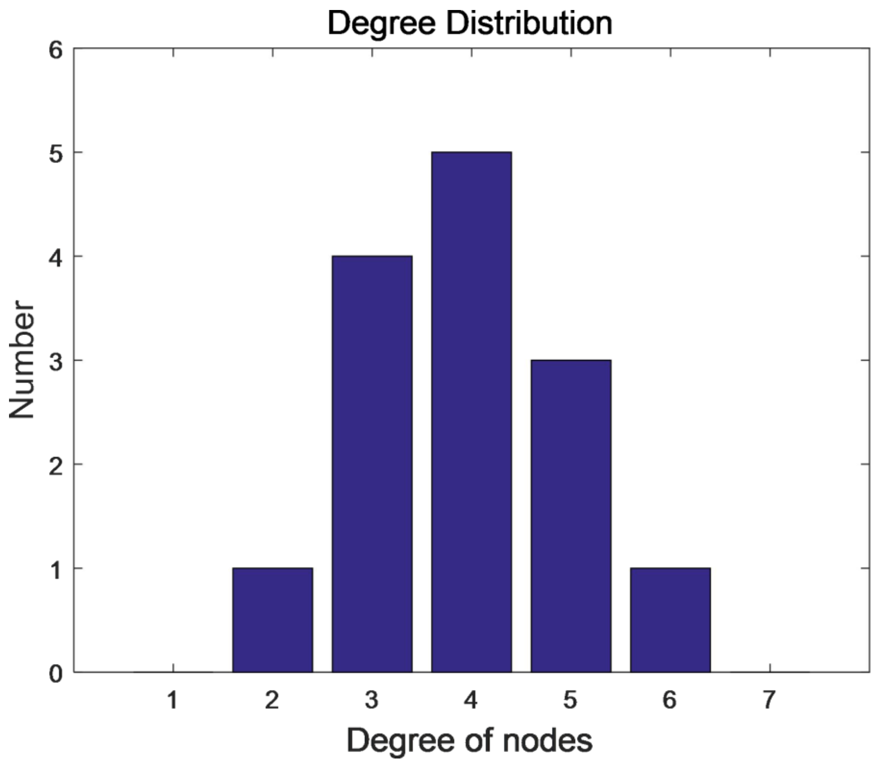


Figure 15: Degree distribution of the re-edge process

Experiment 3: Combining small-world networks with dynamical models

The dynamics model of Experiment 1 and the small-world network of Experiment 2 are combined for joint formation simulation. Different unmanned vehicles will be connected to each other because of the establishment of a complex network, while constantly changing the direction and speed of motion under the action of joint external forces, and the formation will also realize the change of formation under the complex network over time [24-26]. Unmanned formations form a wide variety of formations during the course of motion, are as shown in Figure 16.

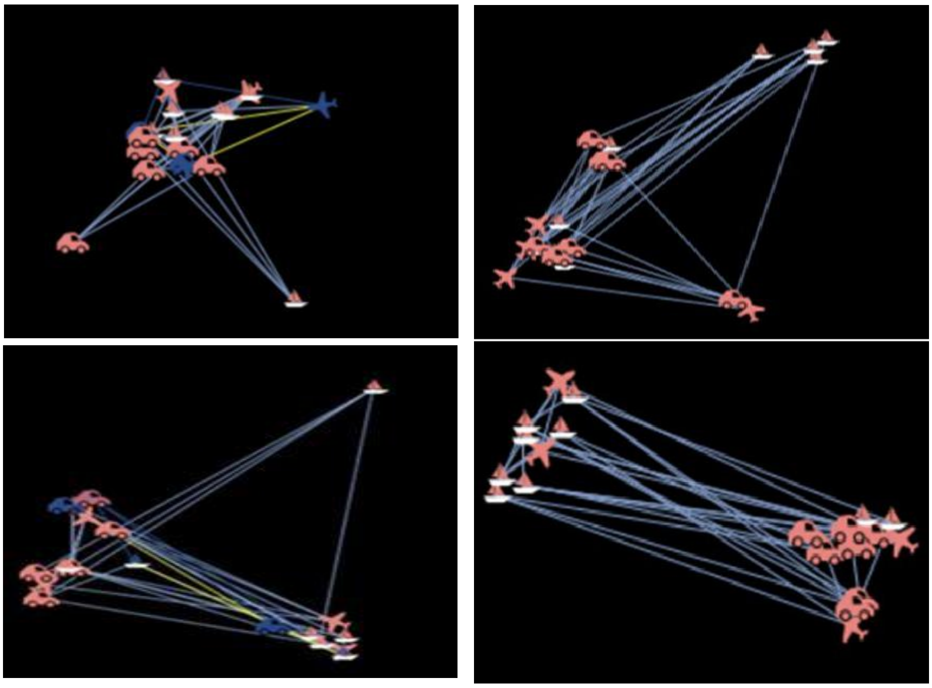


Figure 16: Multiple complex network formations based on dynamics models

In the process of movement, the formation of unmanned cluster will change, accordingly, the connected edges between each unmanned device will also be reconnected, then the average path length, clustering coefficient, degree distribution, etc. will also change accordingly. In the simulation experiment, a formation is selected from formation to dispersal. 0-8 s is the process from dispersal to gradual clustering of unmanned vehicles, and 8 s-20 s is the process of dispersal of clustered unmanned vehicles.

Clustering coefficients and average path length are as shown in Figures 17 and Figure 18.

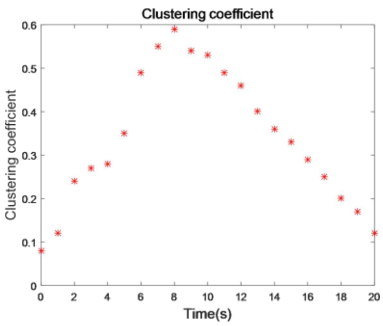


Figure 17: Clustering coefficients of formation transformation process

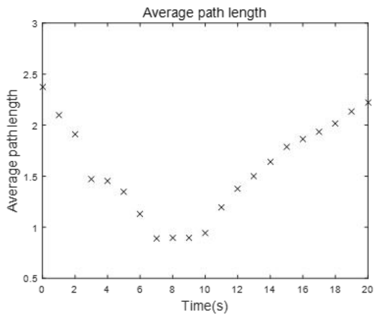


Figure 18: The average path length of queue transformation process

The average path length significantly decreases and the clustering coefficient significantly increases from 0 s to 8 s due to the mutual proximity of unmanned vehicles. The average path length significantly increases and the clustering coefficient significantly decreases from 8 s to 20 s as unmanned vehicles spread out from each other in preparation for forming the next formation. The node degree distribution is as shown in Figures 19 and 20.

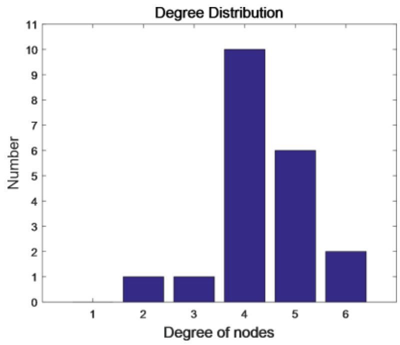


Figure 19: Degree distribution at 8s

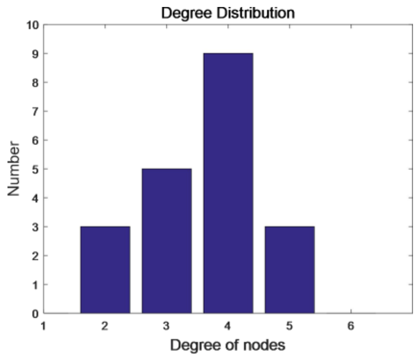


Figure 20: Degree distribution at 20s

The unmanned vehicles' formation is the most compact at 8 s. The node degree distribution deviates from the normal distribution and favors the part with larger node degrees; the unmanned vehicles' formation is the loosest at 20 s. The node degree distribution deviates from the normal distribution and favors the part with smaller node degrees.

Experiment 3 reflects that the network structure has not been destroyed by analyzing the three important parameters of complex network in the process of formation change: average path length, cluster coefficient and degree distribution over time, and verifies that heterogeneous formation network is stable when combined formation and formation transformation are carried out using complex network.

IV. Discussion

This experiment chose three medium-sized unmanned vehicles, namely AZ90 UAV, "Yunzhou" automatic sampling and inspection USV, and Zhong Yun 2.0 UGV, as specific research objects to conduct three experiments. Experiment 1 verified the dynamics of the unmanned vehicle in the formation of the formation, so that the unmanned vehicle under the dynamics of the law to achieve safe and orderly movement and formation, to provide theoretical support for the realization of the joint formation of land, sea and air. Experiment 2 verifies the application of complex networks in the formation of unmanned vehicle, and constructs a circular formation suitable for the battlefield through complex networks, and this joint formation can remain stable and unchanged in the process of movement, so as to keep stable and durable in the ocean monitoring. Experiment 3 integrates the kinetic model and complex network, and through the method of complex network, the unmanned vehicle moves under the law of kinetics to realize the transformation of formation, so as to flexibly adapt to the complex and changing battlefield. Overall, these three kinds of vehicles validate the applicability of the complex network approach to joint air, land, and sea formation ocean monitoring. The next step will be to study the specific ocean monitor under different connection methods and the evolution model of the complex network model under dynamic conditions, reflecting the realistic monitor process.

V. Conclusions

Complex network theory is an effective method for conducting research on unmanned vehicle formations. In this paper, three specific types of UAV, UGV and USV are selected as research objects, the dynamics characteristics of the unmanned vehicle movement process are analyzed, the corresponding network structure model is established based on complex network theory, and then the joint formation of three kinds of unmanned vehicles based on complex network under the dynamics model is studied through three simulation experiments. Simulation analysis of joint formation ocean monitoring of land, sea and air is carried out in the experiments, and a robust and applicable circular formation and formation transformation strategy for the actual battlefield are proposed. The three important indicators in complex networks: clustering coefficient, average path length and degree distribution, are analyzed purposefully, and the corresponding complex network indicators change as the unmanned vehicle formations are reconnected with the edge and the formation movement, and the variation rules are consistent with the basic characteristics of complex network, which verifies that the complex network method has a good performance when applied to the joint formation of unmanned vehicles.

VI. Patents

Author Contributions: Authorship: Peng Xie; Conceptualization, Peng Xie and Zhuonong Xu; methodology, Peng Xie; software, Peng Xie; validation, Peng Xie, Zhuonong Xu and Runfeng Zhang; formal analysis, Peng Xie; investigation, Peng Xie; resources, Yongming Liu; data curation, Peng Xie; writing—original draft preparation, Peng Xie; writing—review and editing, Peng Xie and Zhuonong Xu; visualization, Renfeng Zhang; supervision, Yongming Liu and Renfeng Zhang; project administration, Zhuonong Xu; funding acquisition, Yongming Liu .All authors have read and agreed to the published version of the manuscript."

Funding: This work is funded by the National Natural Science Foundation of China under Grant No.31870532; the 13th five-year plan fund of Hunan Province (No. XJK20BGD048).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Acknowledgments: Thanks for Beijing Anzhou Technology Co., Ltd for providing the parameters of AZ-90 UAV, Zhuhai Yunzhou Intelligent Technology Co., Ltd. for providing the parameters of "Yunzhou" fully automatic sampling and testing USV, Beijing Zhongyun Zhi vehicle Co., Ltd. for providing the parameters of Zhong Yun 2.0 UGV.

The National Natural Science Foundation of China under Grant No.31870532; the 13th five-year plan fund of Hunan Province (No.XJK20BGD048).

Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

.

References

[1] Zhao, Y.; Hui, X. B.; Liu, Y. C. Complex network-based aircraft swarm combat modeling and simulation[J]. Firepower and Command and Control, 2017,42(05):10-13.

[2] Wang, X. H.; Yuan, Z.; Wang, L. Z. Robustness evaluation method for unmanned aerial vehicle swarms based on complex network theory[J]. Chinese Journal of Aeronautics, 2020, 33(1): 352-364.

[3] Bian, H. F.; Zhang, Q. Y. Research on air defense operation model of ship formation based on complex network[J]. Ship Electronics Engineering, 2015,35(04):29-32.

[4] Liu, Z. H.; Hu, B. ; Wu, R. H. Reliability study of complex network system of ship formation based on repair strategy[J]. Computer Science, 2012, 39(S1): 139-141.

[5] Zhang, L. W. Research on unmanned vehicle following control method based on pilot following method[D]. Beijing Jiaotong University, 2018.

[6] Li, T. Research on low-speed unmanned vehicle formation control. Computer and Digital Engineering, 2019. 47(06):1539-1544.

[7] www.caigou.com.cn. Available online: https://www.caigou.com.cn/product/2019081551.shtml

[8] www.yunzhou-tech.com. Available online: http://www.yunzhou-tech.com/

[9] mp.ofweek.com. Available online: http://mp.ofweek.com/auto/a145673921326

[10] Wang, J. H..; Han, J.; Li, X. D. Time-varying formation of second-order discrete-time multi-agent systems under non-uniform communication delays and switching topology with application to UAV formation flying[J]. IET Control Theory & Applications, 2020, 14(14): 1947-1956.

[11] Liu, T. L. Modeling and performance analysis of military communication networks based on complex networks [J]. Systems Engineering and Electronics Technology, 2020. 42(12):2892-2898.

[12] Chen, Z.; Liu, W. D.; Zhang, Y. Study on the static characteristics of cooperative air warfare cooperative network structure model in beyond visual range[J]. Journal of Naval Aviation Engineering College, 2013, 28(01):77-84+94.

[13] Shao, S. K.; Yu, P.; He, C. L. Efficient path planning for UAV formation via comprehensively improved particle swarm optimization[J]. ISA Transactions, 2020, 97:415-430.

[14] Zhao, T. F.; Xie, Y.; Xu, S. Flocking of UAV formation with wireless ultraviolet communication[J]. Defense & Aerospace Week, 2020, :1-18.

[15] Yang, J.; Wang, S, Z.; Lei, L. A Multi-UAV formation maintaining method based on formation reference point[J]. Journal of Physics: Conference Series, 2020,1:18.

[16] Yusuf, K.; Kamesh, S.; Nicholas, R. Distributed backstepping based control of multiple UAV formation flight subject to time delays[J]. IET Control Theory & Applications, 2020, 14(12):1628-1638.

[17] Wei, X. Q.; Yang, J. Y.; Fan, X. R. Fully distributed guidance laws for unmanned aerial vehicles formation flight[J]. Transactions of the Institute of Measurement and Control, 2020, 42(5):965-980.

[18] Wang, S. F.; Li, X.; Chen, G. R. Complex network theory and its applications[M]. 1nd ed. Beijing: Tsinghua University Press 2006.

[19] Watts, D. J.; Strogtz, S. H. Collective dynamics of 'small-world' networks [J]. Nature, 1998, 393 (6684): 440~442.

[20] Das, A. B. Small-world networks of prognostic genes associated with lung adenocarcinoma development[D]. Xi'an University of Electronic Science and Technology, 2020,112(6):4078-4088.

[21] Wang, H. OODA-based operational effectiveness assessment of ship formation air defense system[J]. Modern Defense Technology, 2020. 48(06):19-25+38.

[22] Sun, Q. B.; Yang, G. Y.; Zhang, A. An entropy-based self-adaptive node importance evaluation method for complex networks[J]. Complexity, 2020.

[23] Yue, Z. G. Research on joint UAV-UAV air-ground formation control[D], Chang'an University. 2017, 48(06):19-25+38.

[24] Calzavara, G.; Consolini, L.; Kavaja, J. Structured identification for network reconstruction of RC-models[J]. System & Control Letters, 2021, 147.

[25] Yue, Z. G.; Thunberg, J.; Pan, W. Dynamic network reconstruction from heterogeneous datasets[J]. Automatic, 2021, 123.

[26] Azad, F. E.; Sardou, I. G.; Abedini, S. Distribution network reconfiguration based on LMP at DG connected busses using game theory and self-adaptive FWA[J]. Energy, 2021, 215(PB).

ISSN: 0010-8189