# *Research on Synchronizability of Layered Network for Aircraft Swarm Coordinated Reconnaissance*

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***Abstract:*** Based on the principle of complex network and aircraft swarm theory, ordinary complex network synchronization was expanded to layered network's outer synchronization in this paper. Layered aircraft swarm network has been built using neural network model which was amended. By constructing and using the layered network model, synchronization control of members in aircraft swarm was demonstrated available. Then the function of different topology and couplings were studied due to the result of numerical experimentation. The rule of layered aircraft swarm network's synchronizability was discovered by results of computer simulation. It indicate that, when the strength of internal coupling is strong, outer synchronization is easier to be achieved under a condition of tighter correspondent couplings and weaker un-correspondent couplings. When internal coupling is weak, the function of outer couplings gives a contrary result. As a result of un-correspondent connections lack, synchronization will completely disappear. It will provide guidance for aircraft swarm reconnaissance in military applications.

## 1. Introduction

Nowadays, traditional forms of warfare is facing enormous challenges, it is believed that the single air combat platform will be replaced by multi-platform system called aircraft swarm gradually in future air battle. Aircraft swarm is composed of a certain number of single function air vehicle or multifunction air vehicle which is manned or unpiloted. It shows great advantage in performing coordinated reconnaissance and attacks missions. The sympathetic network is structure foundation of aircraft swarm, and adaptive ability emerging based on the sympathetic network is a basic feature of aircraft swarm. Aircraft swarm is a typical sub-complicated network, the members in this network must have strong connection with each other to build effective communication, therefore, synchronization of sympathetic network turn into a significant factor in aircraft swarm operations.

As a significant collective behavior, synchronization of complex networks has attracted more and more attention. Generally speaking, investigators would like to regard complex network as a set of interconnected nodes, in which a node is fundamental unit with specific dynamical contents and study the inner synchronization between different nodes. However, another type of network synchronization which is called outer synchronization is also exit. It describes the phenomenon of synchronization between two coupled networks, the so called layered network. Parting from inner synchronization, people named it "outer synchronization". It is much more meaningful and useful to study the outer synchronization for layered network for aircraft swarm for its coordinated reconnaissance.

## 2. Models of Layered Network

Consider double-layer network with outer coupling, each of them consists of N dynamical nodes ,which could be described as following,

$$\begin{aligned} \dot{x}_i(t) &= f(x_i) + g\sum_{j=1}^{N} a_{ij}x_j + k_i\sum_{j=1}^{N}\delta_{ij}(y_j - x_i) \quad i = 1,2,\cdots,N \\ \dot{y}_i(t) &= f(y_i) + h\sum_{j=1}^{N} b_{ij}y_j + k_i\sum_{j=1}^{N}\delta_{ij}(x_j - y_i) \quad i = 1,2,\cdots,N \end{aligned} \tag{1}$$

Where $x_i$ and $y_i$ is the state vector of the i-th node, $f_i(x_i)$ and $f_i(y_i)$ are the nonlinear vector function governing the evolution of the i-th isolated nodes $x_i$ and $y_i$ , $g$ and $h$ stand for the inner coupling parameters while $k_i$ is outer coupling parameter. $A = (a_{ij})_{N*N}$ ( $B = (b_{ij})_{N*N}$ ) means the connection inside a network and $(\delta_{ij})_{N*N}$ is connection matrix of connected nodes between two networks. The definition is what follows, $a_{ij}(b_{ij}) = 1$ when $i \neq j$ and node $i$ has a link to node $j$ , $a_{ij}(b_{ij}) = 0$ when $i \neq j$ and node $i$ has no link to node $j$ , $a_{ij}(b_{ij}) = -\sum_{j=1, j\neq i}^{N} a_{ij}$ when $i = j$ .

Matrix $(\delta_{ij})_{N*N}$ are defined as

$$\delta_{ij} = \begin{cases} 1, \text{when node } i \text{ in network X has a link to node j in network Y} \\ 0, \text{when node } i \text{ in network X has no link to node j in network Y} \end{cases}$$

Suppose $f(x_i)$ and $f(y_i)$ was partial Lipschitz continuous, so there is at least one constant L which satisfy the following equation:

$$\|f(x) - f(y)\| \leq L\|x - y\|, x, y \in R_{N*N}$$

We give the definition of outer synchronization as: let $x_i - y_i = e_i$ , if $\lim e_{i(i\to\infty)} = 0$ , network X and network Y are considered as synchronous.

The error system is:

$$\begin{aligned} \dot{e}_i = \dot{x}_i - \dot{y}_i &= f(x_i) + g\sum_{j=1}^{N} a_{ij}x_j + k\sum_{j=1}^{N}\delta_{ij}(y_j - x_i) - f(y_i) - h\sum_{j=1}^{N} b_{ij}y_j - k\sum_{j=1}^{N}\delta_{ij}(x_j - y_i) \\ &= (g\sum_{j=1}^{N} a_{ij} - k\sum_{j=1}^{N}\delta_{ij})x_j - (k\sum_{j=1}^{N}\delta_{ij} - h\sum_{j=1}^{N} b_{ij})y_j - (k\sum_{j=1}^{N}\delta_{ij} + f(x_i) - f(y_i))e_i \end{aligned} \tag{2}$$

Found the Lyapunov function as:

$$V(t)=\frac{1}{2}\sum_{i=1}^{N}e_i^T(t)e_i(t) \tag{3}$$

On both sides of the equation derivation:

$$\begin{aligned}\dot V(t)&=\sum_{i=1}^{N}e_i^T(t)\dot e_i(t)\\&=\sum_{i=1}^{N}e_i^T[(g\sum_{j=1}^{N}a_{ij}-k\sum_{j=1}^{N}\delta_{ij})x_j-(k\sum_{j=1}^{N}\delta_{ij}-h\sum_{j=1}^{N}b_{ij})y_j-(k\sum_{j=1}^{N}\delta_{ij}+f(x_i)-f(y_i))e_i]\\&=-\sum_{i=1}^{N}e_i^Te_i[k\sum_{j=1}^{N}\delta_{ij}+f(x_i)-f(y_i)]+\sum_{i=1}^{N}e_i^Te_j((g\sum_{j=1}^{N}a_{ij}-k\sum_{j=1}^{N}\delta_{ij})x_j-(k\sum_{j=1}^{N}\delta_{ij}-h\sum_{j=1}^{N}b_{ij})y_j)\end{aligned} \tag{4}$$

When

$$g\sum_{j=1}^{N}a_{ij}-k\sum_{j=1}^{N}\delta_{ij}=k\sum_{j=1}^{N}\delta_{ij}-h\sum_{j=1}^{N}b_{ij},$$

$$\begin{aligned}\dot V(t)&=-\sum_{i=1}^{N}e_i^Te_i[k\sum_{j=1}^{N}\delta_{ij})]+\sum_{i=1}^{N}e_i^Te_j((g\sum_{j=1}^{N}a_{ij}-k\sum_{j=1}^{N}\delta_{ij})x_j-(k\sum_{j=1}^{N}\delta_{ij}-h\sum_{j=1}^{N}b_{ij})y_j)\\&\le e^T(-L-2k\Delta+gA)e\end{aligned} \tag{5}$$

Adjust coupling parameter $h$, $g$ and $k$, we can make the equation $-L-2k\Delta+gA\le 0$ holds, so equation $\dot V(t)\le 0$ holds, therefore, condition of equation $\lim e_{i(t\to\infty)}=0,(i\in N_+)$ can be met, what means network X and network Y achieved outer synchronization.

## 3. Coupling Effects on Synchronizability

### 3.1. Coupling and Topology

We built a double-layer network, whose both sub-networks were consisted of ten HR models, and designed the following coupling relationship for HR model to express the connection between neurons. Supposing neuron 1 has connection with neuron 2, so

$$\begin{aligned}u_1&=v_1-mu_1^3+nu_1^2-w_1+I+\beta(-u_1+mu_1^3-nu_1^2+u_2-mu_2^3+nu_2^2)\\v_1&=p-qu_1^2-v_1+\beta(qu_1^2-qu_2^2)\\w_1&=r(s(u_1-\bar u)-w_1)\end{aligned} \tag{6}$$

And

$$\begin{aligned}u_2&=v_2-mu_2^3+nu_2^2-w_2+I+\beta(u_1-mu_1^3+nu_1^2-u_2+mu_2^3-nu_2^2)\\v_2&=p-qu_2^2-v_2+\beta(qu_2^2-qu_1^2)\\w_2&=r(s(u_2-\bar u)-w_2)\end{aligned} \tag{7}$$

Where $\beta$ was the inner coupling parameter. It will be replaced by $g$ in network X and by $h$ in network Y.Figure 1 to Figure 3 show the topology's changing of double-layer neural network along with the number of un-corresponding outer couplings increasing.

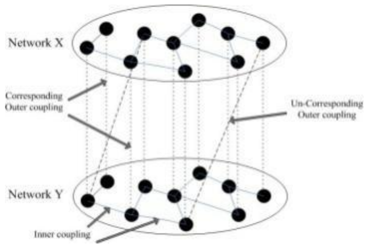



Figure 1: Double-layer network with low un-correspondent connection.

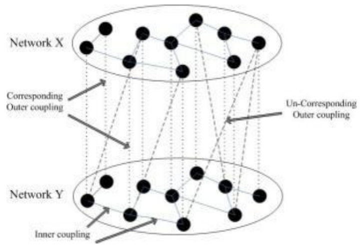



Figure 2: Double-layer network with middle un-correspondent connection

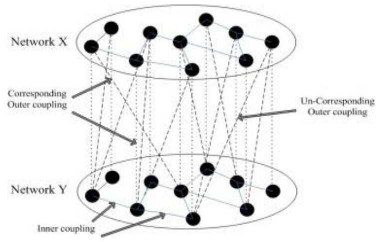



Figure 3: Double-layer network with high un-correspondent connection.

3.

When the topology of the double-layer network was the type of Figure 3, we observed outer coupling's effect. Firstly supposing the inner coupling was weak, and then, effects was tested with tighter inner coupling.

The first six figures were obtained when $g = h = 1$.

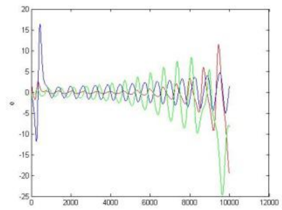


Figure 4-1. $k^{'} = 5, k^{''} = 3$

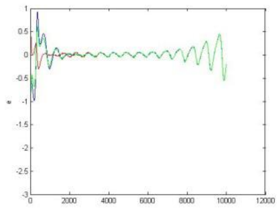


Figure 4-2. $k^{'} = 10, k^{''} = 3$

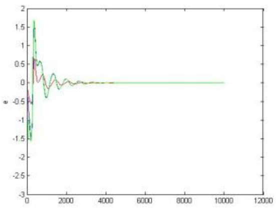


Figure 4-3. $k^{'} = 20, k^{''} = 3$

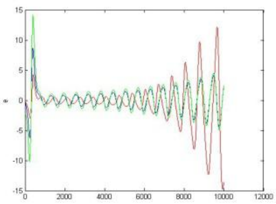


Figure 5-1. $k^{'} = 25, k^{''} = 25$

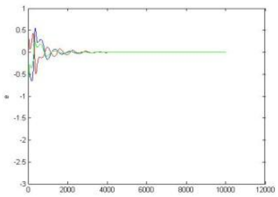


Figure 5-2. $k^{'} = 25, k^{''} = 5$

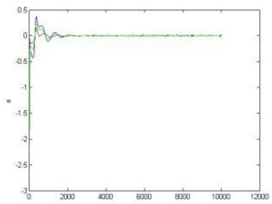


Figure 5-3. $k^{'} = 25, k^{''} = 3$

It is obvious to see from figures that when the inner coupling is not strong, bigger correspondent nodes coupling parameter and smaller un-correspondent nodes coupling parameter will accelerate the outer projective sychronization between networks.

The following figures show the variety of synchronization error according to change of $k^{'}$ and $k^{''}$ when $g = h = 20$.

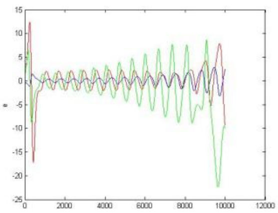


Figure 6-1. $k^{'} = 1, k^{''} = 5$

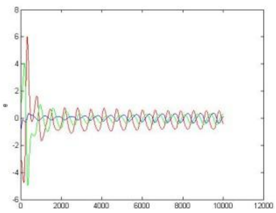


Figure 6-2. $k^{'} = 1, k^{''} = 10$

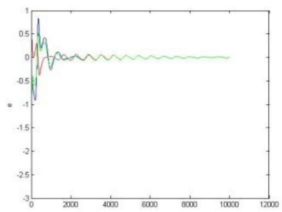
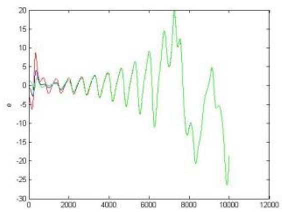
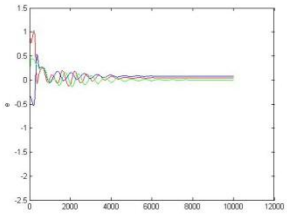


Figure 6-3. $k^{'} = 1, k^{''} = 20$





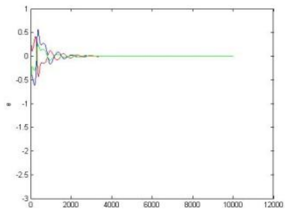


Figure 7-1. $k^{'}=10, k^{''}=15$ Figure 7-2. $k^{'}=3, k^{''}=15$ Figure 7-3. $k^{'}=1, k^{''}=15$

Figure 6-1 to Figure 7-3 demonstrated that as the un-correspondent nodes' coupling growing and correspondent nodes' coupling fading, phenomenon of outer sychronization is easier to achieve under the condition of a tight inner coupling.

When the network's topology type was like what shows in Figure 1 and Figure 2, synchronization is hard to be achieved no matter how we debug the coupling relationship.

As we can learn from the simulation experiments above, when inner connection is strong, outer synchronization is easier to be achieved under a condition of tighter correspondent couplings and weaker un-correspondent couplings. When inner coupling parameter is not big enough, the function of outer couplings shows a contrary results. And if the number of un-correspondent connections is not enough, synchronization will never happen. So, when carrying out military reconnaissance operations by aircraft swarm, we should control the coupling in sympathetic network properly to achieve enough synchronization.

## 4. Conclusion and Outlook

Synchronization of nodes in layered network for aircraft swarm coordinated reconnaissance is an important issue to enhance reconnaissance capability in modern battlefield. In this paper, we constructed the model of double-layer neural network for simulating coordinated reconnaissance network's synchronization by separating the neurons' coupling relationships to three kinds, fond out the operation rule of couplings using numeral experiment and gave the interpretation.

This paper could do some contribution on the synchronizability and co-operation between two coupled networks, the so called layered network, and provide coaching for the network framework in aircraft swarm coordinated reconnaissance. But what we do is still not very general and detailed for some concrete problem like choosing of formation topology in reconnaissance, we will keep working on it in our future research.

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