A Method for Adaptive Adjustment of Command and Control Structure

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Abstract. The adaptive adjustment of command and control organizational structure is a hot issue in the field of agile command and control. First of all, the basic components of command and control organization are described. For the emergent events with changes in the action plan, the optimization constraints and optimization objectives of the command and control organizational structure are analysed, an optimization model for the adaptive adjustment of the command and control organizational structure is constructed, and a model solving method based on the discrete firefly algorithm is designed. The specific flow of the discrete firefly algorithm is adopted. Finally, the simulation model of the adaptive organization adjustment model and its solution algorithm are verified and compared by concrete examples. The simulation results show the feasibility and efficiency of the solution method.

1. Introduction
In the face of a complex and changeable battlefield environment, Command and Control (C2) organization structure should be adapted to changes in the battlefield environment [1].

The current research on adjustment of C2 organization structure has achieved some results. The literature [2] considers parameters such as response time, average backup number and load balance, and uses colored Petri nets to study the adaptive adjustment of C2 organization structure; Levchuk proposes an adjustment method based on three-phase idea [3]; literature [4] proposes an adaptive design method for organizational structure based on granularity calculation. During current research, algorithm time-consuming can be improved to meet the rapidly changing battlefield environment.

This paper presents a method for measuring the performance of C2 organization structure. An adaptive structure adjustment model is proposed for the change of the action plan, and a solving method based on the discrete firefly algorithm is proposed. Finally, the validity of the algorithm is verified by case simulation.

2. The entity of the command and control organization
There are three kinds of entities in C2 organization [4], namely, Task (T), Platform (P) and decision entity (Decision-Maker, DM). These three types of entities are the elements of the C2 organization.

Definition 1 Task: A task is an activity that requires a set of relevant resources to be processed. The set of all tasks in organization is recorded as \( S' = \{T_1, T_2, \ldots, T_{NT}\} \) and \( NT \) is the total number of task.
**Definition 2 Platform**: A platform is a physical entity with specified resource capabilities that can be used to process tasks. The set of all platforms is recorded as \( S^p = \{P_1, P_2, ..., P_{NP}\} \) and \( NP \) is the total number of platform in the organization.

**Definition 3 DM**: DMs are intelligent entities who utilize knowledge and wisdom of the planning domain to select an appropriate plan among a range of alternative scenarios. Tactical Decision-makers (TDMs) that control the platform to perform specific combat missions. The set of all TDM is recorded as \( S_{\text{DM}} = \{TDM_1, TDM_2, ..., TDM_{ND}\} \) and \( ND \) is the total number of TDM in the organization.

3. Modelling of adaptive adjustment of C2 organization structure

3.1. Variables definition

The various relationships in the C2 organization are defined as follows.

1) Command and control relationship between TDM and platform \( R_{\text{TDM-P}} \)

\[ R_{\text{TDM-P}} = \left( m^\text{TDM-P}_{ij} \right)_{ND \times NP} \]

\[ m^\text{TDM-P}_{ij} = \begin{cases} 1 & \text{if } TDM_i \text{ control } P_j \\ 0 & \text{otherwise} \end{cases} \] (1)

2) Cooperative relationship between tactical decision-maker \( R_{\text{TDM-TDM}} \)

\[ R_{\text{TDM-TDM}} = \left( m^\text{TDM-TDM}_{ij} \right)_{ND \times ND} \]

\[ m^\text{TDM-TDM}_{ij} = \begin{cases} 1 & \text{if } TDM_i \text{ control } TDM_j \\ 0 & \text{otherwise} \end{cases} \] (2)

3) The processing relationship between platform and task \( R_{\text{T-P}} \)

\[ R_{\text{T-P}} = \left( m^\text{T-P}_{ij} \right)_{NT \times NP} \]

\[ m^\text{T-P}_{ij} = \begin{cases} 1 & \text{if } P_j \text{ is assigned to process } T_i \\ 0 & \text{otherwise} \end{cases} \] (3)

4) Relationship between TDM and task \( R_{\text{DM-T}} \)

When \( M^{T-P} \) and \( M^{TDM-P} \) are determined, \( M^{TDM-T} = \left( m^\text{TDM-T}_{ij} \right)_{ND \times NT} \) can be determined by equation (4).

\[ m^\text{TDM-T}_{ij} = \begin{cases} 1 & \text{if } m_{ij}^{TDM-P} = 1, m_{ij}^{T-P} = 1, 1 \leq k \leq NP \\ 0 & \text{otherwise} \end{cases} \] (4)

3.2. The optimization objective of C2 structure adjustment

The performance of the C2 organization structure can be measured by the workload level of the TDM within the organization. The workload is composed of the command load and the cooperative load [4].

3.2.1. Definition of workload. As for \( \forall TDM_i \in S_{\text{DM}} \), when \( TDM_i \) performs its responsible task \( T_j \), the set of platforms controlled by \( TDM_i \) is recorded as \( S^p_{\text{TDM,-T}_j} = \{P_i \mid m^\text{TDM-P}_{ik} = 1, m^\text{T-P}_{ij} = 1, 1 \leq k \leq NP\} \). When this task is performed, the set of TDM that have a collaboration relationship with \( TDM_i \) is \( S^\text{TDM}_{\text{TDM,-T}_j} = \{TDM_k \mid m^\text{TDM-T}_{ik} = 1, i \neq i, 1 \leq k \leq ND\} \), so the workload of executing \( T_j \) is as follows.

\[ W_{\text{TDM}_i} = \omega_{c2} \cdot \left\| S^p_{\text{TDM,-T}_j} \right\| + \omega_{tc} \cdot \left\| S^\text{TDM}_{\text{TDM,-T}_j} \right\| \] (5)

Here, \( \omega_{c2} \) is the command load factor, \( \omega_{tc} \) is the cooperative load factor, \( \left\| S^p_{\text{TDM,-T}_j} \right\| \) is the number of elements in the set \( S^p_{\text{TDM,-T}_j} \), and \( \left\| S^\text{TDM}_{\text{TDM,-T}_j} \right\| \) is the number of elements in the set \( S^\text{TDM}_{\text{TDM,-T}_j} \).
Here, $W_{TDM}^i$ refers to the load that TDM$_i$ command task before time $t$.

### 3.2.2. The root mean square of workload

The RMS (Root Mean Square, RMS) load of all in the organization is as follows.

$$\text{RMS}_{TDM}^T = \sqrt{\frac{1}{ND} \sum_{i=1}^{ND} \left( W_{TDM}^T \right)^2}$$

$$= \sqrt{\left( W_{TDM}^T \right)^2 + \frac{ND-1}{ND} D_{TDM}^T}$$ (7)

$W_{TDM}^T = \frac{1}{ND} \sum_{i=1}^{ND} W_{TDM}^i$ is the average load in the organization; $D_{TDM}^T$ is the variance of the full load.

The smaller the $\text{RMS}_{TDM}^T$, the lower the mean and variance of the work load of TDM, the more reasonable the design of the organizational structure is. Therefore, minimum $\text{RMS}_{TDM}^T$ can be used as an objective function of adaptive adjustment.

### 3.3. The optimization objective of C2 structure adjustment

After mission plan is changed, the C2 organization structure is adjusted to improve the performance of the organization. The C2 relationship between TDM and platform before adjusting is $R_{TDM-P}^1$, and the matrix $M_{TDM-P} = (m_{TDM-P})_{ND \times NP}$. After adjusting the relationship is $R_{TDM-P}^2$, $M_{TDM-P} = (m_{TDM-P}^2)_{ND \times NP}$.

When the action plan is changed, the model of adjustment of organizational structure is as follows.

$$\min \text{RMS}_{TDM}^T$$

$$\text{s.t.} \left\{ \begin{array}{l} N_P^{T_{\text{Plan}}} = \frac{1}{2} \sum_{i=1}^{ND} \sum_{j=1}^{NP} m_{TDM-P}^{1i} - m_{TDM-P}^{1j} \leq \sigma \\ \sum_{j=1}^{NP} m_{TDM-P}^{1i} = 1, j = 1,2,\ldots, NP \\ \sum_{i=1}^{ND} m_{TDM-P}^{1j} = 1, i = 1,2,\ldots, ND \end{array} \right. $$ (8)

In equation (8), the objective function is $\min \text{RMS}_{TDM}^T$, the purpose of adjustment is to get a better C2 structure. The smaller the $\text{RMS}_{TDM}^T$, the better the performance of the corresponding C2 structure.

$\sigma$ is the maximum adjustment cost that an organization can afford. The first constraint indicates that the adjustment cost must be within the scope of the organization; the second constraint indicates that each platform in the organization can be controlled by only one TDM. The third constraint represents each TDM control at least one platform.

### 4. Model solving method based on discrete firefly algorithm

#### 4.1. Discrete firefly algorithm

In 2008, Yang, a scholar of University of Cambridge, proposed the Firefly Algorithm (FA) [5] that simulates the firefly population behaviour. The discrete form of firefly algorithm is applied in task scheduling, assembly sequence planning and traveling salesman [6]-[10] combination optimization problems. In the process of the adaptive adjustment problem of C2 organization structure, several key elements of discrete firefly algorithm are: firefly position, objective function, distance and movement.
4.1.1. Firefly location initialization and coding. Combined with command and control relation matrix adjusted in this paper, integer coding is selected in the coding method. Each firefly represents a $M^{TDM-P}$. For any firefly $i$, an n-dimensional vector $X_i = (x_{i,1}, x_{i,2}, \ldots, x_{i,k}, \ldots, x_{i,n})$ is used to represent the position of firefly $i$, and n is determined by total number of platform in organization $x_{i,k} \in [1, ND]$. $x_{i,k}$ indicates that $P_k$ is under the command and control of $TDM_{i,k}$. Based on this coding rule, for the $M^{TDM-P}$ shown below. After encoded, it is $(1,3,2,4,2,1,3,1)$.

$$
M^{TDM-P} = \begin{bmatrix}
1 & 0 & 0 & 0 & 1 & 0 & 1 \\
0 & 0 & 1 & 0 & 1 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1 & 0 & 0 & 0
\end{bmatrix} \rightarrow X_i = (1,3,2,4,2,1,3,1)
$$

(9)

4.1.2. Objective function. In order to find the solution with the smallest solution, each firefly $i$ decoded matrix has the corresponding RMS value. The smaller the RMS value, the better the corresponding solution of the firefly. Therefore, brightness is defined as follows. If $N_{P_{max}} \leq \sigma$ is not satisfied, the brightness value is 0, a solution satisfying the condition is randomly generated.

$$
I_{i0} = \begin{cases} 
\frac{1}{RMS}, & N_{P_{max}} \leq \sigma \\
0, & N_{P_{max}} > \sigma
\end{cases}
$$

(10)

4.1.3. The distance between fireflies. The distance between two fireflies reflects the degree of differentiation of two schemes. Therefore, in this paper, the distance between firefly $i$ and firefly $j$ in discrete space is calculated using equation (11).

$$
r_{ij} = \left\| X_i \oplus X_j \right\| = \sqrt{\sum_{k=1}^{n} (x_{i,k} \oplus x_{j,k})^2}
$$

(11)

4.1.4. The movement of the firefly. Based on the optimization and adjustment features of the $M^{TDM-P}$, the following equation for updating the position of the firefly is constructed

$$
X'_i = X_i \oplus \beta_i e^{-\gamma r_{ij}^2} (X_j \Theta X_i) \oplus \alpha \left( \text{rand} - \frac{1}{2} \right)
$$

(12)

4.2. The steps of the discrete firefly algorithm
The implementation steps of discrete firefly algorithm are as follows.

Step 1: Set parameters of discrete firefly algorithm, initialize the firefly population, the maximum number of iterations, and the light intensity absorption coefficient $\gamma$, the maximum degree of attraction $\beta_i$.

Step 2: Follow the integer encoding method, the maximum brightness of each firefly is calculated by equation (10).

Step 3: Calculate the distance between each firefly by equation (11). Further, the relative brightness $I$ and the attractiveness $\beta$ are calculated according to equations.

Step 4: Firefly moves according to equation (12). The brightest firefly searches for the nearest optimal solution and moves toward to it.

Step 5: After moving, calculate the brightness of all the fireflies and rank the brightness. Record the brightness value of the firefly with the highest brightness and the corresponding position. The number of iterations increases by 1.

Step 6: If the maximum iteration number $Max_{cycle}$ is reached, end the algorithm and output the optimal solution saved in step 5, otherwise go to step 3.

The optimal solution is decoded, and the resulting $M^{TDM-P}$ is the best C2 relationship.
5. Results and analysis of the simulation

5.1. Simulation case

This paper selects the joint operations scenario in [11] as an experimental case, verifies the performance of the discrete firefly algorithm to solve adaptive adjustment problem of C2 structure. The experiment was carried out in the windows 7 system environment using Matlab 2014a for simulation analysis. The initial task-platform relationship and the TDM-platform relationship are shown in Tables 1 and 2, respectively.

| Table 1. Relationship of task and platform before adjusting |
|------------------------------------------------------------|
| Task | Platform |
| T₁ | P₂,P₆,P₇,P₁₆ |
| T₂ | P₁,P₃,P₁₅,P₁₉ |
| T₃ | P₁₁,P₁₂,P₁₃ |
| T₄ | P₃ |
| T₅ | P₄,P₁₄ |
| T₆ | P₅,P₯,P₁₈ |
| T₇ | P₁₀,P₁₁,P₁₂,P₁₃,P₂₀ |
| T₈ | P₃,P₅,P₉,P₁₈ |
| T₉ | P₆,P₈ |

| Table 2. Relationship of tactical decision-maker and platform before adjusting |
|--------------------------------------------------------------------------------|
| TDM | Platform |
| TDM₁ | P₁,P₁₀,P₁₁,P₁₄,P₁₃ |
| TDM₂ | P₂,P₆,P₈,P₁₆,P₁₉ |
| TDM₃ | P₇,P₁₂,P₁₅,P₂₀ |
| TDM₄ | P₃,P₅,P₉,P₁₇,P₁₈ |

5.2. Simulation experiment

In order to verify the validity of this method, 20 simulation experiments are carried out and compare with other methods. Comparisons are made with Greedy Search Algorithm (GSA) [4] and Discrete Artificial Bee colony algorithm (DABC) [12], which can also be used to solve the model of this paper. The experimental results are shown in figure 1 and figure 2.

5.3. Simulation analysis
In figure 1, the RMS values after the adjustment by DFA algorithm, GSA algorithm and DABC algorithm are all lower than RMS value before the adjustment indicates that these three methods can solve this problem. The DFA algorithm has the largest reduction in the RMS value, which shows that the DFA algorithm is better than the DABC and GSA algorithm in solving the adaptive adjustment of C2 organization structure, and the effect of the DABC and GSA algorithms is close. In the time consuming of algorithm, the time consuming of DFA algorithm is the lowest, and the time consumption of GSA is the highest, which shows that DFA algorithm is the most efficient.

In summary, using the DFA algorithm can better reduce the RMS value of the load, and has a great advantage in the algorithm time-consuming. It can meet the requirement of the timeliness of the adjustment of C2 structure in the battlefield environment.

6. Conclusion
This paper studies adaptive adjustment of C2 structure. Based on the discrete firefly algorithm, the adaptive adjustment method is proposed. The algorithm is simulated and compared with GSA and DABC algorithm. The results verify the feasibility and efficiency of the discrete firefly algorithm used in C2 structure adjustment.

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