A Research Framework on Mission Planning of the UAV Swarm

Xin ZHOU[1], Weiping WANG[2], Tao WANG[3], Xiaobo LI[4], Zhifei LI[5]
System of System Engineering Group
College of Information System and Management
National University of Defense Technology
Changsha, Hunan, China
1: zhouxin09@nudt.edu.cn, 2: wangwp@nudt.edu.cn, 3: wangtao1976@nudt.edu.cn,
4: lixiaobo@nudt.edu.cn, 5: lee.nudt@gmail.com

***Abstract* — Unmanned aerial vehicle (UAV) swarm, a new form of system of system (SoS), is the focus of various countries at present. Mission planning, however, is the key to successfully accomplish mission of UAV swarms. Although the mission planning technology has achieved a lot of results, there are not many achievements in the field of UAV swarms. In this paper, the mission planning of the UAV swarm is described in detail in the following aspects: basic concept, command and control (C2) modality of swarm, contents and key technologies of UAV swarms mission planning. This paper regards the biggest difference of mission planning between the UAV swarm and general UAV system is the distributed architecture of swarm. Based on Anticipation-Influence-Reaction (AIR) distributed architecture, a new command and control modality of the UAV swarm is put forward in the paper. Generally, this paper provides a way of overall understanding and thinking on UAV swarms mission planning.**

Keywords — Mission planning; The UAV swarm; Command and control modality of the UAV swarm; Anticipation-Influence-Reaction; Key technologies of UAV swarm mission planning

I. INTRODUCTION

UAVs, a focus of most nations, are widely used in various fields of society presently [1][2], such as disaster response and military missions in hostile environments. Large multifunctional UAV are often limited to a perspective or a point at a certain time. However, due to the limitation of fuel, weight, size and other factors, small UAV cannot accomplish complex mission by itself.

The UAV swarm technology is one of the most effective and efficient means to this problem. With the development of miniaturization technology, new sensors, embedded control systems and communications technology, gradually the application of UAV swarms becomes a reality, which undertakes more and more complex missions. As for many applications, a large number of small and low-cost UAVs is the most appropriate tools to some degree. Because a UAV swarm can collect information from multiple locations at the same time, sharing the situation to get the overall environment information, and being more robust. Even if the swarm lost a few UAVs, it won't influence the completion of missions.

In this paper, the UAV swarm mission planning is decomposed into five parts: basic concepts, command and control modality of the UAV swarm, contents, key technologies of mission planning and conclusions. Command and control modality of the UAV swarm is the distinguishing feature compared with general UAV system.

II. BASIC CONCEPTS

A. Mission planning

The word "mission" refers to the responsibility or assigned task, while "planning" represents a comprehensive and long-term development activities. As for the aviation field, the mission is concerned with activities carried out by aircraft [3], such as air interception, close air support, reconnaissance, electronic warfare, air transportation, refueling etc. Currently, there is no standard definition of mission planning in the official warfare doctrine.

In addition, the word "planning" and "allocation" is likely to lead to ambiguity [4]. Some scholars believe that "planning" is to answer the problem of "what must be done", regardless of how the work is distributed to subordinates. However , "allocation" is to answer the problem of "who does the task". Additionally, there are also some scholars tending to refer to the problem of "what must be done" as task decomposition, since this approach usually involves simplifying complex task iterations into simpler tasks. In this case, "planning" refers to these two stages of the problem, that is, the combination of "task decomposition" and "task allocation".

B. The UAV swarm

The study of swarms began in behavior study of insect communities by Grasse in 1953 [5]. For example, the behavior of the single ant is quite simple, but the group of ant colony composed of these simple individuals, shows a highly structured social organization, which can accomplish complex tasks far beyond the individual's ability. Swarm definitions used by various agencies are the include following.

- Swarming occurs when several units conduct a convergent attack on a target from multiple axes [6].

- Swarming consists of a group of partially autonomous unmanned aircraft systems operating in support of both manned and unmanned units in a battlefield while being monitored by a single operator [7].
- Swarm behavior is self-organizing behavior among a group of entities that achieves or attempts to achieve a common goal [8].

In the light of above definitions, the definition of the UAV swarm used here is a group of UAVs with a common goal. The self-organization is the coordinated behavior when the swarm acquires or attempts to acquire the common goal. However, the swarm behavior is the integration of superior command and self-decision. That means it is the combination of top-down design and bottom-up self-organization. As for top-down design, the UAV swarm should obey orders of its leader. However with bottom-up self-organization, the leader may not take all the factors into consideration, which are required to exert subjective initiative of every UAV. In most circumstances, high intelligence UAVs do not need instructions from the control center, or just require the most minimal authorizations. At the same time, their behaviors are dynamically adjusted based on each individual-specific task and situation.

The UAV swarm operation refers to the combat mission process completed by a group of UAVs with partial autonomy. Generally via man / unmanned devices, the UAV swarm is monitored by one or more advanced operators. Behavior of the UAV swarm is a seemingly random, but a rigorous coordination tactics in reality. It is composed of multiple scattered small or large UAVs, building up formations from multiple directions to the target area. The overall goal is to carry out full-scale attacks on targets from some specific area by means of continuous pulsating firepower, requiring the ability of rapid building up of formations or dispersing of formations, and combination to differing capability modules at any time according to the mission requirements.

C. The UAV swarm mission planning

Based on different task types and load of the UAV and environment, UAV mission planning [9] is to complete the specific task of determining pre-set or real time balanced governance. The main objective is to consider the conditions of UAV performance, arrival time, fuel consumption, threat and airspace control according to the information of the environment, planning one or more routes from the starting point to the target point, determining the load configuration, the usage and measuring work plan of data link, to ensure the successful completion of a single UAV mission and then return to the base safely.

The UAV swarm mission planning is similar to the mission planning of UAV in most of the contexts. The main difference between them is the number of UAVs in the swarm is far more than that of general UAV systems. Due to the limitation capability of processing and communicating, it is hard to control all the UAVs in a swarm directly from the ground stations or warning aircraft. Therefore, it is quite important that some UAVs with high intelligence play the role of decision maker in a UAV swarm. Meanwhile some rational command and control modalities should be applied to the organization of UAV swarms to get the most effectiveness and efficiency.

III. C2 Modality of The UAV Swarm

The UAV swarm mission planning is different from UAV mission planning, as the UAV swarm owns many new features. One of the most obvious features is the large number of UAVs in the swarm, which is difficult to perfectly control through the current centralized UAV mission control station. At this point, some high intelligence UAVs with the capacity of autonomy and decision-making should act as sub-swarm leader or swarm leader, sharing part of the control and planning tasks. On this occasion, UAVs in swarm can organically and spontaneously perform tasks such as reconnaissance, surveillance, tracking, strike, transport and evaluation by exchanging sensor information [10].

Currently, researchers generally classify the UAV swarms into two formal control modalities: centralized control modality and decentralized control modality [11]. In centralized control modality, the entire UAV swarm is controlled by one UAV or mission control station, which collects all the relevant information about the swarm, and plans the behavior of every UAV in the swarm. The optimal solution of centralized modality of the UAV swarm can be acquired theoretically. As for decentralized control modality, each UAV mainly relies on local knowledge to make decisions. The advantage of decentralized control modality is fast and flexible response to the situation change, owning robust architecture which would not be destroyed easily. However, it is difficult to get the total information though interaction due to the limitation of bandwidth and processing ability, so decentralized modality often produce suboptimal solutions.

In current practice, such control modalities are quite simple, and are difficult to apply to large-scale UAV swarms. So it is necessary to put forward new command and control modality to manage the entire UAV swarm effectively. Here, we regard the UAV swarm as a distributed SoS with SoS influencer based on the AIR model [12]. We call the SoS influencer as swarm leader, which can be a ground control station, a high intelligence UAV, or a warning airplane. The swarm leader grasps the overall situation of the UAV swarm. What's more, it is better to use hierarchical structure to control the swarm, easing pressure of the swarm leader. There is another role in the UAV swarm, called sub-swarm leader which is a bridge between the swarm leader and UAVs. This paper divides the UAV swarm into two hierarchies without loss of generality. Generally, the swarm leader and sub-swarm leaders should have high autonomy. In accordance with distributed SoS [12], the UAV swarm can be divided into four modalities: directed UAV swarm C2 modality, acknowledged UAV swarm C2 modality, virtual UAV swarm C2 modality and collaborative UAV swarm C2 modality. Now we introduce them in detail as follows.

A. Directed UAV Swarm C2 Modality

Figure 1 shows the directed UAV swarm C2 modality [13]. In Figure 1, swarm leader plays the role of SoS influencer, while sub-swarm leaders are likely to be department leaders. In leaders. In directed C2 modality, the swarm leader has a strong ability to control sub-swarm leaders and gets no feedback from sub-swarm leaders. Based on the anticipation to the decision-making of sub-swarm leaders and the actual action of every UAV in the swarm, the swarm leader directly makes decisions and affects the sub-swarm leaders. At the same time, the swarm leader can replace part of responsibilities of sub-swarm leaders, and make the decisions belonging to sub-swarm leaders.

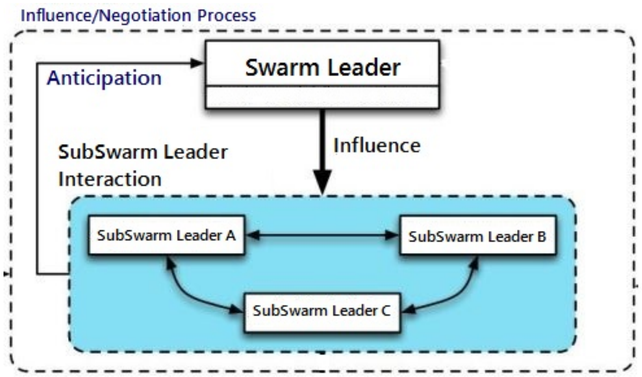

Fig. 1. Directed UAV swarm C2 modality

This does not mean that sub-swarm leaders are no longer independent. In contrast, sub-swarm leaders still have independencies of operation and management. Thus, many key problems should be solved in directed C2 modality. For example, how many authorities should retain in sub-swarm leaders, how many authorities should pertain to the swarm leader, how to anticipate the decisions of sub-swarm leaders, and how the swarm leader and sub-swarm leaders make decisions.

In the directed UAV swarm SoS, each UAV is controlled by their direct sub-swarm leader with sub-swarm leaders led by the swarm leader. Although the swarm leader has the right to perform sub-swarm command, it often does not directly transfer orders to UAV, while would indirectly affect UAVs through the decision of sub-swarm leaders. A sub-swarm leader could negotiate with the other sub-swarm leaders and share information via the wireless network.

Specifically, the directed C2 modality is suitable to the situation where the swarm leader is high intelligent and sub-swarm leaders are less intelligent. The swarm leader is able to obtain information about the environment and actions of all the UAVs in time. The directed C2 modality should not contain too many UAVs, so as to reduce pressure of the swarm leader.

B. Acknowledged UAV Swarm C2 Modality

Many real situations do not meet the requirements of the directed C2 modality, such as the situation with a large number of UAVs and low communication quality. We treat the system that the swarm leader is willing to observe the results of decision making of sub-swarm leaders as the acknowledged C2 modality, which is shown in Figure 2.

The acknowledged C2 modality is similar to directed C2 modality in many places. For example, the swarm leader needs to anticipate the decision-making of sub-swarm leaders and actions of all UAVs, and makes decisions to affect sub-swarm leaders. Sub-swarm leaders receive the decision results and information of other sub-swarm leaders through the mutual communication. Sub-swarm leaders make decision to control UAVs which are subordinate to them.

Nevertheless, there are two main differences between the acknowledged C2 modality and the directed C2 modality. Firstly in the acknowledged C2 modality, the swarm leader lacks of authority to replace roles of sub-swarm leaders. That is to say, the swarm leader does not have full control to the sub-swarm leaders, but has a variety of means to influence sub-swarm leaders. Secondly, the sub-swarm leaders can indirectly affect the swarm leader by direct feedback or indirect influence by issuing orders to its subordinated UAVs. In such system, sub-swarm leaders have choices to reject the advice of the swarm leader.

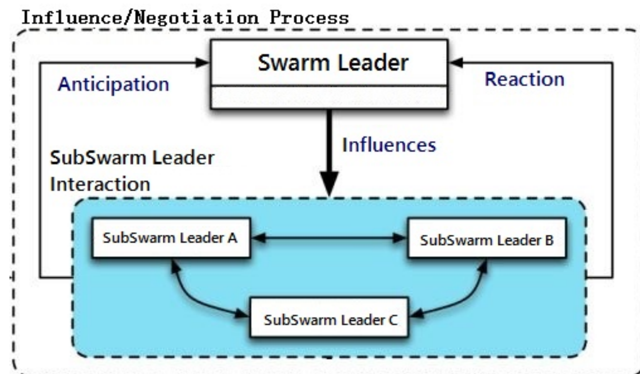

Fig. 2. Acknowledged UAV swarm C2 modality

C. Virtual UAV Swarm C2 Modality

As for the situation without the SoS influencer, we call it virtual C2 modality [13], which is shown in Figure 3. Figure 3 shows the biggest difference between the virtual C2 modality and other types of C2 modality. The virtual C2 modality does not have a global decision maker. In this circumstance, all sub-swarm leaders should have high intelligence. A sub-swarm leader cooperates and shares information with other sub-swarm leaders, controlling their subordinated UAVs through orders. However in the virtual C2 modality, sub-swarm leaders cannot fully grasp the overall situation, while they just know part of information.

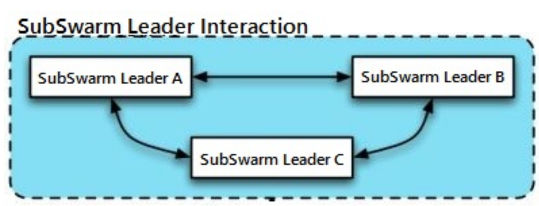

Fig. 3. Virtual UAV swarm C2 Modality

Specifically, the virtual C2 modality is suitable for situations with a wide range of tasks, sub-swarm leaders owning a high degree of intelligence, large amount of UAVs, and low communication quality. Intuitively, the modality of virtual C2 modality is simpler than other modalities. However, it is quite complex to operate in reality. Due to the lacking of SoS decision-maker, it is difficult for sub-swarm leaders to assess decision results of other sub-swarm leaders and the real state of other sub-swarms. So it is hard to make appropriate decisions to maximize the overall effectiveness.

D. Collaborative UAV Swarm C2 Modality

The collaborative UAV swarm C2 modality [13] is shown in Figure 4, which is different from the above three C2 modalities. The collaborative C2 modality contains a plurality of swarm leaders, which may be the sub-swarm leader, or a leader specialized working on SoS decision making.

The word "cooperative" of cooperative C2 modality mainly reflects the communication process between swarm leaders. Among them, the sub-swarm leaders may play the role of a swarm leader or not. Sub-swarm leaders which do not act as swarm leader are similar to sub-swarm leaders in the acknowledged C2 modality. It is important to note that these swarm leaders may be subordinated to different organizations, representing different interests. In short, the cooperative C2 modality is suitable for the situation in which different teams, groups and organizations have shared interests and responsibilities to build up large scale UAV swarms together.

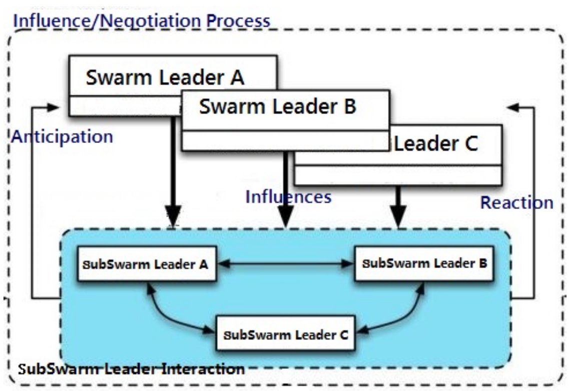

Fig. 4. Collaborative UAV Swarm C2 Modality

IV. CONTENT OF UAV SWARM MISSION PLANNING

The UAV swarm mission planning is a complex SoS engineering. There are a large number of UAV mission planning systems [14] up to now. In short, the mission planning process can be abstracted as five stage which applies to Canadian military [15]: the initiation stage, the orientation stage, the COA development stage, the plan development stage and the plan review stage.

The goal of the UAV swarm mission planning is to complete the task and achieve kill chains. The core of UAV swarm mission planning can be abstracted as getting course of action (COA) of each UAV. Specifically, the input of mission planning is the performance of each UAV, combat missions, costs, environmental threats and the other factors which worth considering. The output of mission planning is the action sequence of each UAV. Actions are hierarchical, which are relative to the environment, tasks, constraints and the other factors that people care.

The designation of COA is a hot problem in recent years. The appropriate COA plays a significant role in improving the effectiveness and efficiency of the UAV swarm. The military language of American Department of Defense [16] points out that COA is a series of actions taken by combat units or combatants to carry out operational missions. COA is an orderly behaviors of one organization to fulfill missions. In short, COA can be described as follows: The combat unit takes a series of actions on some targets at some points, starts and ends at a certain time, and changes the targets from one state to another state. As we all know, the successful of the war results from well-planned plans. Therefore the scientific theories and methods should be used to generate appropriate COAs of the UAV swarm.

The contents of UAV swarm mission planning should include the following sections [9]: route planning, task load planning, data link planning, and emergency disposal planning etc. Results of the above planning are COAs in different hierarchies. The detail information is presented as following.

- Route planning. Route planning refers to the process of planning route of UAVs from the starting points to the target points, and executing the route inspection of planning. The planned routes must meet the performance requirements of UAVs and the assigned tasks, also they must have good security. The main contents of route planning include information acquisition and processing, threat penetration model, planning algorithm and so on.
- Task load planning. Task load planning refers to reasonable allocations of UAV load resources to determine the working conditions of load devices according to combat tasks and the intelligence information. For example, planners plan the work state and work type of reconnaissance loads in different stages.
- Data link planning. Data link planning refers to the usage policies of tracking telemetry and command link in different flight phases based on the requirement of control frequency and the feature of battle environment. Data link planning includes the selection of line of sight or satellite links, working frequency bandwidth, the usage of time, power control, control transfer and so on.
- Emergency treatment planning. Emergency treatment planning refers to the emergency disposal of planning at different stages in case of emergency situation, including planning of emergency routes, return routes, alternate airports and emergency response of link problems etc.

V. KEY TECHNOLOGY OF UAV SWARM MISSION PLANNING

As described above, the goal of mission planning is to obtain the optimal COA. There are different key technologies of mission planning produced by scholars till now. This paper introduces three of the key technologies of the UAV swarm mission planning: mathematical programming, Markov decision process and game theory [11].

A. Mathematical programming

The mathematical programming theory essentially transforms the mission planning problem into numerical optimization problem, and then solve it. It forms the objective function by analyzing the internal relations of decision variables, and then abstracting the constraints of various real conditions as equality and inequality constraints to establishes the mathematical programming model. According to different factors, the mathematical programming model can be classified as following: linear programming, nonlinear programming, integer programming, combinatorial planning, multi-objective programming, dynamic programming, stochastic programming, rough programming, fuzzy programming and so on.

Many researchers have studied the UAV swarm mission planning based on mathematical programming. These methods include traditional methods such as vehicle routing problems from operational research and artificial intelligence. Some precise methods are put forward to solve the problem of improving the accuracy, such as branch and constraint, branch and cut, constraint satisfaction problems, and dynamic programming optimization methods. Although these methods can guarantee the best solution, they are computationally intensive. When the problem has strict boundary constraints, complexity becomes an important problem. These complexity problems usually make previous methods unusable, so researchers put forward a large number of approximate methods. Classical heuristic methods, such as two-stage methods, have been used to solve the problem of large vehicle routing problems relatively quickly. Different heuristic methods such as tabu search, cross entropy, particle swarm optimization, and genetic algorithm are also proposed to solve these complex optimization problems. These approximations help reduce the computational time compared to the precise methods, but for most real-time re-planning environments with complex constraints, most of these algorithms are still computationally difficult to handle.

B. Markov Decision Process

Markov decision theory is one of the uncertain planning methods. In combat planning of the UAV swarm, it not only considers current effects of behavior, but also needs to consider the impact of behaviors on future decisions. Therefore, the problem of UAV swarm mission planning can be regarded as a multi-step sequential decision problem. The purpose of UAV swarm mission planning is to generate an optimal policy that could be performed in the future.

Markov decision theory is broad and profound, such as Markov decision process, partially observable Markov decision process, decentralized partially observable Markov decision process etc. Taking the Markov decision process into consideration, during the decision horizon, the UAV firstly obtains the state from the environment and selects an action to perform so as to influence the environment according to the state and reward. Secondly, the action changes the system from one state to another state, and at the same time the UAV gets a certain income. And then UAV determines the action of next step according to the previous action, reward and state.

C. Game theory

Game theory is an alternative way to solve the problem of UAV swarm mission planning by combining the game among UAVs. The idea behind game theory is that UAVs are independent decision entities that perform actions based on the knowledge of other agents and the environment to maximize their local utilities. So the game theory framework is a natural method to solve the problem of autonomous task allocation in a decentralized way. As the game theory allows UAVs to make their own decisions, it is quite useful in modeling UAVs' non-cooperative behaviors. However, it is difficult to perform cooperation because it should ensure the utility of individual to be consistent to that of the swarm mission.

Thus, the main challenges associated with the game theory cooperative planning include the designation of appropriate utility functions and negotiation strategies to ensure proper coordination between agents to maximize global task performance. Because military operations often have significant confrontational characteristics, so the task of solving the problem of planning is actually used in non-cooperative game theory. The four non-cooperative game models are: complete information static game, complete information dynamic game, incomplete information static game and incomplete information dynamic game.

VI. Conclusion

This paper illustrates the UAV swarm mission planning in four parts: basic concepts, command and control modalities, research contents and key technologies. Essentially these four parts are closely related with each other. Concept is the common features abstracting from the reality. The command and control modalities throw light upon how to design the organization of the UAV swarm in the top frame. Research contents of the UAV swarm mission planning represent what should be planned. Key technologies are methods to solve mission planning problem in mathematics.

As for solving the UAV swarm mission planning problem, there are several steps as following: firstly, analyzing study objects , determining the research targets and granularity of consideration about the UAV swarm according to requirements. For example, there is a task to make real-time coarse-grained route planning and generate the best COAs of the UAV swarm. The paper introduces four planning types which may be incomplete, containing route planning, task load planning, data link planning and emergency disposal planning. Secondly, design the C2 modality of the UAV swarm based on the performance of UAVs, the battle environment and the assigned tasks. The paper provides four modalities of the UAV swarm: the directed modality, the acknowledged modality, the virtual modality and the collaborative modality. However, they are abstracted templates which need to be further refined on the basis of real situation. The designed C2 modality may be one of these four modalities, or a integration of them. Thirdly, build up the problem by mathematical modeling and construct appropriate algorithms to solve the mathematical modeling. Three classical mission planning theories are put forward in the paper. The best result is to find some algorithms to acquire the optimal solution.

ACKNOWLEDGMENT

In this paper, the research was supported by National Nature and Science Foundation of China (No. 71373282, 71401167, 61503402).

REFERENCES

[1] AIR FORCE U.S, "Small Unmanned Aircraft Systems (SUAS) Flight Plan: 2016–2036," Washington, DC, USA, 2016.

[2] DoD, U. S, "Unmanned systems integrated roadmap: FY2013-2038," Washington, DC, USA, 2013.

[3] Shen, Lincheng, Jing CHEN, and Nan WANG, "Overview of air vehicle mission planning techniques," Acta Aeronautica et Astronautica Sinica, vol. 35, pp. 593-606, 2014.

[4] Mosteo, Alejandro R., and Luis Montano, "A survey of multi-robot task allocation," Instituto de Investigación en Ingenierıa de Aragón, University of Zaragoza, Zaragoza, Spain, Technical Report No. AMI-009-10-TEC, 2010.

[5] Theraulaz G, Bonbeau E, "A brief history of stigmergy," Artificial Life, vol. 2, pp. 97-116, 1999.

[6] Edwards, Sean J. Swarming and the Future of Warfare. RAND CORP SANTA MONICA CA, 2005.

[7] Force, US Air, "Unmanned aircraft systems flight plan 2009–2047," Headquarters Department of the Air Force, Washington DC, 2009.

[8] Teague, Edward, and Robert H. Kewley Jr, "Swarming Unmanned Aircraft Systems," No. DSE-TR-0808. MILITARY ACADEMY WEST POINT NY OPERATIONS RESEARCH CENTER, 2008.

[9] Baohong M, "Unmanned aircraft mission planning," Beijing, PRC, 2015.

[10] Ollero, Anbal, and Ivn Maza, "Multiple heterogeneous unmanned aerial vehicles," Springer Publishing Company, Incorporated, 2007.

[11] Ponda, Sameera S., et al, "Cooperative mission planning for Multi-UAV teams," Handbook of Unmanned Aerial Vehicles. Springer Netherlands, 2015.

[12] Shah, Nirav B., Joseph M. Sussman, Donna H. Rhodes, and Daniel E. Hastings, "Influence strategies for systems of systems," In 2012 7th International Conference on System of Systems Engineering (SoSE), pp. 471-478, 2012.

[13] Maier, Mark W, "Architecting principles for systems‐of‐systems," INCOSE International Symposium, vol. 6, 1996.

[14] Yang WANG, "Joint Operation Design and Mission Planning," Computer & Digital Engineering, vol 44, pp. 1493 – 1497, 2016.

[15] Boukhtouta, A., et al, "A survey of military planning systems," The 9th ICCRTS Int. Command and Control Research and Technology Symposium, 2004.

[16] Gortney, William E. Department of Defense Dictionary of Military and Associated Terms. No. JP-1-02. Joint Chiefs of Staff Washington United States, 2016.