The Combat Cooperation of Manned Aerial Vehicle and Unmanned Aerial Vehicle: Main Challenges and Key Problems

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Abstract—With the development of unmanned aerial vehicle (UAV) technologies in recent years, the unmanned combat aerial vehicle (UCAV) has become the darling in the informationized combat environment, which also promotes the UAV becoming more intelligent and automatic. However, being affected by relative technological problems, a practical combat mode of cooperating manned aerial vehicle (MAV) with UAV is proposed to improve the automatic level and make intelligent inadequacy of unmanned systems. The target of MAV–UAV cooperation is to increase the cooperative capability and global efficiency of the whole system. However, there still exist lots of challenges, such as the crossing of multiple subjects, the complexity of the MAV-UAV cooperative model, large-scaled optimization algorithms, and stochastic accidents. Moreover, many critical problems, such as battle environment sensing and perception, MAV-UAV interaction control, cooperative capability expression and supplement mechanism, cooperative capability evaluation and overall efficiency evaluation, and response to accident affairs, still need to be studied furtherly. This paper introduces the composition of a MAV-UAV cooperative combat system briefly, and discusses the major challenges and key problems of this field mainly. It is expectable to show clear direction for further research.

Keywords—UCAV, informationized combat, MAV–UAV cooperation, cooperative capability, human-computer interaction.

I. Introduction

In recent years, aircrafts have developed rapidly towards hypersonic speed (Ma⩾5), new structure (morphing, flying wings, etc), near-space (height varies from 20 km to 40 km), high stealth and unmanned direction (many kinds of UAVs). These developing aircraft technologies make the control of UAVs faces new challenges and chances [1], and eventually lead to much more research on UAVs with the rapid development of autonomous control technology, which play an important role in military and civil domains and have been prevalent in both military and civil operations.

With above technologies, realizing increased intelligence and automation to improve the combat capability is the development trend of current UCAVs [2]. UCAVs cannot finish the execution of complex manipulation tasks alone because of the limitation of their own capability, so UCAVs cannot supplant MAVs completely. In this way, MAV-UAV cooperation becomes the powerfully successful and important actual combat mode which can realize increased automation and make up for some disadvantages of UAVs. A complicated human-computer system is an organic integrity consisting of human and artificial systems in a dynamic, open, hard-controlled, and complex network environment, and the MAV-UAV cooperative combat is to achieve coordinated attack based on the communication tools sharing the environment situations and some coordination mechanisms essentially. "Unmanned Systems Integrated Roadmap FY2013-2038" provided by the Department of Defense of the USA also points that the new unmanned systems suitable for air, land and sea must be integrated into the Manned-Unmanned System Teaming (MUM-T) by technology improvements and military specialisations [3]. In this way, objects like MAV-UAV cooperative combat system have been widely investigated as they have potential applications in military domains, especially in developed countries.

Developed countries, such as USA and UK, have done some researches on the MAV-UAV cooperative system. For instance, in a project named AMUST began in 1966 for the MAV-UAV cooperative system, the flight performance of human-computer interaction systems was tested by Boeing Company, and an experiment about the joint tactics of UAV systems was carried out by the United UAV Office of USA, etc. Furthermore, a number of aircraft platforms have emerged for some flight experiments and information interaction experiments [4-5]. At present, MAV-UAV cooperative combat system tries to finish cooperative mission in multiple aspects, such as the resources, information, and attack plans, and always owns the cooperative mechanism is that manned vehicle makes decisions and UAV receives the commands to attack targets. In the future, the systems should not only focus on this simple cooperative mechanism, but also combine the human wisdom and computer intelligence. In this way, the MAV-UAV cooperative combat system could establish better capabilities to complement each part.

This paper briefly covers the previous work and preliminary results. Next section will introduce the composition of a MAV-UAV cooperative combat system. Based on this, the main challenges and key problems of this system are focused on mainly. It is hoped that this paper could provide the direction for further difficulty breakthrough and experimental tests.

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II. Composition of a MUV-UAV cooperative combat System

According to the function, a MUV-UAV cooperative combat system can be characterized into the following four parts: MAV system, UAV system, communication link system, and command & control system.

A. MAV system

Relying on the human wisdom, the MAV system could distribute missions, decide the flight path, and evaluate the situation. This system also receives commands from command & control system via communication link system, and send commend information for UAV system. Meanwhile, the situation sensing and target attack also are carried out with the cooperation of UAVs.

B. UAV system

Taking the advantages of UCAVs, UAV system mainly carries out the sensing task, including regional monitor and investigation, object detection, target tracking, etc. UAV system would receive command information from MAV system and command & control system via communication link system. Moreover, this system sends necessary information about situation to MAV system and attacks targets with MAVs.

C. Communication link system

A system without information interaction may always mean destroy in modern informationized combat environment. So MUV-UAV cooperative system requires for this bidirectional channel for information instruction.

D. Command & control system

Command & control system is the control and guidance center of a MUV-UAV cooperative system which provides significant combat information and mission requirements when it is necessary.

"The Role of Autonomy in DoD Systems" indicates that the true value of unmanned systems is not to provide a direct human replacement, but rather to extend and complement human capability by providing potentially unlimited persistent capabilities and reduce the exposure of human to life threatening tasks with proper design [6]. Computers are largely repeatable, predictable, dependable, and consistent, and human beings are rarely repeatable, predictable, dependable, or consistent [7]. Whereas, humans are with the advantage in learning capability, creativity, adaptation, etc. compared with computers. MUV-UAV cooperative combat systems could make full use of the advantages of humans and computers, making humans and computers carry out tasks that they are good at respectively. As a result, the cooperative systems could be more intelligent beyond human capability. What should be paid attention to is that the MAV system which is based on human beings cannot be replaced by any machine anyway. For one thing, machines with relative autonomy and independence are the product of human wisdom and labor. For another, the essence of human thought is the response to objective events, and design process and decision making process needs logical and divergent thinking that depends on human creativity and unique characteristics of activity, which cannot be replaced by any machine.

By introducing human wisdom, a UCAV can finish complex manipulation tasks, and its autonomy could be improved under uncertain dynamic environment which could broadens its task scope. And by the practical application of UAV system, pilots can reduce their learning time, pressure of memory, and other working pressure, and the errors due to the unilateral inadequacy of human, such as lapse of concentration, changes in mood, fears, and prejudices, could be avoided. As a result, for MUV-UAV cooperative combat systems, even any human-computer cooperative systems, the key factor is always regarded as the close cooperation of human wisdom and computer intelligence, which needs MAVs and UAVs to play their strong points.

The MAV-UAV cooperative combat systems should devote to cooperative detection, cooperative combat and cooperative attack to realize the efficiency of "1+1>2" at all. For this purpose, how to represent the cooperative capability, how to build the capability complementary mechanism, how to perceive and understand the combat environment in time based on the communication link system and command & control system, etc., would be the key issues that affect the actual cooperation of MAVs and UAVs, and the research emphasis for the improvement of the MAV-UAV cooperative capabilities.

III. Challenges of MAV-UAV cooperative combat systems

Over the last few decades, computer science, automation, artificial intelligence, virtual reality technology, and digital communication have developed markedly. At the same time, wars have been with the confrontation of "system to system" rather than platform confrontation anymore. Aircrafts under informationized combat environment need wider flight envelope, more advanced layout, higher strength body materials, deeper computer system, more advanced communication system, and more convenient control method [1]. MAV-UAV cooperative combat systems are also faced with many challenges, which could be regarded as extensions above.

A. Crossing and integration among the multiple subjects

The structure design, control system design, and implementation of an UCAV require crossing and integration among multiple subjects with trend that information-oriented integration of control, computing, and communication becomes more and more obvious [1]. Analogously, to improve the cooperative capability of MAV-UAV cooperative combat systems, their hardware should be improved firstly via crossing and integration among multiple subjects (weapon, material, etc.) to meet requirements of different combat situations, for example, an UCAV in these environment needs a new layout and structure, as well as the mixed, multiple, heterogeneous, and innovative control functions to cooperate with the MAVs, which would require crossing and integration among multiple subjects absolutely. In addition, accurate and fast situational sensing and information interaction would be good for human-computer cooperative system to implement cruise flight, attack or hide behavior according to the change of the air combat situation flexibly to improve the combat efficiency, but it always calls for the information acquisition, classification, processing, and transfer of different platforms that are concerned with multiple subjects also.

Overall, the analysis and design by crossing and integration among multiple subjects would be benefit to structure optimization of whole system and improvement of system performance. In this way, systems would not be affected by a short board which may weaken the advantages of other aspects. However, it would accompany with enormous workload to integrate so many subjects without doubt.

B. The complicated mathematical model of the MAV-UAV cooperative combat system

The mathematical model of the cooperative system according to the change of the air combat situation not only contains the dynamic models of the UAV and MAV, but also contains the cooperative mechanism of the human-computer cooperative system. If the UAV system consists of many UCAVs, it would also include the dynamic task scheduling of multiple aircrafts. Because the dynamics of the aircraft with advanced layout is affected by the wide nonlinear and unsteady aerodynamic forces as well as strong coupling, the dynamics modeling of UAV or MAV has faced too many problems [1]. In addition, based on the dynamics models of the MAV and UAV, the cooperative system requires precise definitions of the cooperation capabilities to realize the complementarity of UAV capabilities and MAV capabilities, which is the core content of the cooperative model and is the basement of mathematical characterization of cooperative capability, the establishment of complementary mechanism, and the evaluation and analysis of a cooperative capability. What's more, when involving dynamic task scheduling of multiple UCAVs, the model of task scheduling of multiple UAVs and the architecture of distributed task scheduling [8] should also be in consideration which would also increase the difficulty of modeling further

The model of a MAV-UAV cooperative combat system needs to be improved and optimized according to the cooperative capability, environment requirement, and task requirement. Above processes and model structure may be very complex.

C. Wide-ranged and various optimization algorithms

For an UCAV control system and a pilot assistance decision system, the control problem would be with an infinite number of solutions because of the increase of mixed, diverse, heterogeneous, and innovative control action in the future. However, in order to obtain the optimal control effect under objective demands, such as limited space, maximum speed, and maximum angle, the control function should be allocated optimally and real-timely. On the other hand, in terms of the MAV-UAV cooperative combat system, to realize the capability of cooperative system is greater than the simple sum of capabilities of MAV and UAV, not only the cooperative mechanism of MAV-UAV cooperative systems should be built, but also we have to consider the optimal complementary mechanism of MAV and UAV to make full use of human wisdom and machine intelligence in different tasks. So the control of a MAV-UAV cooperative system model may be considered as the solution of a real-time optimization problem requiring information acquisition, processing, and interaction, aiming at a task under uncertain combat situation and some capability constraints.

In this way, optimization algorithm would directly affect the capability achievement of the MAV and UAV, the performance of the MAV-UAV cooperative system, and the quality of task realization, even the safety of pilots. And the requirement for wide-ranged and multidisciplinary real-time optimization algorithms would generate an inevitable challenge in the future combat environment.

D. The accidents that occur at any time

MAV-UAV cooperative systems under the combat environment can be regarded as a complex human-computer cooperative system under the unstructured and changeable environment, which requires for preparations to deal with accidents. In the modern informationized combat environment, MAV-UAV cooperative systems are often required to finish the complex manipulation tasks under a complex environment. So these systems have to deal with not only some objective factors, such as the changes of terrain and weather, but also military attacks from the enemy. As the emerging modern battle field weapon, the informationized environment not only offers distributed sensing, communication, and computing environment, but also provides more choices for a military strike. That is, more choices of the military strike are provided, and destroying the enemy physically may be no longer the only combat way. In many cases, preventing enemies from effective information would be more effective than improving own weapon equipment performance, which also makes the accidents in the combat environment more multiple.

The MAV-UAV cooperative system as a complex human-computer cooperative system with multi-actuators, multi-sensors, and less hardware redundancy is easy to suffer all aspects of faults. And the aircraft structure characteristics and the working environment make that a small fault may cause fatal consequences. Because of the uncertainty of modern combat field and the non-intervention of people to the environment, the probability of these faults would increase significantly. The common faults of the cooperative system occur mainly in the sensors and actuators, which would affect the normal environment sensing and information interaction between platforms, even the stability of the flight. As far the UCAV, the controller faults should also be attached.

IV. The key problems of MAV-UAV cooperative systems

The Ref. [9] briefly states the general operational process and key technologies, including cooperative control, cooperative situation sensing and evaluation, cooperative target assignment, and cooperative route planning, based on a simple human-computer cooperative system that MAV system serves as mission planner, and UAV system serves as mission performer. Although the relevant methods for above key technologies have been gotten, the following key issues remain to be devoted to ensure the whole capability is greater than the simple sum of the capabilities of MAV and UAV.

A. *Sensing and perception of combat environment*

The sensing of the combat environment is the process that MAV and UCAV extract related attributes from objects via sensors. In this process, the system will finish the target detection, tracking, and recognition. Based on this, the perception of the combat environment is always needed to understand the battle field situation and the tracking target [10]. In fact, the perception of the situation is the further demand of environment sensing, which includes many aspects, such as state assessment, state comprehension, and target behavior understanding. In terms of MAV-UAV cooperative system and common UCAV, the sensing and perception of combat system are always the key points of searching battle field information and collaborating to make decisions, which also cover many research fields, such as computer vision, image processing, and pattern recognition, and belong to the field of high-leveled information fusion, so excellent system architecture and technologies are required assuredly [10].

As for a MAV-UAV cooperative combat system, it should make full use of the advantages of multi aircrafts cooperation based on the environment sensing and perception of UCAVs to achieve the complementary cooperation of different sensors. Moreover, environment perception system of cooperative combat mission should be established [12] that could make use of the wisdom of humans to make up for the disadvantages of computer intelligence, perfect the understanding of the environment, and improve the use ratio of environment sensing information. Besides the critical technologies, such as dynamic object tracking and behavior understanding, knowledge expression and environment modeling, situation evaluation and threat assessment, etc., the interaction and decision about environment sensing and perception should also be studied further to make it develop towards the direction of multiple platforms, and achieve the transition from sensing to comprehension, and from reasoning to learning [10].

B. *Human-computer interaction control*

Human-computer interaction control is the hot issue in the MAV-UAV cooperative combat system, especially in the process of a complex manipulation task. On the one hand, the pilot of the UAV would receive command information and combat task information from the command & control system, and receive situation sensing and object information from the UAV system. For the other hand, the pilot has to operate aircraft according to the actual situation, and correct the UCAV’s task planning. All of these issues make the pilot have much work to do. Therefore, a more convenient, much easier, and more humanized human-computer interaction interface is always required.

In terms of the MAV-UAV cooperative combat system with a MAV and an UAV, the interaction behavior in the manipulation of tasks can be divided into 3 aspects: the interaction process of releasing tasks, querying information and detecting gusty threats [13]. To achieve different purposes, such as assigning tasks, checking the status, and adjusting the route, different process structures need to be designed in different interactive processes. For the achievement of different interactive process, human-computer interaction interface system requires identification module and task instruction code module [14] to transmit, recognize even understand the interactive information, such as text, image and language. Anyway, no matter what kind of interactive information is used, the key issue is building complete task command set and reliable instruction code [14] to meet control requirements under different platforms. With the rapid development of computer technology and pattern recognition, human-computer interaction control should be modular, robust, and autonomous to make the human-computer interaction more convenient and faster, which will improve the performance of the whole system indirectly.

C. *Characterization method and complementary mechanism of cooperative capability*

The accurate definition to the capability of MAV-UAV cooperative system, the characterization methods of capabilities, and revealing the varying patterns and complementary laws of different capabilities in the combat environment are gradually in-depth, and would be the foundations for the cooperative decision and the keys to realize the capability promotion of collaborative detection, coordinated attack, and cooperative combat in the combat environment. Therefore, constructing characterization methods and complementary models for cooperative capabilities become the essential segments to model a MAV-UAV cooperative combat system. The construction of mathematical expression for a cooperative capability is based on the accurate definition and classification of cooperative capability, and the access to the effect law of human wisdom and computer intelligence. This effect law is of great help for finding out the optimization method for the complementary mechanism to achieve the complementation of pilot wisdom and machine intelligence.

According to the decision process model OODA (Observe, Orient, Decide, Act) proposed by the U.S. army colonel John Boyd in 1995, a combat process can be expressed as the circulation of "Observation, Orientation, Decision, Action" abstractedly. This model is widely used in the performance analysis of aircraft, and the representation of a multi-UAVs cooperative process [15]. The classification of the MAV-UAV cooperative combat capability involves many segments, such as flight, mobility, invisibility, detection, attack, and perception. All of above capabilities need to be penetrated in the four segments of OODA. If the pilot of a MAV longs for completing the combat system circuit of "Cooperative Observation, Cooperative Orientation, Cooperative Decision, Cooperative Action" rapidly, the requirements for cooperative capabilities are needed. Moreover, constructing optimization methods for cooperative capabilities and designing the extensive and versatile optimization algorithms are also necessary. All of them ensure the optimization of every segment in “OODA”.

D. Cooperative capability and global performance evaluation

It is necessary to evaluate and analyze a cooperative capability, aiming to establish and perfect the characterization of the cooperative capability and the complementary mechanism. Based on the requirement of air combat theory and combat mission, according to the battle efficiency evaluation index systems of unmanned combat aircraft and advanced warcraft, an independent, integral, hierarchical, and scientific battle efficiency evaluation index system model should be established for the cooperative capability and global performance of the MAV-UAV cooperative combat system to evaluate overall effectiveness [16]. In order to get a definite data with physical meaning, which is able to evaluate cooperative capability and guide the establishment of capability characterization and complementary mechanism, this index system is supposed to cover all aspects of cooperative capabilities, and quantize the level of capability. Moreover, the corresponding quantitative evaluation about the working load and situation sensing of the pilot is also in urgent needed [17-18], which should be involved in the global estimation of the performance to optimize cooperative capability and maximize global performance under a certain workload.

E. Responses to accidents

The accidents occur at any time are great challenges which MAV-UAV cooperative systems are faced with in a cooperative combat environment, so researching on responses to accidents become a critical problem to guarantee the safety and reliability of the human-computer system undoubtedly.

The responses to the accidents caused by environment, weather, and enemy attack can be described by several OODA circles as well, which require for the establishment of complete accident response mechanisms for the sake of invoking appropriate cooperative action in the light of various battle field situation. The formal modeling for some emergent response mechanism is the basis of above response mechanisms. However, the modeling process will be hard to be expressed with mathematical format due to the complexity of response process. Consequently, the mechanism featured with modularization, formalization, and hierarchicalization, such as Discrete Event System Specification (DEVS) and so on can be put into it [19]. What’s more, there is a need to design fault-tolerant controllers to ensure the stable functioning of the system, even the ideal performance faced with sensor, actuator, and controller faults of MAVs and UAVs [20]. The fault-tolerant controller has to be equipped with faster fault detection and diagnosis (FDD) method and more robust control reconfiguration and reestablishment method in view of the specific application environment and component in human-computer cooperative system.

V. CONCLUSION

As the leader in the research of MAV-UAV cooperative combat system, western countries provide good references through their own strategies [9]: In order to form cooperative combat capability, the theoretical research and related experimental verification work should be carried out at the same time; the MAV-UAV cooperative combat system should be melted into current combat system to deal with the evolution that the war is with the confrontation of “system to system” rather than platform confrontation anymore. It is of great importance to demonstrate that cooperative combat system of MAV and UAV is an operation mode that enhances the level of automation on the condition that the intelligence and autonomy of UAV are limited by technology, and UCAV should still be with a highly intelligent system and highly precise sensors to a direction towards high automation constantly.

Above all, the introduction of the MAV-UAV cooperative system could reduce the utilization of pilots’ energy when they are on the mission, and allow them to apply precious human intelligence to some key decisions. On the other hand, it improves the autonomy of UCAVs under complex missions and uncertain dynamic environments, and extends the range of missions. Review on the composition, challenges and key problems of this cooperative combat system is desired to point out the direction for the difficulty breakthroughs and experimental verifications in the future work.

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