A Review of Manned/Unmanned Aerial Vehicle Cooperative Technology and Application in U.S. Military

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***Abstract*—The paper is to learn the experience in the field of Manned/Unmanned Aerial Vehicle (MUAV) cooperative technology and enlighten the technology development and progress of our country. First of all, it is to collect the typical research projects and tracke experiment dynamic, excavate the development in the field of MUAV cooperative technology route; And then, attention is paid to the related typical application cases to analyze the current technical maturity; Second, from the perspective of technology development, application, analysis is executed from the human-computer interaction control technology, intelligent decision-making technology, communication anti-jamming technology, open hardware and software technology to MUAV; Finally, the experience of the U.S. military in the field of MUAV collaborative technology are summarized, and the enlightenment for the development of China in the field is given.**

Keywords-Manned/Unmanned Aerial Vehicle; Collaborative technology; Test platform; Application case

I. INTRODUCTION

In 2010, the US Army released “the Army UAV System Roadmap (2010-2035)”. Thereafter, the Army reevaluates the roadmap every two years to keep it up with the rapid pace of technological developments. The roadmap divides unmanned aerial vehicle (UAV) development into three phases. The goal of the near-term development phase (2010-2015) is to rapidly integrate UAV systems into tactic-level units to meet the force's current operational requirements. The medium-term development phase (2016 to 2025) aims to increase the degree of automation of UAV systems that can quickly and fluently support combat operations, and establish the link between manned and unmanned systems, opening the way for collaboration between manned and unmanned systems. The long-term development phase (2026 to 2035) aims to greatly improve the ability of

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manned and unmanned systems to cooperate in combat operations.

In the "2011-2036 Comprehensive Roadmap of Unmanned Aerial Vehicle Systems" issued by the U.S. Department of Defense, the definition of Manned/Unmanned Aerial Vehicle (MUAV) cooperative operations is that a unified formation is established between manned and unmanned aerial vehicles (UAVs) to complete a certain mission, and the process of finally completing the established mission objectives through cooperative control, platform interoperability and resource information sharing [1]. This is for the first time, the American MUAV cooperative engagement has made the definition.

In 2018, the US Navy released a Roadmap for Naval Unmanned Systems. The Navy's vision for the development of unmanned systems is to seek to establish a future force that can adapt to all-domain operations with efficient manned/unmanned cooperation. It aims to improve the Navy's combat capabilities by reducing the operating costs and risks of unmanned systems in the air, surface, underwater and ashore, enhancing the endurance of unmanned systems, and providing better situational awareness.

It is easy to see that the US military has always attached great importance to the construction of its unmanned system combat capability, and has taken the realization of manned/unmanned cooperative operations as its long-term development goal and vision. This article is embarked from the American MUAV cooperative development, tracking its research projects and typical test platform, excavating its technical maturity, analyzing the American MUAV cooperative engagement case and its capabilities; After that, combined with the next development plan of the US military, the enlightenment of our MUAV collaborative combat capability construction is given.

II. TYPICAL RESEARCH PROJECTS

A. Skyborg

Skyborg is a large-scale artificial intelligence program of the U.S. Air Force Research Laboratory. It aims to develop an artificial intelligence software system that can control UAVs to fly, take off and land autonomously, and cooperate with human pilots in combat. The ultimate goal is to improve the efficiency of UAV mission planning and the performance of human-machine collaboration to deal with various threats in high-confrontation combat environments [2].

In March 2019, the Air Force first unveiled the Aerial Borg program, and officially released the project proposal in May 2020. In December 2020, the Air Force awarded contracts to General Atomics, Boeing, and Kratos Defense and Security to build the Loyal Wingman prototype to carry the artificial intelligence software systems of the Aerial Borg program.

At the end of April 2021, the UAP-22 Mackerel Shark UAV developed by Kratos Defense and Security became the first test flight platform of the Aerial Borg program. On May 5, 2021, the second flight test was carried out, and it was flown in coordination with an F-16C fighter jet. The U.S. military claimed that this flight test was the closest coordinated flight between an autonomous UAV and a manned fighter jet in the history of the U.S. Department of Defense. The Air Force has also conducted a series of flight tests to test the capability of manned aircraft and multiple unmanned aerial vehicles to cooperate with each other. Figure 1 is the air's projects designed by MUAV layered fighting style.

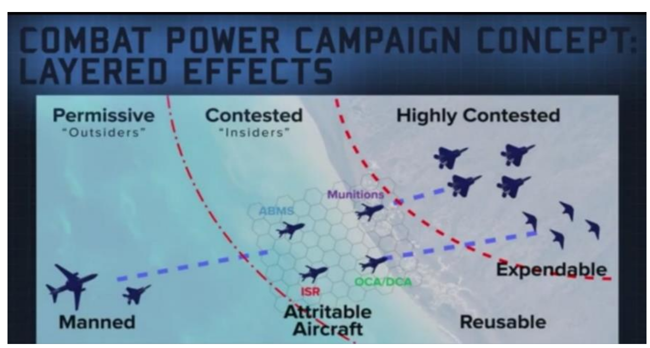

Figure 1. Hierarchical combat style of the Aerial Borg project

B. Project Carrera

John Clark, Lockheed Martin Vice President and general manager of "Skunk Works," detailed the company's newly launched Flexible Autonomy program, internally known as "Project Carrera," during a press conference call with the release of the official concept video on Sept 14, 2022 [3-4]. The project's first experiments was planned to take place at Skunk Works and involve Racing drones and F-35 strike fighters, which fly four Racing drones under the wings of the F-35 and launch the drones in the air. Figure 2 shows the manned/unmanned combat model designed by Project Carrera.

Figure 2. Lockheed Martin manned-unmanned combat scenario

Skunkworks' vision of Project Carrera, especially in the first phase, is mainly to explore and refine various future manned/unmanned cooperative combat concepts, and is very optimistic about the vision of manned/unmanned cooperative combat. More details are expected to emerge as Project Carrera nears the start of flight tests.

C. Air Combat Evolution Project (ACE)

The Defense Advanced Research Projects Agency (DARPA)'s Office of Strategic Technology launched the Air Combat Evolution project in May 2019. The purpose is to overcome the problem of autonomous performance in human-machine cooperative close air combat, enhance the confidence of warfighters in autonomous combat systems, and develop a scalable, trusted, human-level artificial intelligence autonomous system [5].

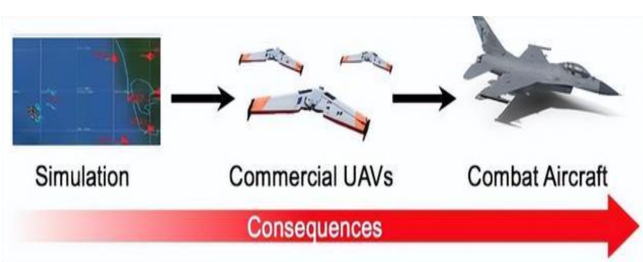

Figure 3. The three phases of the Air Combat Evolution program

The ACE program can be specifically divided into three phases, which are expected to last five years: The first phase is a simulated environment study lasting 18 months, focusing on the validation and development of its key capabilities in a simulated environment and simulation. The second phase, UAV flight trials, will last 16 months. The third phase, MUAV flight trials, will use full-size aircraft and small aircraft to conduct tests. Figure 3 shows the three phases of the ACE program. The DARPA announced on March 18, 2021 that more than half of the first phase of the Air Combat Evolution program has been completed, and several key phase results have been achieved.

Information on other manned/unmanned collaborative technology projects in the United States is shown in Table Ⅰ.

TABLE I. OTHER PROJECT INFORMATION

Time	Project name	Verification platform	Main content
1993	Bird Dog	/	Develop the concept of manned/unmanned collaboration
1997	TCS	P-3C, F/A-18, AV-8B/ RQ-8A, MQ-4C, X-47B, UTAP-22	The focus is on the test and verification of cooperative combat projects to achieve the 5-level control of UAVs
2006	HSKT	AH-64D /RQ-5B	Verify manned helicopter /UAV/ fighter aircraft coordination capabilities
2021	UxS IBP21	E-2C, EA-18G, MH-60/ MQ-9	The focus is on assessing the capabilities of manned/ unmanned systems in areas such as intelligence, surveillance and reconnaissance
2022	The Marines train in tandem with the Navy	UH-1Y, AH-1Z/ MQ-8C	Verify the ability of manned/ unmanned formations to work together in future coastal environments

III. TYPICAL TEST PLATFORMS

A. *XQ-58A Valkyries UAV*

Figure 4. XQ-58A Valkyria UAV

American "loyal wingman" project, designed to mix fifth-generation fighter with UAV formation, coordinated various combat missions. In the composite wing, human-computer play the role of "commander", is responsible for his orders, UAV is responsible for "charge" and strike enemy [6]. XQ - 58 Valkyries UAV is a typical representative of "loyal wingman" project, by "carat," defense security company research and development, in collaboration with the air force research laboratory is a ranged attack, high subsonic UAV, mainly for the combined with man-machine, surveillance and reconnaissance and long-range strike missions. Figure 4 shows the XQ-58A Valkyrie UAV, and its performance parameters are shown in Table Ⅱ.

Kratos initially developed three demonstrators, one of which was delivered to the US Air Force Research Laboratory for flight testing, and the remaining two were used for internal testing. In March 2019, XQ - 58 Valkyries demonstrate a prototype successfully in Yuma proving ground for the first time for the flight. Subsequently, the second and third flight tests were conducted in June and October 2019, respectively, and the fourth flight test was conducted in January 2020. At this point, XQ - 58 a Valkyries the accumulative total of UAV flight time has been more than five hours, is beyond the goal of the programmed of flight test. In August 2023, the U.S. Air Force conducted its first flight test with an AI-autonomously piloted XQ-58A Valkyria. At present, XQ - 58 Valkyries drones can have a and F - 22 or F - 35 fighter fleet, realize the cooperative engagement, to carry out reconnaissance and combat tasks.

TABLE II. XQ-58A PARAMETERS

Serial number	Parameters
1	Length 8.8m
2	Wingspan 6.7m
3	Maximum take-off weight 2.7t
4	Maximum speed Mach 0.72
5	Maximum range 4800km
6	The maximum combat radius is 2500km

B. *Unmanned modification of the F-16*

In recent years, the US Air Force has begun to refit the F-16 fighter jet in depth, mainly planning to put the transformed F-16 fighter jet completely under the command of artificial intelligence system in actual combat. At present, the first flight test of the program has been completed, which also lays the foundation for the US Air Force to explore MUAV cooperative operations, and provides the possibility for the US military to form the world's first unmanned fighter formation.

Compared with the XQ-58A Valkyries, the unmanned F-16 has unparalleled advantages in range, bomb load and maneuverability. The advantages of the XQ-58A Valkyries are light and small fuselage, stealth ability and low manufacturing cost, but its independent combat ability, especially air combat ability, is far from the F-16 combat UAV, which plays the role of fire multiplier and is a real unmanned wingman.

It is said that in the future, the US Air Force plans to develop a fleet of at least 1,000 UAVs to serve as wingmen for the F-35 fighter and the next generation of advanced fighters. The coordinated drones could carry missiles or other weapons, carry out electronic warfare missions, or perform intelligence, surveillance and reconnaissance missions ahead of other manned aircraft [7].

C. *Elf UAVs*

The Elf is a U.S. DARPA program of UAVs, code-named X-61A, launched in 2015. It is capable of being launched in the air by a manned transport aircraft, retrieved, and maintained before being used again [8].

Figure 5. A C-130 transport aircraft carrying a Gremming drone

During the flight demonstration, the X-61A was launched from a C-130 wing hantry, and the drone was controlled by two control platforms, one mounted on the C-130 and the other on the ground. During the recovery, the cap sting-recovery system on the tailgate of the C-130 transport aircraft became the key technology, and the X-61A UAV completed the automatic docking with the C-130 through the docking system at the end of the cap sting-towed cable. When the X-61A is successfully docked, the UAV will shut down its engines, redraw its wings, and then be pulled back to the aircraft cargo bay by the towing cable.

In November 2019, the X-61A was launched for the first time on a C-130A transport aircraft. In August 2020, the X-61A made its second free flight and finally landed successfully with the help of a parachute. In October 2021, the recovery of the X-61A by a C-130 transport aircraft was successfully tested. Figure 5 shows the C-130 transport aircraft carrying X-61A UAVs.

IV. TYPICAL APPLICATION CASES

A. Manned/ unmanned cooperative reconnaissance

Since 2020, the US MQ-4C Poseur unmanned aerial vehicle has begun to deploy around the South China Sea and conduct joint reconnaissance with P-8A Poseur anti-submarine patrol aircraft. As an upgraded version of the RQ-4N Global Hawk UAV, the MQ-4C Mermaid Posei UAV not only improves the strength of the fuselage to better adapt to the wind environment at sea, but also adds anti-ice measures, which can repeatedly cross the clouds to the lower airspace for close reconnaissance, which is very suitable for carrying out a wide range of reconnaissance and surveillance missions at sea. Figure 6 show the MQ-4C and P-8A are working together on reconnaissance

Figure 6. MQ-4C and P-8A are working together on reconnaissance

According to the plan, the US Navy will use 68 MQ-4C Merman Posei UAVs and 117 P-8A Posei anti-submarine patrol aircraft to jointly carry out maritime patrol and surveillance and reconnaissance missions to replace the old P-3C patrol aircraft. MQ - 4 c "mermaid" a sea drones in the anti-submarine mission for P - 8 a maritime intelligence support, and P - 8 a is MQ - 4 c "mermaid" a sea of UAV control and communications relay platform.

In December 2020, two US Navy B-1B strategic bombers opened the way for the MQ-4C Poseur to conduct reconnaissance close to the South China Sea. Some scholars believe that if the MQ-4C UAV and B-1B bombers carry out missions in coordination, the MQ-4C UAV can be used for search, detection and targeting missions, and the B-1B will drop AGM-158C long-range anti-ship missiles on the target.

B. Cooperative manned/unmanned anti-submarine

In May 2023, the US Navy held the Unmanned Systems Integration Operations-23 (USIBP-23) exercise, which focused on surveillance, reconnaissance, maritime and submarine long-range firing, command and control, and reorganizing intelligence, and focused on cooperative manned/unmanned anti-submarine operations [9]. During the exercise, the participants used the MQ-9B Ocean Guardian UAV and the MH-60R Seahawk helicopter to quickly complete the association and location of the target, and then transmitted the tactical report to the commander of the anti-submarine Warfare Center at the Pearl Harbor Naval Base through the MQ-9B Ocean Guardian UAV [10]. The ASW commander then used the MH-60R Seahawk helicopter to drop torpedo training rounds against the simulated submarine.

C. Coordinated manned/unmanned strike

"In 2015, the sea - air l" exercise, F - 16 VISTA (flight simulator) successfully verified the route to follow, autonomous formation flight, air collision avoidance ability and the ability to rejoin the formation, promote the autonomy of the craft level, and command the autonomy of the command and control of UAV [11]. In addition, "sea - air l" also verified the F - 16 VISTA have the capacity of planning and ground attack missions. While performing a mission, the F-16 VISTA determines mission priorities based on the priorities given by the command aircraft to achieve all mission objectives.

The US military successfully verified the autonomous strike capability of the unmanned combat aircraft during the "Hepher-Air Raider II" exercise held in 2017. The demonstration set and achieved three key objectives: first, it successfully planned and completed an autonomous strike mission to the ground; Second, the ability to adapt to changes in the environment during the execution of a mission; And the successful use of a software integration environment that is fully compliant with the Air Force's Open Mission System (OMS) standard[12-13].

V. SYNERGISTICAL KEY TECHNOLOGIES

A. Human-computer interaction control technology

In the future air combat battlefield, human-computer cooperative operation is a dialectical unity. The pilot plays the role of driving the fighter to carry out air combat tasks, and also acts as the commander of the MUAV mixed formation, conveying the decision-making instructions of the rear command center, integrating battlefield information, and issuing instructions such as interim guidance. Pilots need to be responsible for the "fighting" in the past, but in the future pilots would need to be "battlefield commander", to be able to communicate, to other UAV in the composite wing give orders. The clear, fast and accurate transmission of commands by human-computer interaction control technology has a direct impact on the battlefield situation. The development of deep learning, data mining and other technologies has provided infinite possibilities for human-computer interaction control technology based on natural language understanding. Even in the noisy and thundering environment of the battlefield, the pilot can easily express the intention and clearly indicate "how to do", "what to do" and "when to do", and the UAV can quickly understand and execute these instructions to realize the command and control of the pilot over the UAV.

B. Intelligent assistant decision-making technology

In MUAV hybrid formation, pilots can clearly and quickly convey strategic and tactical intentions to UAVs through natural language, thus reducing the burden of pilots. The hybrid formation usually consists of one manned aircraft and multiple UAVs. Even if the interactive control mode between the pilot and the UAV is simplified, the interaction pressure is still large. Therefore, how to further reduce the pressure of pilots has become one of the important issues in the maturation of MUAV cooperative operations. Intelligent assistant decision-making technology can assist pilots in decision-making through intelligent algorithms. A small number of decision-making tasks with higher priority are assigned to the pilot for decision-making, and a large number of decision-making tasks with lower priority are completed by the machine independently. This can effectively reduce the decision-making pressure faced by pilots, so that they can have more energy and time to deal with more important affairs.

C. Communication Anti-jamming technology

In MUAV cooperative operations, maintaining good communication is the key to maintaining cooperation. MUAVs can usually achieve effective communication before entering enemy airspace. However, once inside hostile airspace, they will face various means of communication jamming. Man-machine and UAV at the individual level can keep certain single combat ability. However, on the whole, MUAVs still need to rely on high-speed and secure communication to exchange instructions and important intelligence information. At the same time, using the frequency hopping communication method with strong anti-jamming ability can minimize the possibility of being interfered by the other side, which is also one of the technologies worthies of continuous research and application.

D. open hardware and software technology

As a hybrid combat formation, the MUAV cooperative combat system needs to have multiple functions such as surveillance, reconnaissance, electronic jamming, damage assessment, and strike implementation. The UAVs in the hybrid formation need to adopt various types or carry different payloads and sensors to perform diverse tasks. Therefore, integrating heterogeneous UAVs from different manufacturers and efficiently integrating sensors and payloads from different manufacturers into the overall system are realistic challenges faced by the MUAV cooperative combat system in terms of operation, maintenance and upgrading. Open hardware and software technology has become an effective means to solve this problem, which can realize the seamless integration of software systems and hardware products produced by different manufacturers, thus simplifying the subsequent maintenance and upgrading work.

VI. REFLECTIONS AND IMPLICATIONS

A. Continually promote the collaborative combat between the fifth-generation fighter and UAV

In the future, the US military will still attach importance to the collaborative operations between the fifth-generation fighter jets and advanced UAVs. The US military is not only studying and testing the networking and intelligent upgrade of the fifth-generation fighter, but also actively exploring the formation combat of the fifth-generation fighter with stealth unmanned reconnaissance aircraft and unmanned bombers. The goal is to build and improve the overall collaborative combat ability of the fifth-generation fighter and UAV/UAV group based on information sharing. So that the fifth-generation fighter can effectively command and control the UAV or even the UAV group for combat.

B. Vigorously try to make unmanned transformation of manned fighter aircraft

The unmanned transformation of manned aircraft has huge potential advantages, which can not only save research and development costs, but also greatly improve the combat capability after transformation by taking advantage of the load advantage of manned aircraft. The DARPA announced that the artificial intelligence system developed by the agency has been installed on the F-16 fighter jet after a special unmanned modification, making it an artificial intelligence unmanned aircraft, which can be used as a "loyal wingman" to cooperate with the F-35 fighter jet, improving the combat capability of the US military to a certain extent.

C. Focus on the development and actual use of multifunctional large unmanned wingmen

Large unmanned wingmen usually have the advantages of high ceiling, long flight range, long flight duration and heavy load, which are suitable for long-distance combat. The United States is actively developing large unmanned loyal wingmen, such as the XQ-58A Val force, which can cruise at Mach 0.72, reach a maximum altitude of 13,000 meters, have a maximum range of 5,556 kilometers, a maximum takeoff weight of 2,700 kg, and a payload of 540 kg. It can form a formation with F-35 fighters or F-22 fighters. To carry out long-range strike and reconnaissance missions, which can be commanded by manned aircraft?

China should also speed up the research and development and practical use of large multi-functional unmanned wingmen with high ceiling, long range, long endurance and heavy payload, which requires continuous upgrading of existing UAV platforms to improve their tactical and technical performance and fully tap the combat potential of large multi-functional unmanned wingmen.

VII. CONCLUSIONS

This paper focuses on the research status, application cases and key technologies of the US military in the field of MUAV cooperative operations. The results show that the US military has long been committed to the research and development of MUAV cooperative operations in the future strong confrontation combat environment, and has made great progress in the exploration of cooperative operations theory, the research and development of key technology platforms, and the innovation of operation modes. By dynamically tracking the current situation of the US military in the field of MUAV cooperative operations, the direction and suggestions are presented for China to strengthen the construction of MUAV cooperative operations.

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