

The Application of Micro Coaxial Rotorcraft in Warfare: An Overview, Key Technologies, and Warfare Scenarios

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ABSTRACT The mode of future wars is mainly local wars and regional conflicts. This style of war is characterized by unpredictability and instability, which can happen anytime and anywhere. Once it happens, the battlefield is vast, short-range and fast-changing. In order to adapt to the characteristics of this kind of warfare, simple equipment and short reaction time have become two important factors in selecting weapons. Coaxial rotorcraft has been widely studied and applied in future wars due to its convenient carrying, strong environmental adaptability, and rich load capacity. This paper conducts an overview of the Coaxial rotorcraft. Furthermore, we also identify its key technologies, warfare scenarios and future directions. We anticipate that this survey can shed new light on the coaxial rotorcraft systems.

INDEX TERMS Micro aerial vehicles, coaxial, rotorcraft, warfare, application.

I. INTRODUCTION

Modern technology has changed the combat methods of various services and arms. The development trend of modernization, networking, informatization, and clustering of weapon systems is unstoppable. Information on the battlefield can be understood by the command center as soon as possible. Once a valuable target is found on the battlefield, the first strike will become the norm. These put forward higher requirements for the development of future weapon systems. Especially the weapon system based on the application background of chaotic and obscured space combat such as urban street fighting and jungle combat. How to shorten the time for value target discovery, how to process and judge this information in the first time, how to improve the accuracy of value target destruction, and how to evaluate the destruction effect in the first time have become the focus and direction of research in various countries.

First of all, the closer you get to the enemy on the battlefield, the more true the information you get, which is crucial to the study and judgment of the value of the target. However, approaching reconnaissance will place reconnaissance personnel and equipment within the detection range of the enemy's detection network. Therefore, the detection nodes in the system have small size, low noise and low

electromagnetic wave radiation and reflection characteristics to reduce the probability of being discovered and improve survivability. The location of the detection node release and control must be outside the detection range of the enemy's detection network. After the node is released, it can quickly "fly" to the deployment location to effectively guarantee the life safety of combat personnel. For streets, indoors, jungles, mountains and other places that are "inaccessible, and invisible", small detection nodes have irreplaceable advantages, and they are a necessary reconnaissance weapon for modern battlefield reconnaissance.

Furthermore, in order to improve the accuracy of battlefield situational awareness, similar network nodes in the system can detect suspicious targets through different detection methods or from different detection angles, which greatly enriches the target information. Once the network node that penetrates into the enemy is found by the enemy, it is easy to be destroyed. All of this requires a robust network to support, so a system network with strong anti-interference ability and reconfiguration ability when the network node is lost can greatly improve combat effectiveness.

Finally, after the detection node in the weapon system finds the target, it needs to carry the warhead to attack, or call the follow-up battle node to attack through the network, so that the target can be found and destroyed in time and the damage effect can be evaluated. Therefore, the main functions of each network node in the weapon system are different, so the

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diversity of the mission equipment that can be carried can also improve the efficiency of “checking”, “fighting”, and “transmitting”.

Micro Aerial Vehicles (MAV) [1]–[6] have attracted much attention because of their special applications. An important application is military reconnaissance, which can be equipped to soldiers’ squads for enemy reconnaissance and surveillance, monitoring chemical, nuclear or biological weapons, and reconnoitre inside buildings. It can be used in urban, jungle and other war environments. Because it has the advantages of easy to carry, simple operation and good security, it can be equipped in a large number of troops. In the nonmilitary realm, micro-air vehicles equipped with sensors could be used to search for disaster survivors, sources of toxic gases or chemicals, and kill crop pests. Because of the great advantages of the application of micro aircraft in modern military and civil aspects, it has been paid great attention and attention by all countries in the world, and has become the forefront of science and technology research in advanced countries.

II. DEVELOPMENT STATUS OF MICRO AND SMALL COAXIAL AIRCRAFT

The countries that are researching micro coaxial rotorcraft mainly include the Czech Republic, the United States, Israel, and China.

A. THE CZECH REPUBLIC “PHOLOS”

Czech Defense Systems has developed the “PHOLOS” (Fig.1) [7], a coaxial reverse propeller drone that has been described as a “sniper’s nightmare”. The Unmanned Aerial Vehicle(UAV) is characterized by portability, situational awareness and instant strike. As a drone for individual soldiers, it has a flying time of only five minutes and a remote control distance of one kilometer. Once the sniper’s location is roughly determined, the operator can release the PHOLOS and control it remotely using a tablet computer. It has a day and night camera that can send back footage in real time. It’s too quiet for snipers to pick up. When the operator sees the sniper through the camera, it can be manipulated to rush down, detonate the fragments carried by the warhead, complete the sniper kill. It doesn’t matter if someone is hiding in bushes or debris, the camera’s thermal infrared feature can easily spot them.

B. THE UNITED STATES “SPIRIT”

Ascent Aero Systems has developed the “Spirit” (Fig.2) [8], a coaxial rotorcraft UAV. It weighs only 1.36 kg and can carry 4.5 kg. It has two batteries and a payload weighing about 0.9 kg. The vertical rugged actuator configuration reduces the fuselage size to an absolute minimum. It can be carried in a backpack, making it truly portable. The endurance is up to 50 minutes. Because of its simple structure, excellent waterproof and dustproof performance, it has become the smallest, strongest and most environmentally friendly UAV



FIGURE 1. The Czech Republic “PHOLOS” coaxial rotorcraft.



FIGURE 2. The United States “Spirit” coaxial rotorcraft.

model of the company. It is designed to perform public security, military and intelligence missions.

C. THE ISRAEL “FIREFLY”

The tactical loitering ammunition “FireFly” (Fig. 3) [9], jointly developed by Rafael and the Ministry of Defense, weighs only 3kg, and provides concealed and precise attack capabilities for infantry in urban warfare. It can resist wind speeds of 37 km/h and the maximum cruising speed is 60 km/h. The aircraft can hover within a range of 500-1500 meters for up to 15 minutes, and can increase its endurance by quickly removing and replacing batteries during tactical reconnaissance missions.

D. THE CHINA “CH-817” AND “HENG”

China Aerospace Rainbow UAV Co., LTD developed the CH-817 miniature attack drone (Fig.4) [10]. The CH-817 has a power module in the top half, a coaxial twin rotor in the middle, a high-explosive warhead in the bottom half, and reconnaissance equipment in the bottom layer. The UAV weighs 850 grams, has a maximum flight speed of 18 meters/s, an endurance of 15 minutes, and a warhead of 50 grams.

TABLE 1. The overall parameters of “HENG” series aircraft.

Parameters	Value			
	029-300	029-100	029-50	029
Weight(g)	4500	1200	450	350
Size(mm)	$\Phi 108 \times L800$	$\Phi 70 \times L450$	$\Phi 58 \times L270$	$\Phi 58 \times L190$
Payload(g)	2000	600	50	100
Endurance(min)	60	70	25	56
Speed(km/h)	96	70	70	40



FIGURE 3. The Israel “FireFly” coaxial rotorcraft.

The UAV can take off and land autonomously in complex environments and has the function of environment awareness and obstacle avoidance. It can be used in narrow environments such as street fighting, and can be controlled by scattered platoon or small combat units to detect the movement of targets inside buildings and carry out high-precision deadly attacks on the enemy.

The “HENG” series aircraft(Fig.5) [11] are developed by Zhuhai Xuanji Technology. They are four models of 029-300, 029-100, 029-50 and 029, weighing from 300 grams to 3 kilograms. The product breaks through the technical bottleneck of UAV industry in the endurance time, and the endurance time is about twice as long as that of multi-rotor UAV of the same level. It has the characteristics of low noise, folding, easy to carry, modular and so on. It can achieve different task requirements by replacing different functional modules, providing all-round support and solutions for the military and police, public security, and special industries. The overall parameters of HENG series aircraft are shown in the Tab. 1

E. THE OPEN SOURCE “TDRONE”

Some aircraft enthusiasts have carried out innovative research on this aircraft. The typical representative is the Tdrone



FIGURE 4. The China “CH-817” coaxial rotorcraft.



FIGURE 5. The China “HENG” coaxial rotorcraft.

coaxial twin-propeller UAV (Fig.6) [12]. Tdrone is an open source aircraft developed in October 2015. The first generation of Tdrone was initially capable of flying in April 2016.

Tdrone uses two modified 1806 brushless motors to provide power, and two steering gears are used for swashplate control and yaw control. The flight control adopts CC3D. It is equipped with a two-axis stabilized sports camera. Tdrone uses a single-layer variable pitch structure. The lower rotor can change the pitch, and the upper rotor has a fixed pitch. The advantage of this layout is that it simplifies the mechanical structure to the greatest extent, which is conducive to the manufacture and later maintenance of the aircraft.



FIGURE 6. The open source “TDrone” coaxial rotorcraft.

F. THE ADVANTAGES OF COAXIAL ROTORCRAFT

Micro aircraft can be mainly divided into fixed wing and rotors. The main advantages of coaxial rotorcraft can be summarized as follows:

- 1) The structure is stronger and more compact. Multirotor aircraft are bulky and unwieldy. Coaxial rotorcraft can use a vertical cylindrical fuselage design, the body compact and strong.
- 2) Have higher flight efficiency. The main rotor does not need to be accelerated and decelerated frequently when the coaxial rotor produces pitch and roll control moment, which reduces the energy loss. For the same load and battery capacity, coaxial rotors have longer endurance than multi-rotor vehicles.

- 3) Have better quietness. For the same take-off weight, the coaxial rotor speeds are lower than the multi-rotor, resulting in less noise.
- 4) Fast modular load handling. Coaxial rotors are designed with a vertical cylindrical fuselage, enabling modular loading and unloading in the form of sleeves for quick load replacement and expansion.
- 5) Easy to carry and transport. Coaxial rotor blades can be folded and stored conveniently. There is no complicated arm folding locking mechanism of multi-rotor aircraft, so the fuselage is more orderly when folded, which is convenient for carrying and transportation.

The typical performance comparison of coaxial, fixed wing and multi - rotor are shown in Tab.2.

TABLE 2. The typical performance comparison of coaxial, fixed wing, and multi rotor.

Performance	Coaxial	Fixed wing	Multi rotor
Fly speed	△	○	△
Payload	△	○	⊗
Endurane	△	○	⊗
Takeoff environment	○	⊗	○
Space environment carrying	○	⊗	△

High: ○; Middle: △; Low: ⊗

III. KEY TECHNICAL FEATURES

Coaxial rotorcraft, like other large aircraft, have complex systems. A typical coaxial UAV system consists of an UAV platform, a data link system, a portable ground station, and an integrated support system as shown in Fig.7. UAV platform includes body structure, control and navigation system, energy and power system, mission payload system which can work at $-40^{\circ} \sim 70^{\circ}$; The data link system includes an integrated picture-digital radio to realize the functions of data transmission and image transmission; The ground station includes ground master control terminal and portable control terminal; The integrated support system consists of carrying equipment, indoor simulation training devices, packaging boxes, etc. The composition of the coaxial rotor UAV is shown in Fig. 8.

A. AERODYNAMIC ANALYSIS TECHNIQUES AT LOW REYNOLDS NUMBERS

Compared with conventional large aircraft, the aerodynamic characteristics of micro-small aircraft are quite different [13]–[17]. The Reynolds number of conventional large aircraft is very large, about 10^6 to 10^8 , and the viscous effect of air can be ignored. However, the Reynolds number is very small due to its small size and low flying speed, usually around $10^4 \sim 10^5$. At low Reynolds number, the viscous effect of air is significant, leading to some adverse effects, mainly manifested as an increase in drag and a decrease in lift-to-drag ratio.

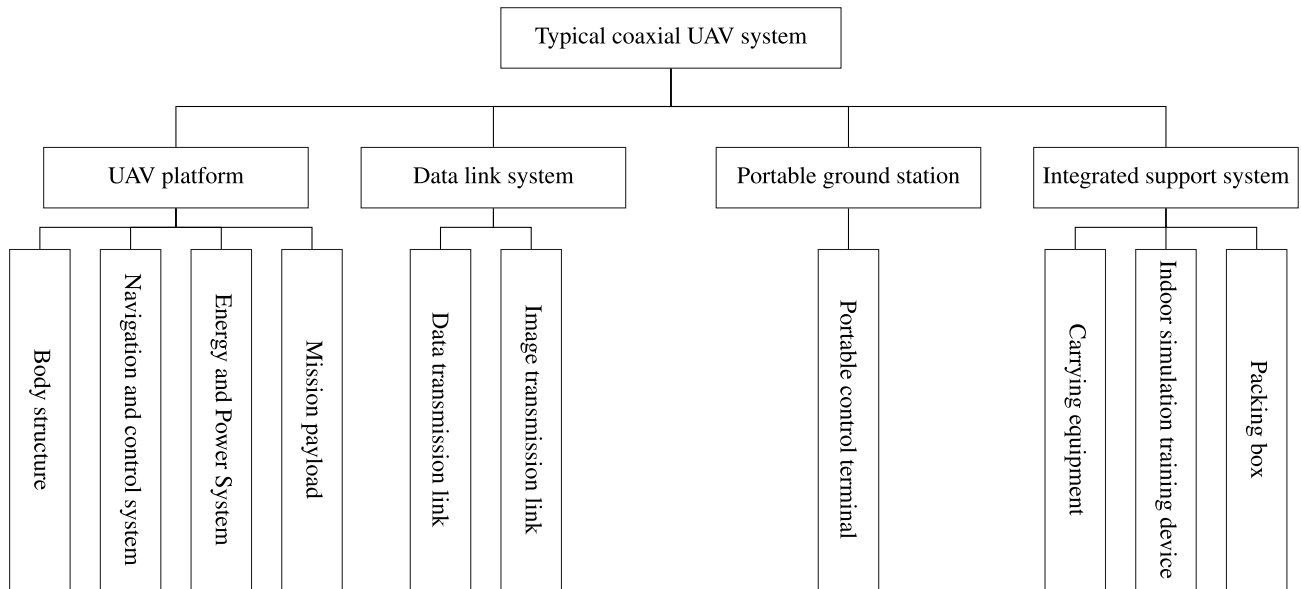


FIGURE 7. Typical coaxial UAV system.

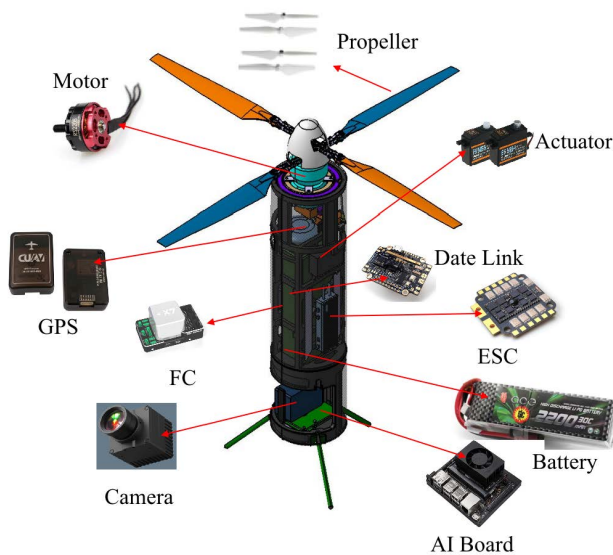


FIGURE 8. Coaxial rotor UAV.

B. MICRO POWER AND ENERGY TECHNOLOGY

The main requirements for the power and energy system [18]–[20] of the miniature aircraft are: light weight and small size; With high energy and power density, it can provide enough power for the aircraft; The vibration is small and does not interfere with the normal operation of the mission equipment; Low noise to ensure the concealment of the aircraft; The power system should be easy to start and highly reliable. From statistical data, the largest part of the mass distribution of micro-aircraft is the power system, which accounts for about 48%. The large size and weight of the power and energy system and low efficiency are important aspects that limit the

difficulty of reducing the size and weight of the micro-small aircraft.

C. ANTI-INTERFERENCE STABILIZATION TECHNIQUE

Due to its small size, low flying speed, low weight and moment of inertia, the micro-aircraft has a weak ability to resist air disturbances. The conventional proportional-integral-derivative (PID) control method of UAVs is no longer applicable [21], [22], [22]–[26]. Intelligent flight control methods must be established according to different types of micro-aircraft.

D. AUTONOMOUS NAVIGATION AND OBSTACLE AVOIDANCE TECHNOLOGY

Some mission modes set by the miniature aircraft determine that it often needs to fly out of the sight of the operator, which means that the miniature aircraft must have an autonomous navigation system [27]–[29]. The development of this system is extremely difficult. On the one hand, the control and navigation systems are very complex, and on the other hand, their volume and weight are required to be as small as possible.

E. PHOTOELECTRIC SENSING AND IMAGE TRANSMISSION TECHNOLOGY

The most commonly used function of miniature aircraft is as a reconnaissance and monitoring tool. Its intelligence information is provided by the detection system through photoelectric signals, and photoelectric sensors can provide complete real-time image intelligence information [30]–[32]. The ability to achieve high-quality image detection and recognition in a complex flight environment will be a key

technology for miniature aircraft to meet future information warfare.

F. COMPONENT MINIATURIZATION AND SYSTEM INTEGRATION TECHNOLOGY

The miniature aircraft is much smaller than the conventional aircraft in size, and its body volume and load-bearing weight are very limited, so the airborne equipment and payload that it can carry are greatly restricted. In order to achieve further miniaturization and weight reduction of micro-miniature aircraft, it is necessary to realize the miniaturization of various components and airborne components of micro-miniature aircraft [33].

G. COLLABORATION TECHNOLOGY

The characteristics of miniature aircraft determine that its own load capacity is limited, and the corresponding ability to perform tasks alone will also be limited [34]. Therefore, the use of cluster coordination to perform tasks by miniature aircraft will be the main way of using micro-miniature aircraft in the future. This requires a large number of aircraft to be networked and coordinated to perform tasks through the communication network. The network coordination of micro-aircraft mainly involves key technologies such as coordinated guidance and control, payload and data link.

IV. WARFARE SCENARIOS

In recent years, the application of UAV is more and more common in local wars and military conflicts, but with the rapid development of computer and new material technology, small UAV technology has certain advantages. UAVs have been seen in local wars in some parts of the world. The UAVs are having a big impact on warfare. Typical warfare scenarios are shown in Fig. 9, which mainly include the following warfare scenarios: Special Warfare, Synthetic Warfare, Multi-domain Warfare, Coordinated Warfare.

A. SPECIAL WARFARE

With urban street fighting and jungle fighting as the application background, an aircraft that can be carried by individual soldiers is needed. It has the characteristics of convenient carrying, quick response, freedom and flexibility. It can provide combatants with global information such as streets, jungles, and mountains at any time according to their needs, and perform “intelligent” precise strikes on important time-sensitive targets, greatly improving individual combat situation awareness and the ability to strike important targets.

B. SYNTHETIC WARFARE

Synthetic combat is mainly oriented to the future battlefield environment, and achieves the effect of one plus one greater than two through efficient coordination between multiple combat forces. The unified command center conducts unified operational deployment for all arms through the data returned by the frontier drones. UAV information is used to guide the

rear long-range firepower to conduct long-range strikes or implement close-range support to the target.

C. MULTI-DOMAIN WARFARE

The combat environment continues to change rapidly. Future military operations require collaborative, more effective, digital, safe, and cyber-resilient combat space across all domains of land, sea, air, and space. With the continuous penetration and integration of new combat domains such as space, cyberspace, electromagnetic spectrum and information environment into traditional combat domains such as land, sea, and air, future joint operations will have a global combat space.

D. COORDINATED WARFARE

At present, artificial intelligence is gradually becoming the first driving force for the qualitative change of war. Intelligent weapons and equipment represented by unmanned combat aircraft have received unprecedented attention and development. It is foreseeable that manned/UAV smart coordinated air combat. New combat forces will be an effective way to generate system combat capabilities. It will not only bring huge changes to the future air combat style, but also subvert and impact the aviation combat style. In the future, the combat functions of manned and UAV will complement each other. By integrating situational awareness and command cross-linking in intelligent coordinated operations, it will be more conducive to the combat decision-making of coordinated combat forces and quickly improve the ability to seize air supremacy.

V. DEVELOPMENT TREND RECOMMENDATIONS

As a powerful weapon on the battlefield in the future, the miniature coaxial rotorcraft should develop in the direction of miniaturization, intelligence and multi-function.

A. MINIATURIZATION

The micro-aircraft is cheap and light in weight, so it can equip each soldier without increasing the soldier’s load, which can greatly increase the soldier’s combat flexibility. It can be used not only for reconnaissance, but also for strengthening personnel contacts and information sharing. Unlike the current UAV system that requires multi-person operation, it does not need to be equipped with supporting equipment and vehicles. It is completely operated independently by the soldiers themselves, and has good concealment. When it is flying in the air, it is not only difficult to detect with the naked eye, but also difficult to detect by radar detectors. Even if it is “seen”, it is very likely to be regarded as an ordinary bird without attracting attention.

B. INTELLIGENT

In the future, it can be expanded to realize multi-UAV cluster networking and swarm attacks. The various aircraft are interconnected and coordinated through the data link to complete tasks that a single aircraft cannot complete, or to improve

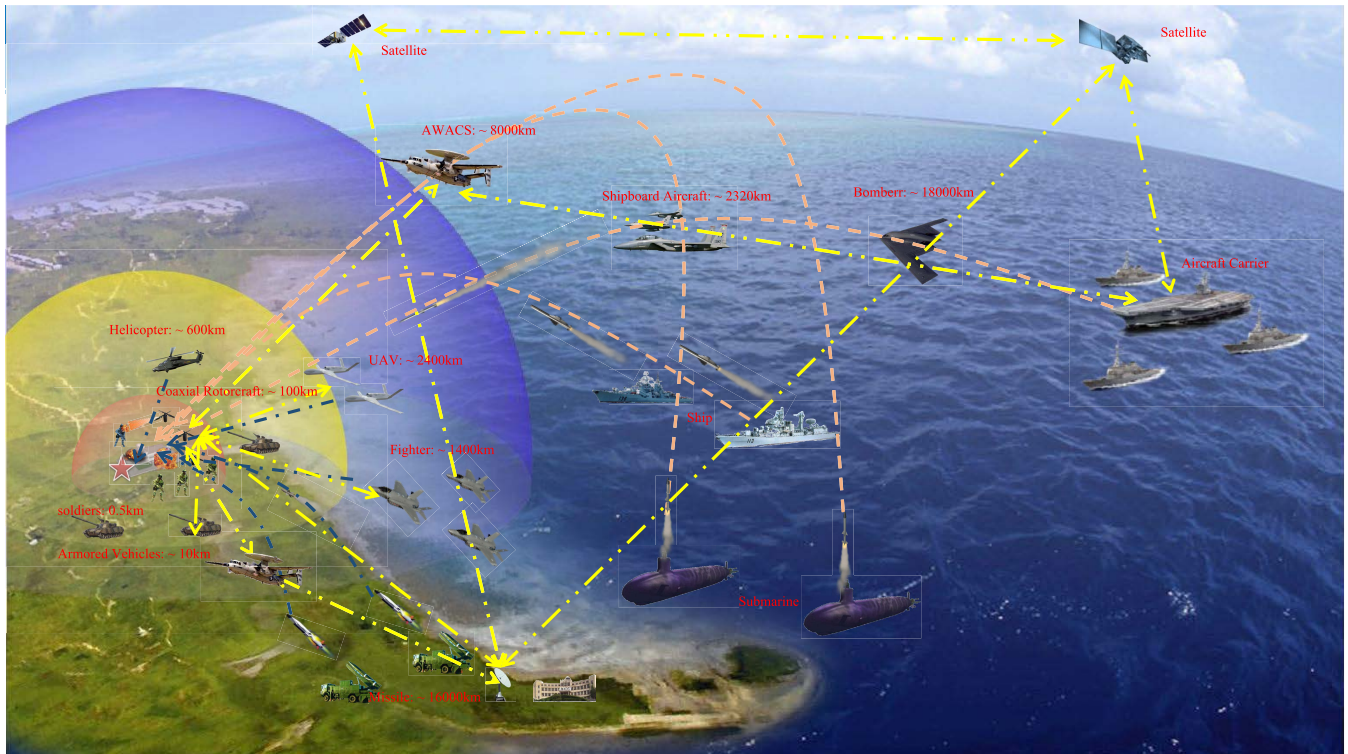


FIGURE 9. Typical warfare scenarios.

the efficiency of the entire system. Such a cluster has higher performance, higher reliability, and lower cost.

C. MULTI-FUNCTION

Adopting generalized and modular design ideas, and by configuring different modular task loads, different operational capabilities such as reconnaissance, surveillance, interference, battlefield damage assessment, and attack can be realized to meet different operational requirements. In order to adapt to different usage requirements, the UAV has the functions of single-person launch and vehicle launch. In the future, it can also achieve air launch and air recovery. It is also possible to develop serialized products of different weights to meet the needs of different users.

VI. CONCLUSION

In recent years, UAVs have been seen in local wars in some parts of the world. In this paper, we focus on the application of micro coaxial rotorcraft in warfare.

- 1) the main advantages of the coaxial rotorcraft are: The structure is stronger and more compact; Have higher flight efficiency; Have better quietness; Fast modular load handling and Easy to carry and transport.
- 2) Coaxial rotorcraft has complex systems. The key technical are: Aerodynamic Analysis Techniques at Low Reynolds Numbers; Micro Power and Energy Technology; Anti-interference Stabilization Technique; Autonomous Navigation and Obstacle Avoidance

Technology; Photoelectric Sensing and Image Transmission Technology; Component Miniaturization and System Integration Technology and Collaboration Technology.

- 3) The typical warfare scenarios of coaxial rotorcraft are: Special Warfare; Synthetic Warfare; Multi-domain Warfare and Coordinated Warfare.
- 4) The development direction of coaxial rotorcraft are: miniaturization; intelligent and multi-function.

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DECLARATION OF CONFLICTING INTERESTS

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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