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CHINA'S CONCEPTUAL APPROACHES TO COUNTER-UAS AND LESSONS DRAWN FROM RECENT CONFLICTS

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EXECUTIVE SUMMARY

The concept of unmanned warfare has gained prominence as technological advancements and the deployment of unmanned systems in recent conflicts have demonstrated their battlefield utility. PLA scholars and strategists have monitored these developments closely and formed a consensus view that future military operations will become increasingly dependent on intelligentized unmanned platforms. As articulated in a 2018 *China Military Science* article, PLA thinkers expect unmanned vehicles to "support joint operations in all domains and throughout the entire duration and the whole process of the combat cycle."[1] Building on this precept, PLA strategists increasingly view the development of unmanned systems and counter-unmanned system technologies and the mastery of unmanned operations and counter-unmanned system operations as strategic imperatives.

This paper focuses on the PLA's views and developing approaches to countering unmanned systems, with a focus on unmanned aerials systems (UAS), or unmanned aerial vehicles (UAVs). While the PLA recognizes the threat of unmanned systems in multiple domains of warfare, most strategic and operational discussion among PLA experts and strategists on unmanned warfare focuses on UAVs rather than other unmanned systems such as unmanned underwater vehicles. This focus is reflected in publicly available academic and technical writings on countering unmanned systems as well, where research and discussions are skewed towards countering UAV systems and tactics. As such, an examination of PLA and PRC defense research on counter-UAS offers a more extensive body of publicly available information from which to draw insights.

This paper draws upon a wide variety of official and unofficial sources of publicly available information, including various editions of the *Science of Military Strategy (战略学)*—volumes considered authoritative representations of the PLA's doctrinal views on warfare,[2] news reports from Chinese state media, academic and technical articles published in military and defense industry publications, and PLA instructional materials intended for military internal distribution only. While this paper covers the PLA's thinking and R&D on counter-UAS operational concepts, it is constrained by the scope and accessibility of available information sources and should not be regarded as an exhaustive or definitive representation of Chinese perspectives and capabilities.

This paper first provides a brief overview of the PLA's views on unmanned warfare before examining writings on counter-UAS operations, tactics, and technologies by PLA and PRC defense industry personnel. It then surveys the lessons learned by PLA and PRC defense industry observers from the employment of UAVs in recent conflicts and attacks. The paper then reviews shortcomings and limitations identified by PLA and defense personnel as they seek to build on existing operational and technical principles on counter-UAS and apply the lessons learned from their observations of UAS/counter-UAS in actual conflict. Lastly, the paper concludes with an assessment of the prospects and trajectories for the PLA's approach to counter-UAS operations and technologies in future conflicts.

This paper's key findings are as follows:

- PLA scholars and strategists believe that future warfare will be "unmanned, invisible, and silent" (无人, 无形, 无声) and expect intelligent unmanned combat systems to become critical components of modern military forces.

- Development of UAV systems and capabilities is informed by the belief of PLA strategists that the development of intelligent weapons and equipment is increasingly confrontational and explicitly targeted for conflicts between major powers. Accordingly, PLA and defense industry observers track foreign R&D efforts in unmanned systems and counter unmanned systems closely, particularly those made by the United States and Russia.[3]
- Writings reviewed for this paper suggest that PLA strategists have long viewed the United States as the uncontested leader in the use of unmanned systems in warfare—not only do they continue to track the U.S. military's employment of unmanned systems closely, U.S. UAV and counter-UAV doctrinal and strategy documents and U.S R&D efforts in UAS/counter-UAS technologies are intensely monitored as well, especially programs led by DARPA, the U.S. Navy, SCO and by defense contractors. Continued monitoring of PLA writings will be necessary to assess whether this continues to hold true in the wake of conflicts such as the Russia-Ukraine war.
- Recent conflicts, particularly the Nagorno-Karabakh conflict and the Russia-Ukraine war, have not only demonstrated the utility and effectiveness of UAV strikes, but have also served to underscore the necessity of robust counter-UAV strategies, tactics, and systems.
- Though PLA strategists are aware of the threats posed by high-altitude long endurance and medium-altitude long-endurance UAV systems, the bulk of counter-UAV research among PLA and defense industry research organizations appears focused on countering "low, slow, and small" (LSS/低慢小) UAVs and swarm technologies.[4] UAV swarm warfare is viewed by PLA and defense industry research personnel as a potential serious threat to the PLA's existing defensive combat capabilities.[5]
- PLA and PRC defense engineers candidly acknowledge that existing counter-UAV measures still face many technical challenges, including poor standardization, insufficient capabilities under complex environmental conditions, and unreliable performance during normal operations.[6]

PLA Views on Unmanned Warfare

PLA writings describe unmanned warfare as an example of intelligentized warfare, in which advanced technologies such as autonomous systems, AI, and robotics will fundamentally reshape the battlefield. PLA strategists and scholars recognize the growing role and prominence of unmanned systems in warfare and anticipate that unmanned combat platforms and highly autonomous weapon systems will feature as critical components of modern military forces.[7] In their view, future warfare will be "unmanned, invisible, and silent" (无人, 无形, 无声).[8]

While unmanned platforms have been a part of the PLA's arsenal since at least the 1950s, the PLA does not appear to have viewed them as a vital platform until the early 2000s.[9] The 2006 edition of the *Science of Campaigns (战役学)*, for instance, articulated only three use cases for the employment of UAVs: electronic warfare, long-range reconnaissance, and suppressing enemy air defenses.[10] A review of PLA writings suggests that the PLA's increased emphasis on and understanding of the utility of unmanned platforms in conflict was first galvanized by the successful deployment of these systems in actual conflict, particularly by the United States.[11]

Scores of scholars, strategists, and engineers within the PLA and the Chinese defense industry closely monitored the U.S. military's operations in the Middle East and Afghanistan, tracking as the role of UAVs in these conflicts expanded from reconnaissance missions to electronic suppression, communication relay, and kinetic strike.[12] It is evident from the body of publications released by the PLA that its understanding of the utility and potential of unmanned platforms were profoundly shaped first by these observations of U.S. unmanned operations.[13]

By 2013, authoritative texts like the *Science of Military Strategy* (2013) not only recognized the increasingly prominent role of intelligent unmanned systems, but argued that intelligent unmanned systems would partially replace the "vital strength within the armed forces" and that "unmanned, invisible, and silent" platforms and systems would gradually be employed massively on the battlefield.[14] These views were further cemented in the 2017 edition of the *Science of Military Strategy*, which described intelligent unmanned systems as an "indispensable battlefield force,"[15] and in the 2020 edition, which proclaimed that intelligent combat systems would inevitably become the dominant force on the battlefield. Notably, the 2020 edition of the *Science of Military* also articulated PLA strategists' belief that the development of intelligent weapons and equipment would be increasingly confrontational and targeted for conflict between major powers.[16]

While there is consensus among PLA strategists that unmanned systems will feature prominently in future battlefields, there does not appear to be specialized doctrine guiding the employment of these systems. While the 2020 edition of the *Science of Military Strategy* includes discussions on how unmanned systems could be deployed in various domains of warfare as well as general guidance for how the various PLA services could employ unmanned platforms, these discussions are constrained to the realms of theory and academia and lack specifics.[17]

Likewise, the PLA lacks a set of specialized doctrine guiding its approach to countering unmanned systems in future conflicts. The *Science of Military Strategy* (2020) again contains a few lines of general discussion on countering mid-to-low and ultra-low-altitude weapons, but groups UAVs among these mid-to-low and ultra-low altitude weapons alongside cruise missiles and armed helicopters. It does not prescribe a distinct set of guidelines for countering UAS.[18] Other strategic guidance texts make clear that the PLA anticipates unmanned platforms to be employed in defensive electronic warfare (EW) operations against enemy platforms, but do not describe their employment in a counter-UAV context.[19]

In contrast, academic and technical writings published in PLA and defense industry publications do lend insight into the PLA's thinking on counter-UAV operations and technologies. Though considered to be less authoritative sources as they are not published with the imprimatur of the PLA Academy of Military Sciences or the PLA National Defense University, the details contained within these writings are nevertheless valuable for understanding the evolving contours of the PLA's approach to UAS and counter-UAS strategies, tactics, and technologies.

PLA Views on Countering Unmanned Aerial Systems

PLA and PRC defense industry writings on both UAS and counter-UAS appear to be heavily informed by foreign developments. Virtually all articles reviewed for this paper featured lengthy and detailed surveys of foreign UAS and counter-UAS R&D initiatives and programs, with a focus on those in the United States and Russia. U.S. UAV and counter-UAV doctrinal and strategy documents and public U.S R&D efforts in UAS/counter-UAS technologies are closely monitored and documented, especially those programs led by DARPA, SCO, the Office of Naval Research (ONR), and private defense contractors.[20]

Counter-UAS Frameworks

Given the PRC's close referencing of foreign developments in counter-UAS, it is unsurprising that PLA and defense industry writings on basic technical principles for counter-UAS commonly reflect this close monitoring. PRC defense researchers and academics typically lay out familiar frameworks categorizing counter-UAS measures into three or four categories: detection, tracking, and early warning measures; jamming and spoofing measures; and kinetic strike and destruction measures.[21] A fourth category emerges in instances where camouflage and deception measures are distinguished from jamming and spoofing measures as a separate category.[22] In some cases, soft kill (non-kinetic) measures such as jamming and spoofing, and hard kill (kinetic) measures, i.e., kinetic strike, destruction, physical capture, etc., are described together broadly as counter-UAS disposal (处置) actions, i.e., mitigation, interception, or neutralization actions.[23]

Regardless of the classification scheme discussed in Chinese writings, the core elements of detection, soft kill (non-kinetic) measures., i.e., jamming and spoofing, and hard kill (kinetic) measures, i.e., kinetic strike, destruction, physical capture, etc., remain consistent. It is important to note that discussions of the above countermeasures in these writings do not appear to be presented in order of assessed preference; instead, they closely follow schemes laid out in foreign military strategy documents and private sector counter-UAS R&D materials.

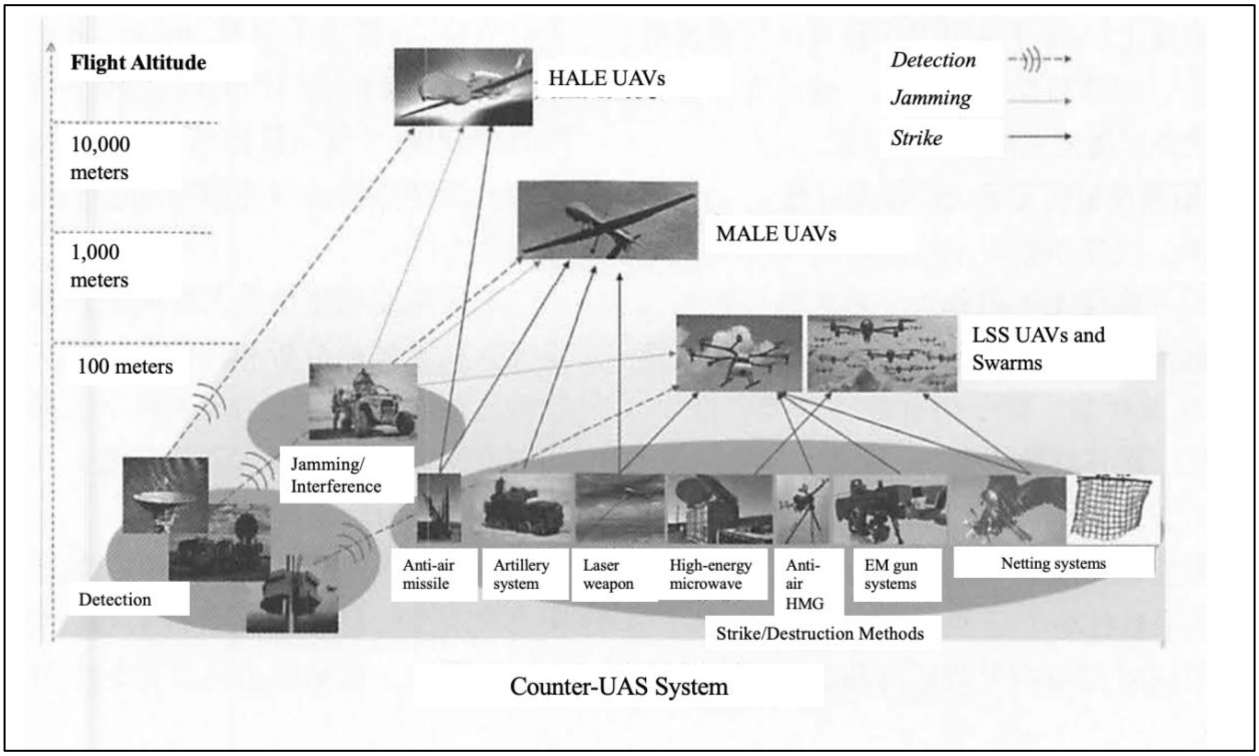

Figure 1: Elements of typical counter-UAS systems, as described by PLA engineers affiliated with an electronic warfare unit.[24]

This general framework has appeared in PLA writings since at least 2015, but has undergone adjustments as PLA strategists recognized the potential threats from "low, slow, and small" (LSS) (低慢小) UAV systems and drone swarms.[25]

COUNTERING "LOW, SLOW, AND SMALL" UNMANNED AERIAL THREATS

PLA and PRC defense personnel view LSS UAVs as a particularly thorny challenge. As engineers with the PLA Army Engineering University (中国人民解放军陆军工程大学) and PLA Unit 95269 summarized in 2018, traditional air defense tactics can be engaged against large- and medium-sized drones; however, LSS UAVs, as distinguished by their smaller size, small radar reflection area, low flight altitude, and slower flight speeds, are difficult to detect and attack, necessitating new equipment and combat methods.[26] Their small size and relatively weak signals also make them difficult to differentiate from birds and insects.[27] PLA and PRC defense industry researchers also point to the low cost and commercial availability of LSS UAVs, which makes acquisition easier and allows the technology to proliferate.[28] PLA writings anticipate that LSS UAVs will become even more ubiquitous.[29]

Outside of combat environments, articles authored by personnel within the People's Armed Police (PAP) make clear that LSS UAVs are viewed as a potential serious threat to domestic security. Researchers affiliated with the People's Armed Police (PAP) Engineering University (武警工程大学) cite the potential employment of LSS UAVs by adversaries or terrorists to attack and/or surveil government facilities, warehouses, and factories and critical infrastructure such as telecom facilities, power plants, and transportation systems.[30] Frequently highlighted in Chinese technical writings is the potential use of LSS UAVs to carry out targeted killings and assassinations.[31] Authors affiliated with the Nanjing Research Institute of Electronics Technology (南京电子技术研究所)[32] and the CETC Key Laboratory of IntelliSense Technology (中国电子科技集团公司智能感知技术重点实验室), for instance, referenced the intrusion of a North Korea drone into a non-fly zone surrounding South Korea's presidential office in December 2022.[33]

Countering UAV Swarms

Scholars affiliated with the AMS Institute of Defense Engineering (军事科学院国防工程研究院) and the PLA Army Academy of Artillery and Air Defense (陆军炮兵防空兵学院) wrote in 2019 on the new challenges for battlefield protection posed by UAV swarms, recognizing that detection and "complete" protection of a battlefield would become significant challenges. Notably, the authors described the emergence of swarm operations as a test for "system stability" and characterized the true threat of UAV swarms as their capability to destroy key nodes of a combat system, thereby causing system dysfunction and reduced combat effectiveness. The authors additionally highlighted the potential for hostile UAV swarms to act as "bait" and "suicide drones" to distract air defenses, leaving battlefield facilities vulnerable to attacks by traditional weapons systems.[34]

These fears have since been echoed by other PLA thinkers and strategists in more recent writings. Researchers affiliated with the PLA Air Force Early Warning Academy (中国人民解放军空军预警学院) similarly described UAV swarm combat as a disruption of traditional weapons systems and predicted that UAV swarm warfare would lead inevitably to new "combat styles." The researchers also assessed that swarm combat in a high-confrontation environment would pose new threats to the PLA's existing defensive combat capabilities.[35] PLA Naval Research Institute (中国人民解放军海军研究院) personnel likewise declared in a 2023 article that swarms would "gradually become a combat force that cannot be underestimated" and argued for the ensuant need to counter such a force.[36]

Outside of extremely technical research publications, PLA and defense industry writings on countering UAV swarms generally note that drone swarms present the same set of challenges for detection, tracking, and mitigation/interception as LSS UAVs. However, they also highlight the additional difficulties posed by their numerical advantage, inherent resiliency, and their potential for autonomous swarm formation and intelligent decision-making as AI technologies continue to mature.[37] As exemplified by a framework laid out by researchers affiliated with the PLA Naval Research Institute, counter swarm measures are typically classified in Chinese writings into three categories: detection and tracking, hard kill measures, and soft kill measures.[38] This classification scheme shares many elements with frameworks articulated for LSS UAVs, but notably incorporates the concept of deploying armed combat drones in swarms against swarms.

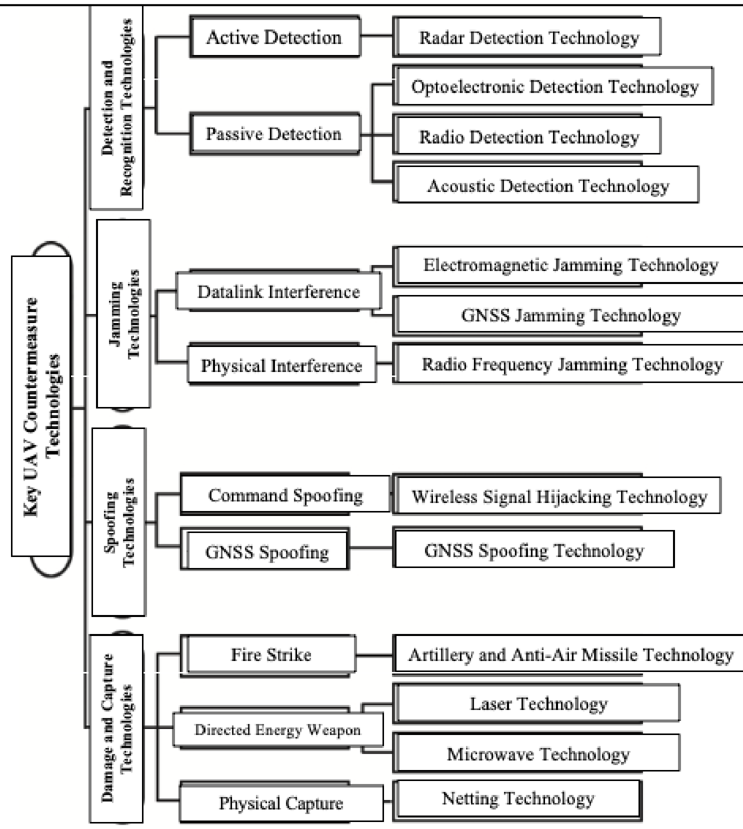

图 1　“低慢小”无人机反制技术分类

Fig. 1　Classification of “low, slow and small” UAV countermeasure technologies

Figure 2: Framework of LSS UAV countermeasures[39]

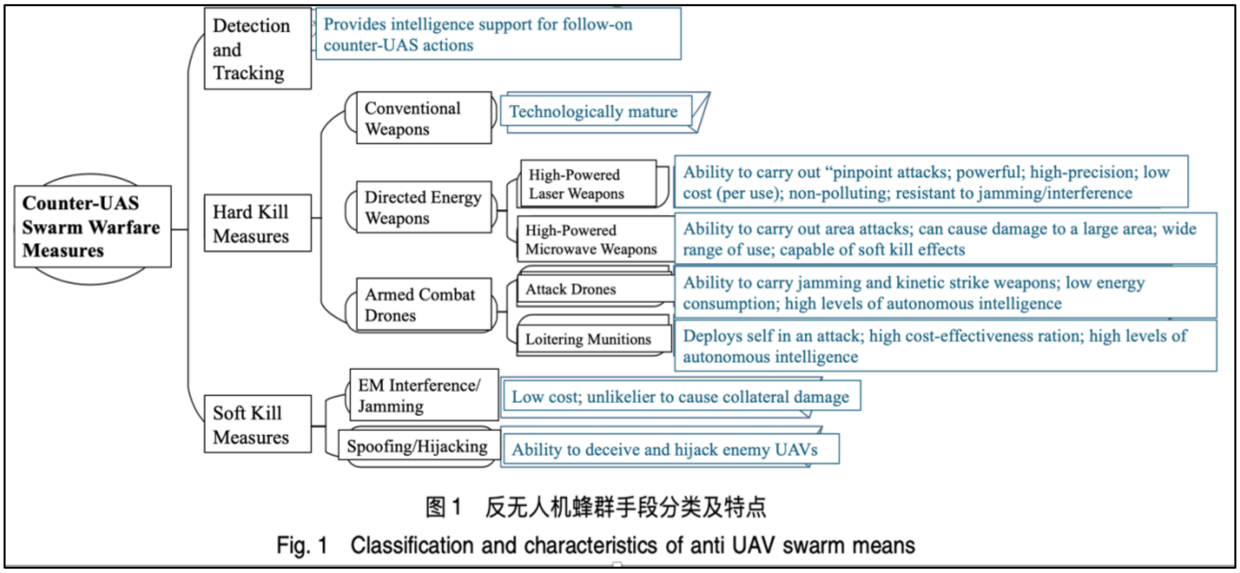

Figure 3: Framework for counter-UAS swarm measures, as laid out by researchers with the PLA Naval Research Institute. The authors noted the advantage(s) of each type of countermeasure in blue.[40]

DETECTION, TRACKING, AND EARLY WARNING

Detection, tracking, and early warning is recognized by Chinese defense researchers as the first step in any counter-UAS action.[41] Accordingly, detection methods for LSS UAVs appear to be a focus of research and investment, as gauged by funding codes noted on academic articles. As articulated by engineers affiliated with the North China Institute of Optoelectronic Technology (华北光电技术研究所) and CETC Electro-optics Technology (中电科光电科技有限公司), both aliases of the CETC 11th Research Institute,[42] defense against hostile LSS UAVs typically take place at close range – successful defense therefore requires counter-UAS systems to detect, identify, and mitigate/neutralize LSS targets rapidly.[43]

PLA and defense industry writings commonly break detection and tracking measures into four sub-categories: radar, photoelectric, radio, and acoustic detection measures and technologies.[44] Chinese engineers acknowledge that each has advantages and limitations, particularly as applied to LSS UAVs.[45]

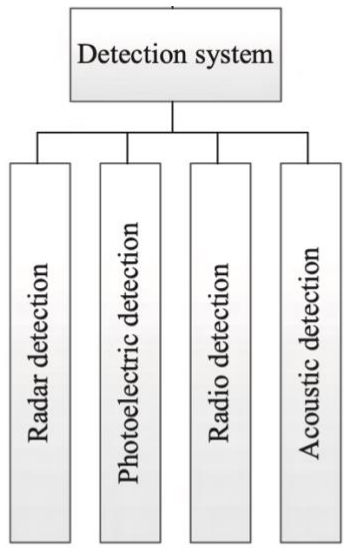

Figure 4: Categories of LSS detection technologies described by PRC defense engineers[46]

Radar Detection

While radar is still viewed as the most effective method to detect UAVs, PRC engineers note that radar detection methods suffer inherently from issues such as blind spots at short-range, low resolution, and susceptibility to electronic interference. The small size and small radar cross section of LSS UAVs make them even more difficult to detect; and even when detected, radar signal returns from LSS UAVs are weak, making them difficult to distinguish from flying birds and insects. Additionally, eliminating ground and sea clutter remains challenging for defense engineers, further complicating LSS UAV detection via radar.[47]

Photoelectric Detection and Tracking

Photoelectric technologies, which serve both detection and identification functions, are similarly challenged by LSS UAVs, which tend to emit lower levels of infrared radiation. This, too, tends to make LSS UAVs difficult to distinguish from birds and other aerial objects, such as kites, balloons, or consumer grade drones used for aerial photography. Additionally, photoelectric sensors tend to perform poorly in bad weather and are easily blocked by physical objects, limiting their utility in complex environments.[48]

Despite these weaknesses, PRC defense researchers assess that this class of technologies to be promising for LSS target detection as it performs well in low-altitude and complex electromagnetic (EM) environments. At the same time, however, researchers acknowledge that detection range and target recognition capabilities need to be improved in current photoelectric detection systems. Crucially, enhancements to target capabilities would depend on further advancements in AI to improve intelligent recognition capabilities.[49]

Radio Frequency Detection and Tracking

PLA and defense personnel consider radio frequency methods to be effective for LSS UAV detection and identification. By analyzing the frequency spectrum associated with flight control and transmission signals, these systems can accurately identify a hostile UAV's model and operational characteristics and locate the drone operator. Additionally, the compact and lightweight nature of radio detection equipment enhances their suitability for all-weather, allterrain, and rapid deployment scenarios. Researchers note, however, that the operational effectiveness of these systems is constrained by the limitations of their frequency band. As a result, detecting hostile UAVs that operate in radio-silence remains a significant challenge.[50]

Acoustic Detection and Tracking

Acoustic detection technology employs highly sensitive acoustic sensors to capture and analyze the sound emitted by drones in flight. These acoustic signals are then cross-referenced with UAV audio library to enable the detection and identification of UAVs. PRC defense researchers note, however, that sound emissions from LSS UAVs during flight are typically low, particularly during slow flight, which can make them difficult to detect. A further critique is that the effectiveness of acoustic detection systems is reliant on the quality and comprehensiveness of their audio fingerprint libraries, limiting their ability to identify UAVs not represented in a library. Additionally, the performance of these acoustic detection systems and sensors can suffer in noisy environments.[51] Despite these criticisms, PRC observers have nevertheless noted the effectiveness of Russia and Ukraine's respective acoustic detection systems in the conflict, suggesting that related technologies will continue to be an area of research and development.[52]

The table below presents a summary of the advantages and limitations (as described by PLA and defense industry engineers) of each category of detection technology described above.

Table 1: Advantages and Disadvantages of Main Categories of LSS Detection Technologies[53]

Detection Technology	Advantages	Disadvantages
Radar	• All-weather operation • Provides distance information • Long detection range • High detection efficiency	• High rate of false alarms • Susceptible to electronic interference • Has blind spots in close-range detection • Inadequate resolution • Low probability of identification
Optoelectronic	• High detection accuracy • Strong identification capability • Visualizes information • Passive detection	• Limited field of view, resulting in a reduced detection efficiency • Lack of distance information in a single installation hinders accurate assessment • Inadaptable to extreme weather conditions • Inability to detect non-line-of-sight targets
Radio	• All-weather operation • High detection efficiency • Ability to identify features of the EM spectrum, aircraft type, and operator location	• Limited detection accuracy • Inadequate performance against electromagnetically silent targets • Vulnerable to interference in complex electromagnetic environments

Acoustic	• All-weather operation • 360° detection, ability to detect targets behind obstacles	• Limited detection range • Suboptimal performance in noisy environments • Reduced acoustic detection accuracy • Challenges in target profiling

Due to the inherent limitations of each category of technology, PLA and defense industry personnel universally assess that building an effective counter-UAS detection and tracking system requires a composite approach, with a layered sensor architecture combining each category of detection technologies to enhance coverage, mitigate gaps, and ensure redundancy and resilience across the system.[54]

UAV Mitigation Measures

As noted previously, PLA and defense industry writings on counter-UAS mitigation actions typically classify these actions as either soft kill or hard kill countermeasures.

Soft Kill Countermeasures

EM interference technologies are described by some Chinese defense researchers as the most important class of drone mitigation/neutralization technologies at present. In a discussion of EM countermeasures against UAV swarms, PLA researchers affiliated with the PLA Army Aviation School's UAV Center (陆军航空兵学院无人机中心) list among the advantages of employing EM countermeasures the capability to affect, control, or damage multiple drones in a specified direction or area without collateral damage. The writers also highlighted the utility of EM countermeasures in enabling defenders to hijack a hostile drone and transmit false reconnaissance and intelligence to deceive the adversary.[55]

PLA and defense writings further break these measures down into two categories: jamming, i.e., GNSS, and radio frequency (RF) jamming technologies, and spoofing, i.e., signal hijacking and GNSS spoofing technologies.[56] Academic writings underscore the ability of these technologies to neutralize drones with limited physical destruction and collateral damage, which enables defenders to capture hostile drones for reverse engineering or intelligence gathering.[57] This capability is regarded as highly valuable—virtually all articles reviewed for this paper discussing soft kill jamming and spoofing technologies reference Iran's reported capture of a U.S. RQ-170 Sentinel drone in December 2011. Discussions of this incident in PRC writings take at face value Iran's claims that its cyberwarfare unit captured the drone through a combination of jamming and signal spoofing, and the incident is framed as an exemplar of the successful application of EM technologies against a UAV.[58]

In discussions of employing EM countermeasures against drone swarms, PLA and PRC defense researchers conceptually favor the idea of disrupting coordination among individual UAVs within a swarm. Techniques to achieve this include jamming and/or spoofing GNSS modules and disrupting or hijacking command datalinks.[59]

In terms of specific systems, a recent article authored by personnel affiliated with NUDT's School of Information and Communication (国防科技大学信息通信学院) argued that large-scale counter-UAS EW systems have limited tactical utility, and are only suitable and cost-effective for covering key locations and high-value strategic targets. The author instead argued in favor of portable counter-UAS EW systems, describing these smaller, hand-operated systems as the "inevitable choice."[60]

Despite the promise to which they ascribe EM countermeasure technologies, PLA experts also caution that the rapid development of UAV technologies means that their ability to resist EM interference and other soft kill measures is improving.[61] As articulated by the PLA Army Aviation School personnel referenced previously, the rapidly evolving nature of EM countermeasures and drone technologies means that EM countermeasures carry the risk of failure. As the authors write, EM countermeasures need to be specifically targeted, which requires acquiring the operating frequency of the hostile drone(s) targeted. Similarly, intrusion control measures are only effective if software vulnerabilities associated with the hostile drone are known. The authors also warn that GNSS jamming and spoofing techniques are only effective against drones that use satellite navigation. These risks mean that EM attacks alone may not be sufficient as a countermeasure to disrupt a hostile drone's operations completely. They also mean that a hostile drone targeted successfully during initial stages could be recaptured by the adversary.[62]

HARD KILL COUNTERMEASURES

In PRC counter-UAS writings, hard kill countermeasures, i.e., kinetic strike and destruction/mitigation/interception measures, are further broken down into conventional weapon, directed energy weapon, and armed combat drone technologies.[63]

Conventional Weapons

Despite the recognition that conventional weapon systems are not cost effective against low-cost drones, academic and technical writings make clear that PLA thinkers are not prepared to dismiss their use against UAS threats entirely.[64] In an article published in 2023, researchers from the PLA Army Engineering University acknowledged that conventional weapons are still the most mature class of counter-UAS technologies.[65] Rather than foregoing their use, PLA thinkers have appeared to explore ways to address the cost effectiveness problem. In an indication that the PLA, too, is likely to pursue the same types of solutions, researchers affiliated with the PLA Naval Research Institute observed in 2023 that foreign countries have focused on improving precision strike capability of conventional weapons, reducing missile costs, and investing in counter-swarm smart missile technologies to correct the cost imbalance associated with deploying such weapons against unmanned aerial threats. In addition to modifying conventional weapons, PLA engineers have also appeared to focus on directed energy weapons (DEW) such as high-powered laser and microwave weapons as hard kill counter-UAS solutions.[66]

Directed Energy Weapons

DEW countermeasures are viewed by PLA and defense industry experts as especially promising against drone swarms. Though they acknowledge that DEW technologies are still relatively immature, defense engineers frequently highlight the projected cost effectiveness per shot of DEW countermeasures as compared to kinetic fire interceptions.[67]

PLA writings also suggest that its interest in DEW countermeasures may be due in some part to the focus and large investments made in DEW as a counter-drone swarm solution by foreign countries, especially the United States. Nearly all writings on counter-UAS research reviewed for this paper discussed U.S. and Russian development initiatives in DEW, including the Leonidas

High-Power Microwave System developed by Epirus and the Tactical High-power Operational Responder (THOR) developed by the Air Force Research Laboratory (AFRL).[68]

Loitering Munitions and Armed Attack UAVs

PLA strategists increasingly recognize the value of loitering munitions and armed attack drones as vital components of a counter-drone swarm solution. Loitering munitions, or suicide drones, are seen as particularly effective due to their integrated reconnaissance and strike capabilities. These munitions can remain airborne for extended periods, allowing them to respond rapidly to threats.[69] Following Russia's example, PLA Army Academy of Artillery and Air Defense personnel have also discussed deploying loitering munitions in formations to serve as an aerial minefield against incoming hostile swarms.[70]

PLA and defense industry experts are also considering the use of attack drones equipped with hard and soft kill effectors of their own in hunter-killer roles to seek out and neutralize enemy UAVs or other platforms. Discussions of attack drones and their utility commonly reference the Raytheon Coyote system as an example.[71] The integration of AI in these platforms is frequently discussed in Chinese scholarly writings, with a focus on enhancing autonomous targeting and engagement capabilities. Additionally, these writings make clear that deploying these systems in swarms against hostile swarms is another concept of great interest to PLA and defense personnel.[72]

In this scenario, a defensive swarm of drones, equipped with weapons, sensors, and advanced communication systems, is deployed to intercept and neutralize an attacking swarm of enemy UAVs.[73] The defensive swarm operates as a cohesive unit, with individual drones working together to identify, track, and engage multiple targets simultaneously. Conceptually, AI-driven algorithms would enable the swarm to adjust its tactics dynamically, optimizing the distribution of firepower and resources in response to a hostile swarm.[74]

As with detection technologies, there is consensus among PLA academics and engineers that successful mitigation of LSS UAVs and UAV swarms requires a layered defense strategy incorporating both soft kill and hard kill measures, as no single capability or countermeasure can mitigate all threats.[75]

LESSONS LEARNED FROM RECENT CONFLICTS

For the PLA, recent conflicts have not only validated existing theoretical and operational concepts of UAS and counter-UAS operations, but have cemented their view of the role of unmanned systems in modern warfare. In addition to demonstrating the transformative potential of unmanned systems in warfare and the threat posed by swarm tactics, the PLA's view that effective counter-UAS systems must be multi-layered and incorporate a combination of hard and soft kill measures has been firmly reinforced.

We can expect however that just as the PLA's understanding of the utility of unmanned systems was expanded and refined by its observations of U.S. military operations in the Middle East and Afghanistan, its thinking on UAS and counter-UAS concepts will continue to evolve as these conflicts continue and feature increasingly sophisticated UAS/C-UAS technologies.

TRANSFORMATIVE POTENTIAL OF UNMANNED SYSTEMS IN MODERN WARFARE

For PLA and defense industry observers, the recent Nagorno-Karabakh conflict and the ongoing Russia-Ukraine war have to varying degrees demonstrated the transformative potential unmanned systems have in modern warfare as well as their potential impact to decide military outcomes.[76] As one PRC defense engineer wrote of the role of unmanned systems in the Nagorno-Karabakh conflict, "UAVs are no longer supplementary; their effectiveness in reconnaissance, direct combat, and operational flexibility has cemented their role as a primary element of modern warfare strategies. The same author pronounced that UAS/counter-UAS operations would become normalized, a belief echoed in other writings by PLA and defense industry researchers on recent conflicts.[77]

In discussions of the Nagorno-Karabakh conflict, PLA and defense researchers writing in defense industry publications have emphasized Azerbaijan's successful use of UAS against Armenian tanks, armored vehicles, and "Repellent-1" counter-UAS system produced by Russia.[78] One defense industry author noted that as of September 30, 2020, just days after the start of the conflict, TB-2 integrated reconnaissance and strike drones alone had destroyed more than 30 tanks and infantry fighting vehicles, 1 BM-27 rocket launcher, and 15 self-propelled air defense missile systems.[79] Particular emphasis is placed in these observations on the Nagorno-Karabakh conflict on the relative low cost of the UAS employed by Azerbaijan and their ability to damage or destroy much more costly tanks and air defense systems. As another expert observed, "relatively inexpensive small attack drones can change the nature of warfare traditionally dominated by ground combat and conventional air forces. Even advanced weapon systems, tanks, radars, and surface-to-air missiles have vulnerabilities…"[80] Several papers reviewed for this paper, including one authored by researchers affiliated with the PLA Army Engineering University and PLA Unit 95269, likened the cost imbalance inherent to employing costly conventional weapons against cheaper drones to "using a cannon to kill a mosquito."[81]

THREAT AND POTENTIAL OF SWARM TACTICS AND TECHNOLOGIES

Conflicts such as the Syrian civil war and the 2019 drone attacks on Saudi oil facilities demonstrated the threat of LSS UAV systems[82] and the burgeoning potential of swarm tactics and technologies to upend traditional weapons systems and disrupt modern combat dynamics.[83]

One favorite example of PLA writers demonstrating the potential of swarm tactics is the January 2018 attack on Russia's Hmeimim base and naval base at Tartus by 13 armed drones thought to have been sent by Syrian rebels. According to the Russian defense ministry, Russian forces ultimately foiled the attack, bringing down seven of the drones with air defense systems and six with its EW units. Researchers affiliated with the PLA Army Engineering University and PLA Unit 95269 wrote that the incident had demonstrated the great potential of UAV swarm tactics, though they acknowledged that the drones deployed in the attack lacked the characteristics of true UAV swarms. To these PLA researchers, the attacks also underscored the importance of counter-UAS operations, especially the development of effective countermeasures against LSS UAVs and drone swarm tactics.[84] Defense engineers additionally highlighted Russia's use of both hard kill and soft kill measures.[85]

Specifically, researchers affiliated with the China Aerospace Academy of Systems Science and Engineering (中国航天系统科学与工程研究院), aka the CASC 12th Academy (中国航天科技集团公司第十二研究院), noted that though Russia had successfully neutralized the drones, it was only able to do so with layered defenses, including soft-kill electronic countermeasures and hard-kill measures such as anti-aircraft missiles. The authors additionally assessed that wide-scale GPS jamming at the bases had probably not been in place, suggesting if such measures had been implemented, the drones may not have even been able to fly within range of Russia's air defense systems.[86]

IMPORTANCE OF ROBUST, MULTI-SENSOR, MULTI-LAYERED COUNTER-UAS SYSTEMS

While recognizing the successful employment of UAVs by Azerbaijani forces in the Nagorno-Karabakh conflict, PLA and defense industry experts have also avoided attributing Azerbaijan's victory in the conflict solely to its successful employment of UAS. Indeed, a key takeaway of many PRC analyses on the conflict is the importance of robust counter-UAS systems and air defenses. Experts point to deficiencies and failures in Armenia's counter-UAS strategies and systems, including its use of outdated Soviet air defense systems, as decisive factors in its defeat.[87] As researchers affiliated with the PAP Engineering University concluded bluntly, "traditional air intercepts or ground-based strikes are not suitable for countering 'low, slow, and small' drones due to the high cost of the air defense systems and the challenges these systems have in countering multiple targets."[88]

Indeed, PLA researchers stress that despite their performance in the conflict, the TB-2 drones employed by the Azerbaijani forces were not particularly sophisticated—they lacked self-defense electronic warfare capabilities and also had inherent deficiencies such as poor maneuverability and slow speed. Though decisive in the conflict against Armenian forces, PLA researchers note that the drones were quickly shot down by more sophisticated air defense systems when they flew near Russian military bases and Iranian airspace, an observation that seems to suggest that outcomes may not have been so heavily in Azerbaijan's favor had Armenian forces had better counter-UAS and air defenses in place.[89]

Another commonly examined aspect of the employment of UAVs in the conflict by Chinese researchers is the successful use of loitering munitions by Azerbaijan's forces. One defense industry engineer characterized the Nagorno-Karabakh conflict as the first large-scale practical use of one-way attack drones. Assessing their performance, the engineer wrote that the drones' effects exceeded prior assessments made by military experts. The Israeli-made Harop drones were small, lightweight, and relatively cheap, making them convenient for large-scale use. They were able to patrol the battlefield for long periods and were effective in striking high-value targets and fortifications. Further, they proved difficult to defend against. The psychological impact of the drones was also highlighted in analyses, with scholars assessing that the Harop drone's ability to make sudden and unexpected strikes played a significant role in undermining the morale and resistance of the Armenian forces.[90]

ESCALATING UAS/COUNTER-UAS ARMS RACE

A recurring theme in PLA writings on recent conflicts involving UAVs is the belief that future conflicts will be increasingly defined by an intensifying UAS/counter-UAS arms race. Numerous papers reviewed for this analysis emphasize the heightened intensity of UAS and counter-UAS operations observed in the Russia-Ukraine war. Researchers from NUDT's College of Information and Communication and the PLAAF Aviation University have argued that the flexible adaptation of new UAV tactics and countermeasures by both sides has not only fueled the conflict but also accelerated the pace of technological and tactical innovation in unmanned aerial warfare.[91]

There is a consensus among PLA and defense industry experts that the future will see continuous advancements in swarm tactics, which will in turn drive the development of increasingly sophisticated swarm countermeasures.[92] This recognition has underscored the necessity for ongoing innovation in UAS and counter-UAS operational concepts, tactics, strategies, and technologies. For Chinese military and defense personnel, the Russia-Ukraine war in particular has highlighted the critical importance of such innovation in achieving and maintaining operational superiority in future conflicts.[93] The recognition that the United States, Russia, and Europe have made low-cost swarms a focus of development both in terms of both technology levels and production capacity no doubt contributes to a heightened sense of urgency for PRC experts.[94]

The next section discusses weaknesses and limitations articulated by PLA and defense researchers as they build on existing technical principles, technologies, and operational thought on counter-UAS and attempt to apply lessons learned from observing UAS/counter-UAS employment in actual conflict.

Technical Challenges and Limitations

As discussed previously, there is strong consensus among PLA and defense researchers that the solution to countering LSS UAVs and swarm tactics and technologies requires the development of multi-layered integrated detection, tracking, identification, and defense systems comprised of a variety of hard (kinetic) and soft kill (non-kinetic) measures. Recent conflicts have only solidified this consensus.[95]

Many PLA and defense industry writings acknowledge that advanced technologies such as artificial neural networks and machine learning are crucial enabling technologies to facilitate tracking, identification, and decision-making in determining the optimal mitigation/interception action.[96] At least one paper, written by authors affiliated with the PLA National University of Defense Technology's College of Information and Communication (国防科技大学信息通信学院) and the PLA Air Force Aviation University (空军航空大学), alleges that AI technology has already been employed by the United States in drone combat as part of its support to Ukraine in the Russia-Ukraine war. Specifically, the authors claim that the U.S. military and other assets used AI to process and analyze information transmitted by drones and satellites and optimize strikes.[97]

Unsurprisingly, technical details for constructing such systems tend to be vague.[98] Aside from national security concerns, at least part of the reason why descriptions of these systems seem more akin to theoretical conceptualizations is likely because they remain just that for the moment—theoretical concepts.

Chinese defense researchers in this field acknowledge that existing counter-UAS measures still face many unaddressed technical challenges. Weaknesses cited include poor standardization, insufficient capabilities under complex environmental conditions, and unreliable performance during routine use.[99] Core command and control systems to coordinate various counter-UAS weapons and equipment are also lacking.[100]

Integrating AI technologies into the complex defense networks conceptualized in PLA and defense industry writings is an even more formidable challenge. Researchers have yet to solve critical issues related to detection, intelligent information integration, interception, and platform integration—key components needed to realize the multi-sensor, multi-layered, end-to-end counter-UAS solutions envisioned.[101]

PAP engineers acknowledged as recently as 2022 in an assessment of domestic counter-UAS development that counter-UAS technologies for more complex environments such as the marine environment and urban areas are still immature, with the latter being a particular challenge for detection, tracking, and target identification due to physical signal obstruction from buildings, ground debris, and birds, as well as from noise and electromagnetic interference. The engineers also assessed countermeasure technology and equipment for drone swarms to be immature, pointing to the same technical challenges with detection and tracking.[102]

In a 2022 study, researchers from the PLA Air Force Early Warning Academy stressed that the key to future drone swarm warfare lies in possessing the most advanced algorithms and acknowledged that the United States holds significant scientific and technological advantages in this area.[103] In this vein, researchers affiliated with the PLA Army Aviation School's UAV Center have underscored the importance of monitoring foreign developments in human-machine swarm technologies, including specifications, functionality, and usage, to enhance the PRC's own capabilities.[104]

PRC defense engineers also recognize shortcomings in their development of DEW technology. While they observed that DEWs have been deployed on the battlefield and have shown potential, researchers from the Northwest Institute of Nuclear Technology emphasized in 2022 that significant challenges remain. They assessed the power-to-weight ratio of these weapons to be inadequate for battlefield needs and conceded that developments to miniaturize and lighten the systems were still required.[105] PLA Army Aviation School's UAV Center researchers seemed to echo these sentiments in 2019 with the critique that existing DEW countermeasure systems were physically large.[106] Observations made by PLA Army Engineering University personnel on Russian DEW weapons such as the Peresvet laser similarly characterized the system as ground-based with limited use scenarios due to its weight and power consumption.[107]

Overall, PLA and defense experts acknowledge that while significant progress has been made in technical development for counter-UAS systems, substantial gaps and challenges remain.

Conclusions/Implications

PLA strategists and researchers have closely monitored foreign developments in UAS and counter-UAS technologies and tactics and have drawn significant insights from the successes and failures of their employment in conflicts such as the Nagorno-Karabakh conflict and the ongoing Russia-Ukraine war. These observations have appeared to not only validate existing theoretical and operational concepts within the PLA but have also served as a catalyst for refining its approach to unmanned warfare.

In particular for counter-UAS, while PRC military researchers and engineers have long emphasized the need for counter-UAS approaches that mirror those discussed in the United States and elsewhere, namely, AI-enabled multi-layered integrated systems comprised of advanced detection, tracking, and early warning systems and soft and hard kill countermeasures, recent conflicts have seemingly demonstrated the vital importance of a multi-layered, multimodal approach. While this understanding will certainly mean continued investments into ever more sophisticated EM interference methods, directed energy weapons, and AI technologies to keep pace with strategic competitors and achieve operational superiority in future conflicts, PRC military and defense researchers have also seen the high impact of less sophisticated, relatively low-cost systems and countermeasures.[108]

In their pursuit of innovation in advanced counter-UAS operational technologies, PRC researchers candidly acknowledge significant gaps between theory and practical implementation and recognize the ongoing technical challenges that must be overcome to achieve the intelligent, integrated end-to-end counter-UAS capability conceptualized in their writings. In particular, the complexities of operating in urban environments and maritime domains present significant obstacles to detection, tracking, and target identification. The integration of AI and machine learning technologies is seen as a critical enabler for overcoming these challenges, particularly in enhancing the intelligence, autonomy, and decision-making speed of detection and mitigation systems. The PLA is thus expected to continue to stress innovation and investment in key areas including AI-enabled dense and small object detection, image enhancement, data processing, and decision-making.

Lastly, while the PLA currently lacks specialized doctrine for countering unmanned systems, it is likely to have oriented aspects of its counter-UAS approach for a possible confrontation with the United States and its allies.[109] Given its of heavy monitoring of foreign UAV operations and technological developments, the PLA can be expected to intensify its collection efforts on U.S. military and private sector UAS capabilities as part of its counter-UAS strategy. Outside of collections on technical specifications, command and control, and personnel, we can surmise based on its emphasis on early warning, detection, and identification that the PLA will seek to augment its libraries of drone profiles with the emissions signals and/or acoustic signatures of unmanned systems likely to be employed by the U.S. and U.S. allies in a future conflict.

ENDNOTES

[1] Li Jiafu (李家福), “A Study of the Operational Employment of Unmanned Aerial Vehicles” (无人机作战运用研究), China Military Science (中国军事科学), 2018 (6).

[2] Various editions of the Science of Military Strategy have been published by the PLA Academy of Military Sciences (中国人民解放军军事科学院) (2013) and the PLA National Defense University (中国人民解放军国防大学) (2015, 2017, and 2020). The Academy of Military Sciences is the PLA’s premier think tank for operations and military strategy, while the National Defense University serves as the PLA’s top military education institution for training flag officers.

[3] Dang Aiguo (党爱国), Wang Kun (王坤), Wang Yanmi (王延密), and Wang Xiaobing (王晓兵). “The Impact of UAVs Swarming Fighting Concept Development on Attack and Defense in Future Battlefield” (无人机集群作战概念发展对未来战场攻防影响), *Tactical Missile Technology* (战术导弹技术), 2019 (1).

[4] Wang Yuanhuang (王远航), Research on the Combat Application of Micro-UAV and Its Response Strategy (小微型无人机作战应用及其应对策略研究), *Ship Electronic Engineering* (舰船电子工程), 2022 (7).

[5] Zhu Tao (朱涛), Li Linjie (李淋杰), and Ling Haifeng (凌海风), “Combat Use and Insights from UAVs in the Syrian War” (无人机在叙利亚战争中的作战运用与启示), *Aerodynamic Missile Journal* (飞航导弹), 2018 (11); Deng Jing (邓静), Chen Peng (陈 鹏), Weng Chengxiang (翁呈祥), et al., “Research into the Jamming Strategy of Measurement and Control Link to UAV Swarm” (对无人机蜂群测控链路干扰策略研究), *Shipboard Electronic Countermeasure* (舰船电子对抗), 2022, 45 (3).

[6] Li Liya (李丽亚), He Song (何松), Zhao Zhu (赵柱), et al., “Construction and development of LSS target prevention and control system” (“低慢小”目标防控体系建设及发展思路), *Infrared and Laser Engineering* (红外与激光工程), 2023, 53 (12).

[7] Xiao Tianliang (肖天亮), Lou Yaoliang (楼耀亮), Kang Wuchao (亢武超), and Cao Renzhao (蔡仁照). *The Science of Military Strategy* (战略学), (Beijing: National Defense University Press (国防大学出版社), 2015).

[8] Shou Xiaosong (寿晓松), ed., Science of Military Strategy (战略学), (Beijing: Military Science Press (中国人民解放军军事科学研究院), 2013).

[9] China's Military Strategy (中国的军事战略); http://www.81.cn/dblj/2015-05/26/content_6507373.htm.

[10] Zhang Yuliang (张玉良), ed., Science of Campaigns (战役学), Beijing: National Defense University Press (国防大学出版社), 2006.

[11] Wu Bing (吴兵), “A Study of Army Transformation in Developed Countries” (发达国家陆军转型发展问题研究), *China Military Science* (中国军事科学), 2013 (3).

[12] Shou Xiaosong, *Science of Military Strategy*, 2013.

[13] Zhao Tianying (赵天缨), “On Advancing the Development of High-and New-Technology Weapons and Equipment” (论推进高新技术武器装备发展), *China Military Science* (中国军事科学), 2013 (3).

[14] Shou Xiaosong, *Science of Military Strategy*, 2013.

[15] Xiao Tianliang (肖天亮), ed. The Science of Military Strategy, 2017. ed. (战略学) (Beijing: National Defense University Press, 2017).

[16] Xiao Tianliang (肖天亮), ed. The Science of Military Strategy, 2020. ed. (战略学), (Beijing: National Defense University Press, 2020).

[17] Ibid.

[18] Ibid.

[19] Zhang Pengfei (张鹏飞); Introduction to Joint Campaign Information Warfare (联合战役信息作战概论), (Beijing: National Defense University Press (国防大学出版社), 2012.

[20] Hu Qiaolin (胡乔林), Jiao Shijun (焦士俊), Liu Jianhao (刘剑豪), et al., "Research on Counter US UAV Drone Combat" (反美军无人机蜂群作战问题研究), *Aerodynamic Missile Journal* (飞航导弹), 2021 (12); Sun Zhao (孙昭), He Guangjun (何广军), and Li Guangjian (李广剑), "Research on American anti UAV technology" （美军反无人机技术研究), *Aerodynamic Missile Journal* (飞航导弹), 2021 (11).

[21] Xue Meng (薛猛), Zhou Xuewen (周学文), and Kong Weiliang (孔维亮), "Research status and key technology analysis of anti UAV system" (反无人机系统研究现状及关键技术分析), *Aerodynamic Missile Journal* (飞航导弹), 2021 (5); Liu Yuwen (刘玉文), Liao Xiaobing (廖小兵), et al., "Basic Frame Constructing of Counter UAV Technique" (反无人机技术体系基本框架构建), *Sichuan Ordnance Journal* (四川兵工学报) (now *Journal of Ordnance Equipment Engineering* (兵器装备工程学)), 2015, 36 (10).

[22] Liu Yuwen et al., *Basic Frame Constructing of Counter UAV Technique*, 2015

[23] Zhou Mo et al., *Research on foreign anti-UAV swarm warfare*, 2023.

[24] Xue Meng et al., *Research status and key technology analysis of anti UAV system*, 2021.

[25] Liu Yuwen et al., *Basic Frame Constructing of Counter UAV Technique*, 2015; Xue Meng et al., *Research status and key technology analysis of anti UAV system*, 2021.

[26] Zhu Tao et al., *Combat Use and Insights from UAVs in the Syrian War*, 2018.

[27] Jiang Rongqi (蒋镕圻), Bai Ruokai (白若楷), Peng Yueping (彭月平), "Overview on Detection Technology of LSS UAV Targets (低慢小无人机目标探测技术综述), *Aerodynamic Missile Journal* (飞航导弹), 2020 (9).

[28] Zhang Jiajun (章佳君), Qian Xiaochao (钱晓超), Zhou Jinpeng (周金鹏), et al., "Simulation-based Exploratory Analysis of Drone Air strike on Saudi oilfields" (基于仿真的无人机空袭沙特油田事件探索性分析), Journal of System Simulation (系统仿真学报), 2020, 23 (6).

[29] Zhang Huawei (张华伟), Liu Haipeng (刘海鹏), and Shi Chunpeng (史春鹏), "Research on Development of Anti Low-altitude and Slow-speed Small Un- manned Aerial Vehicle Technology" (反低慢小无人机技术发展研究), *Electrooptic Technology Application* (光电技术应用), 2021, 36 (3).

[30] Zhang Hao (张皓), Wu Husheng (吴虎胜), and Peng Qiang (彭强), "Summary of Development Requirements of "Low, Slow and Small" UAV Countermeasure Equipment and Key Technologies" ("低慢小"无人机反制装备及关键技术发展需求综述), *Aero Weaponry* (航空兵器), 2022, 29 (5).

[31] Li Liya (李丽亚), He Song (何松), Zhao Zhu (赵柱), et al., "Construction and development of LSS target prevention and control system" ("低慢小"目标防控体系建设及发展思路), *Infrared and Laser Engineering* (红外与激光工程), 2023, 53 (12).

[32] The Nanjing Research Institute of Electronics Technology is also known as CETC 14th Research Institute. It primarily engages in the R&D of radar, ECM, and information systems.

[33] Han Changxi (韩长喜), Deng Dasong (邓大松), Chen Zhuo (陈卓), et al., "Development of field air defense system under the threat of low-slow and small UAV" (低慢小无人机威胁下的野战防空系统发展研究), *Tactical Missile Technology* (战术导弹技术), 2023 (5).

[34] Dang Aiguo et al., *The Impact of UAVs Swarming Fighting Concept Development on Attack and Defense in Future Battlefield*, 2019.

[35] Deng Jing et al., *Research into the Jamming Strategy of Measurement and Control Link to UAV Swarm*, 2022.

[36] Zhou Mo (周末), Sun Haiwen (孙海文), Wang Liang (王亮), et al. "Research on foreign anti-UAV swarm warfare" (国外反无人机蜂群作战研究), *Command Control & Simulation* (指挥控制与仿真), 2023, 45 (2).

[37] Hu Leigang (胡雷刚) and Li Wuzhou (李五洲), "Physical Countermeasures of Bee Colony for UAS" (无人机蜂群物理反制手段), *Unmanned Vehicles* (无人机), 2019, 33 (4).

[38] Zhou Mo et al., *Research on foreign anti-UAV swarm warfare*, 2023.

[39] Zhang Hao et al., *Summary of Development Requirements of "Low, Slow and Small" UAV Countermeasure Equipment and Key Technologies*, 2022.

[40] Zhou Mo et al., *Research on foreign anti-UAV swarm warfare*, 2023.

[41] Zhang Hao et al., *Summary of Development Requirements of "Low, Slow and Small" UAV Countermeasure Equipment and Key Technologies*, 2022.

[42] North China Institute of Optoelectronic Technology and CETC Electro-optics Technology are both aliases of the CETC 11th Research Institute, which is engaged in the development of laser and infrared technologies for military use.

[43] Li Liya et al., *Construction and development of LSS target prevention and control system*, 2023.

[44] Ibid.

[45] Ibid.

[46] Ibid.

[47] Zhang Hao et al., *Summary of Development Requirements of "Low, Slow and Small" UAV Countermeasure Equipment and Key Technologies*, 2022; Li Liya et al., *Construction and development of LSS target prevention and control system*, 2023.

[48] Zhang Hao et al., *Summary of Development Requirements of "Low, Slow and Small" UAV Countermeasure Equipment and Key Technologies*, 2022; Li Liya et al., *Construction and development of LSS target prevention and control system*, 2023.

[49] Li Liya et al., *Construction and development of LSS target prevention and control system*, 2023

[50] Zhang Hao et al., *Summary of Development Requirements of "Low, Slow and Small" UAV Countermeasure Equipment and Key Technologies*, 2022.

[51] Ibid.

[52] "Counter-UAS Combat Methods in the Russia-Ukraine Conflict" (俄乌冲突中的反无人机作战方式), *China Aviation News* (中国航空报), 28 June 2024.

[53] Li Liya et al., *Construction and development of LSS target prevention and control system*, 2023.

[54] Ibid.

[55] Hu Leigang (胡雷刚) and Xu Yanyan (徐艳艳), "Electronic Countermeasure of Bee Colony for UAS" (无人机蜂群电磁反制手段), *Unmanned Vehicles* (无人机), 2019, 33 (4).

[56] Zhang Hao et al., *Summary of Development Requirements of "Low, Slow and Small" UAV Countermeasure Equipment and Key Technologies*, 2022.

[57] Ibid.

[58] Zhou Mo et al., *Research on foreign anti-UAV swarm warfare*, 2023; Hu Leigang and Xu Yanyan, *Electronic Countermeasure of Bee Colony for UAS*, 2019.

[59] Hu Qiaolin et al., *Research on Counter US UAV Drone Combat*, 2021.

[60] "UAS and Counter-UAS Systems, Which Will Remain Laughing at the End" (无人机与反无人机系统，谁会笑到最后), *China Youth Daily* (中国青年报), 25 July 2024, http://zqb.cyol.com/html/2024-07/25/nw.D110000zgqnb_20240725_1-06.htm.

[61] Zhou Mo et al., *Research on foreign anti-UAV swarm warfare*, 2023.

[62] Hu Leigang and Xu Yanyan, *Electronic Countermeasure of Bee Colony for UAS*, 2019.

[63] Zhou Mo et al., *Research on foreign anti-UAV swarm warfare*, 2023.

[64] Han Changxi et al., *Development of field air defense system under the threat of low-slow and small UAV*, 2023

[65] Ling Haifeng, *Current developments and implications of Russian anti-UAV equipment*, 2023.

[66] Zhou Mo et al., *Research on foreign anti-UAV swarm warfare*, 2023.

[67] Han Changxi et al., *Development of field air defense system under the threat of low-slow and small UAV*, 2023

[68] Zhou Mo et al., *Research on foreign anti-UAV swarm warfare*, 2023.

[69] Wang Jiakai (王家凯) and Ying Yun (应运), Research on Operational Application and Development Trendency of Unmanned Equipment (无人化装备作战应用及发展趋势研究), Ship Electronic Engineering (舰船电子工程), 2021 (11).

[70] Wang Xiaomeng (王笑梦). "New Characteristics of Counter-UAV Air Defense Operations" (反无人机空防作战新特点), 中国国防报,26 July 2022. http://military.people.com.cn/n1/2022/0726/c1011-32485825.html.

[71] Zhou Mo et al., *Research on foreign anti-UAV swarm warfare*, 2023.

[72] Zhang Bangchu (张邦楚), Liao Jian (廖剑), Kuang Yu (匡宇), et al., “Research Status and Development Trend of the United States UAV Swarm Battlefield” (美国无人机集群作战的研究现状与发展趋势), *Aero Weaponry* (航空兵器),2020, 27 (6).

[73] Zhou Mo et al., *Research on foreign anti-UAV swarm warfare*, 2023.

[74] Ibid.

[75] Ibid.

[76] Huang Yu (黄宇), Ding Dong (丁东), Wang Feng (王峰), et al. “Enlightenment on logistics equipment support from the “Three Modernizations” integrated operation in the Nagorno-Karabakh Conflict” (纳卡冲突对“三化”融合作战后装保障的启示), *National Defense Technology* (国防科技), 2022, 43 (1); Wang Changhai (王昌海), “Review of Unmanned Combat Capabilities in the Nagorno-Karabakh Conflict” (纳卡冲突中无人作战能力评述), *Aerodynamic Missile Journal* (飞航导弹), 2021 (1); Feng Yang (冯杨), Jiang Chao (蒋超), and Cui Yuwei (崔玉伟), “UAV Operations and Enlightenments in the Russia-Ukraine Conflict (俄乌冲突中无人机作战运用及启示), *Defence Industry Conversion in China* (中国军转民), 2022 (23).

[77] Chen Li (陈黎). “From the Nagorno-Karabakh Conflict: The Future Development of UAV and Anti-UAV Warfare” (从纳卡冲突看无人机 / 反无人机作战的未来发展), *National Defense Science & Technology Industry* (国防科技工业), 2021 (1); (Feng Yang et al., 2022).

[78] Jian Dao (剑道), “The Use of Drones in the Nagorno-Karabakh Conflict” (纳卡冲突中的无人机运用), *Military Digest* (军事文摘), 2021 (1).

[79] Wang Changhai, *Review of Unmanned Combat Capabilities in the Nagorno-Karabakh Conflict*, 2021

[80] Jian Dao, *The Use of Drones in the Nagorno-Karabakh Conflict*, 2021.

[81] Zhu Tao et al., *Combat Use and Insights from UAVs in the Syrian War*, 2018; Wang Yuanhang (王远航), “Research on the Combat Application of Micro-UAV and Its Response Strategy” (小微型无人机作战应用及其应对策略研究), Shipboard Electronic Engineering (舰船电子工程), 2022, 42 (7).

[82] LSS targets generally refers to UAS with a flight altitude below 1 kilometer, a flight speed of less than 200 kilometers per hour, and a radar reflection area of less than 2 meters squared.

[83] Zhang Jiajun et al., *Simulation-based Exploratory Analysis of Drone Air strike on Saudi oilfields*, 2020

[84] Zhu Tao et al., *Combat Use and Insights from UAVs in the Syrian War*, 2018.

[85] Han Changxi et al., *Development of field air defense system under the threat of low-slow and small UAV*, 2023

[86] Hao Yannan (郝雅楠), Kong Chao (孔超), and Guan Xiaohong (关晓红), “Analysis of Combat Employment and Development Trend of Foreign UAVs: Thoughts on the Nagorno-Karabakh Conflict” (国外无人机作战运用与发展态势分析——关于纳卡冲突事件的思考), *National Defense Science & Technology Industry* (国防科技工业), 2021 (2).

[87] Jian Dao, *The Use of Drones in the Nagorno-Karabakh Conflict*, 2021; Wang Changhai, *Review of Unmanned Combat Capabilities in the Nagorno-Karabakh Conflict*, 2021.

[88] Zhang Hao et al., *Summary of Development Requirements of “Low, Slow and Small” UAV Countermeasure Equipment and Key Technologies*, 2022.

[89] Chen Li, *From the Nagorno-Karabakh Conflict: The Future Development of UAV and Anti-UAV Warfare*, 2021.

[90] Chen Li, *From the Nagorno-Karabakh Conflict: The Future Development of UAV and Anti-UAV Warfare*, 2021; Wang Xiaomeng, *New Characteristics of Counter-UAV Air Defense Operations*, 2022.

[91] Zhang Hongbi (张洪碧), Meng Fansong (孟凡松), et al., “UAV Operational Application and Its Enlightenment in a Certain Regional Conflict” (某局部冲突中无人机作战运用及启示), *Command Control & Simulation* (指挥控制与仿真), 2022, 44 (4).

[92] Zhou Mo et al., *Research on foreign anti-UAV swarm warfare*, 2023.

[93] Zhu Tao et al., *Combat Use and Insights from UAVs in the Syrian War*, 2018; (Feng Yang et al., 2022).

[94] Hao Yannan, *Analysis of Combat Employment and Development Trend of Foreign UAVs: Thoughts on the Nagorno-Karabakh Conflict*, 2021.

[95] Wang Yuanhang, *Research on the Combat Application of Micro-UAV and Its Response Strategy*, 2022; Zhou Mo et al., *Research on foreign anti-UAV swarm warfare*, 2023.

[96] Wang, *Research on the Combat Application of Micro-UAV and Its Response Strategy*; Zhou Mo et al., *Research on foreign anti-UAV swarm warfare*; and Sun Zhao et al., *Research on American anti UAV technology*, 2021.

[97] Zhang Hongbi et al., *UAV Operational Application and Its Enlightenment in a Certain Regional Conflict*, 2022

[98] Li Liya et al., *Construction and development of LSS target prevention and control system*, 2023; Zhang Jiajun et al., *Simulation-based Exploratory Analysis of Drone Air strike on Saudi oilfields*, 2020.

[99] Li Liya et al., *Construction and development of LSS target prevention and control system*, 2023.

[100] Ling Haifeng, *Current developments and implications of Russian anti-UAV equipment*, 2023.

[101] Li Liya et al., *Construction and development of LSS target prevention and control system*, 2023.

[102] Zhang Hao et al., *Summary of Development Requirements of "Low, Slow and Small" UAV Countermeasure Equipment and Key Technologies*, 2022.

[103] Hu Qiaolin et al., *Research on Counter US UAV Drone Combat*, 2021.

[104] Hu Leigang and Xu Yanyan, *Electronic Countermeasure of Bee Colony for UAS*, 2019.

[105] Wu Taotao (吴涛涛), Wang Qian (王茜), and Wu Xiaolong (武晓龙), "Winning mechanism and application characteristics of directed energy weapons in unmanned warfare" (定向能武器在无人化战争中的制胜机理及运用特点), *National Defense Technology* (国防科技), 2022, 43 (5).

[106] Hu Leigang (胡雷刚) and Xue Jing (薛静), "Directed Energy Countermeasure of Bee Colony for UAS" (无人机蜂群定向能反制手段), *Unmanned Vehicles* (无人机), 2019, 33 (4).

[107] Ling Haifeng, *Current developments and implications of Russian anti-UAV equipment*, 2023.

[108] "Counter-UAS Combat Methods in the Russia-Ukraine Conflict" (俄乌冲突中的反无人机作战方式), *China Aviation News* (中国航空报), 28 June 2024.

[109] Hu Qiaolin et al., *Research on Counter US UAV Drone Combat*, 2021.