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Technological Perspectives of Countering UAV Swarms

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ABSTRACT

Conventional AD systems have been found less effective for countering UAVs and loitering munitions. This has necessitated the development of counter-UAV systems with different functionalities. A cluster of armed UAVs as swarm formations has further rendered the conventional AD systems far from effective, emphasizing the need to consider countering swarms as the most crucial element in new-generation aerial threat mitigation strategies. In this paper, the capabilities of UAV swarms and vital military assets exposed to such attacks are identified. To protect the vital assets from aerial swarm threats, ideal system characteristics of a counter-UAV (C-UAV) swarm system to overcome the challenges are discussed. Currently available acquisition & engagement technology is analyzed and the application of these systems to counter swarm applications is brought out. New requirements are discussed and a conceptual design of a layered system is derived which can handle a large spectrum of aerial threats including a swarm of UAVs. This system is expected to have a higher rate of engagement and can be designed with low-cost network-integrated systems.

Keywords: UAV swarms; Counter-UAV swarms; Air-defence systems; Heterogeneous swarm configurations; Layered engagement; Autonomous targeting; Soft kill; Hard kill; Target classification; Air-burst ammunition; High energy laser; RF sensing; EO/IR sensor; High power microwave; Anti-aircraft guns

1. INTRODUCTION

As evident in the recent conflicts, well-seasoned armies with their conventional systems and tactics could not anticipate the impact of armed UAVs and loitering munitions on the battlefield. Low-cost, simple-to-operate UAV base weaponry has proliferated widely on the battlefield with varying objectives[1-5]. Most of the present conventional Air-Defence (AD) systems and strategies stand less effective against UAVs exposing vital assets and personnel to such surprise attacks[6-7].

Recent advances in two interconnected critical technologies related to artificial intelligence and machine autonomy have pushed the concept of 'UAV Swarms' which are made up of cooperative, autonomous UAVs that react to battlefield scenarios to accomplish multiple tasks[8]. This development is altering the fundamental rules and nature of warfare in the 21st century where instead of using long-range precision strikes, swarms will be used as a close-in attack means for targets far behind the frontline once considered difficult to penetrate or strongly guarded vital assets[9]. Swarm technology is emerging as the most impactful disruptive technology in the military domain, which will impact almost all domains of conventional defence systems and their deployment tactics. With technological advancement in miniaturizing electronics, sensors and improved communication capabilities, swarms would be used extensively across different domains of the military in the coming years. Featuring simple system design, ease of deployment and larger target outreach, UAV Swarms would be on the frontline of the battlefields.

Countering UAV Swarm attacks for the protection of vital military importance assets would require redesigning Air-Defence systems with a fresh perspective, emphasising low observable large numbers of low-cost distributed threats. Like any other emerging new weapon on the battlefield, efficient and effective countermeasures against the swarm of UAVs will take some time to become widely available as mainstream equipment.

In this paper, an effort is made to understand the requirements of a counter-swarm system and a feasible counter-UAV (C-UAV) Swarm solution is derived which could neutralize such an attack to protect point assets. Systems universality, effectiveness in handling heterogeneous UAV swarm configurations and dynamic scaling to handle larger swarms are emphasised in the study.

2. SWARM THREAT

Swarm technology uses a large number of smaller similar or heterogeneous systems which can interact among themselves to achieve desired collective tasks. Similar to nature, where a large number of individual elements such as birds, fish or insects may collectively work together to accomplish something useful that cannot be done by an individual or any group of non-cooperative individuals[10].

UAV swarm gains its firepower capability from the capability of its agents. UAVs have precision strike capability using laser or GPS-guided weapons; armour defeating

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capability; unguided drop bomb deployment; anti-radiation guided attack; target identification and illumination for secondary weapons; and denying GPS or communications through jamming.

UAV swarm-based attack is relatively simple to develop and cheaper to produce, enabling large-scale use on the battlefield. UAV swarm is a unique weapon system with battle-worthy features like:

- High Survivability: A swarm incorporating both large and small UAVs equipped with different payloads offers better survivability against defences and provides a greater degree of mission flexibility.
- Lower Cost of Engagement: Cost-effective way to successfully execute many types of missions earlier handled by expensive missiles or fighter aircraft.
- Higher Kill Probability: A swarm increases the probability of success of a mission as there are built-in redundancies in the concept.
- Multi-Mission Usage: A swarm can be used in multiple missions such as automatic target engagement, Anti-access/Area-Denial (A2AD), airspace dominance, as ISR sensors, teamed operations with manned platforms and providing armed cover to surface missions.
- Compatible with Multiple Payloads: The UAV swarm platform's compatibility with multiple payloads will allow each type of target on the ground – vehicle, bunker or personnel – to be engaged most efficiently.

Doctrine for swarming attacks might have a centralized strategy but its distinguishing characteristic is the coordinated widely distributed attack approach using smaller units in pulse-like tactics, which makes its command and control structure flatter with loosely controlled smaller units[11]. Such attacks would require close-in strategies to meet the objectives, with different shapes or sizes to reach the targets and then approach them in the best way suitable to overwhelm its defence.

2.1 Types of Attacks

Employing a low-cost solution with large numbers of agents is the fundamental nature of UAV swarms. Therefore UAVs primarily of Class-I and Class-II[12] would be used in large numbers with or without a few larger Class-III UAVs in command & control or standoff suppression of air defence roles.

High altitude and long endurance capable UAVs of Class-IV and Class-V are bigger systems which fly at high speed and can be very well acquired and engaged by conventional AD systems, more over would be expensive to be deployed as part of swarms in large numbers and therefore are not addressed in our study.

This study primarily addresses threats from Class-I, Class-II and Class-III of UAVs in heterogeneous swarm configuration, thus presenting the most difficult challenge on the battlefield, which would require unique solutions.

UAV swarms could be broadly divided based on their command and control architecture, such as centralized control, hierarchical control and distributed control[13]. Central control architecture has a single command & control node controlling all the other agents. If this node is compromised some other agent takes its role and becomes the central node. This architecture is robust but limits the number of swarm agents or their geographical distribution. Hierarchical control follows a hierarchical command & control architecture within a swarm. This approach lacks robustness and handling of dynamic scenarios requiring swarm reconfiguration. Distributed architecture lacks any leader for controls. Decisions are taken collectively by all or multiple dominant agents of the swarms. This architecture provides the required robustness in the swarm and scalability to larger numbers possible.

2.2 Assets Vulnerability

Present AD systems are designed to acquire and engage fighter aircraft, helicopters and other aerial threats which are fast-moving and comparatively larger than UAV-based weapons. Like other UAVs, swarm agents extend much smaller RCS signatures on surveillance systems making them extremely difficult to detect using conventional radars. Also due to their slower speeds and low-altitude flights their radar signal returns are difficult to distinguish among the signals from background clutter and birds. Smaller size further constrains the system's accuracy requirement for engagement by conventional AD weapons in a cost-effective way. Present Air-Defense systems are not capable of simultaneous acquisition and engagement of hundreds of aerial threats in highly dense flights. Most of the assets at the frontline like armoured personal carriers, tanks, artillery deployments, troop deployments, mobile short-range AD weapons etc. are well distributed in a large area and would be very expensive to engage with swarms of UAVs. These assets would mostly be targeted by individual UAVs or loitering ammunition only.

High-value assets behind the frontline like medium to long range Air-Defense installations, Radar sensors, SAM missile deployments; ammunition depots; convoys of troop movements; and communication towers are most probable to be targeted by the UAV swarms. Further deep inside the adversary's territory assets like major airbases and related infrastructure, command and control centres, communication infrastructure, ships/submarines at the naval dockyards and supply chain infrastructure including oil dumps can be targeted by the UAV swarms.

3. COUNTERING UAV SWARMS

AD strategies and systems need to be adapted, changed or completely redesigned to meet the requirements of neutralising /disabling UAV swarm threats. Unlike C-UAV systems operating in an urban environment[14-15], battlefield deployment requires a robust system with high kill probability. When faced with UAV swarms AD systems need to acquire and engage a large number of threats within a very small time overcoming the challenges and constraints in its detection and engagement. Universal AD system should be able to acquire, engage and cue or get cued from other systems on the network for Aircraft, Helicopters, Loitering munitions, Class-I, II & III of UAVs, UAV Swarm attacks and Cruise missiles.

3.1 Layered C-UAV Engagement Techniques

Techniques for different classes of UAVs, comprising both hard kill and soft kill mechanisms for a greater probability of neutralizing these threats are suggested[15].

3.2 Net-Centric Design for Sensor and Weapons Integration

Countering the large threat load during swarming attacks can be efficiently managed by networked systems exchanging target information with other systems and controlling any available secondary weapons systems like universal AD missile launchers or C-RAM (Counter-Rocket, Artillery and Mortar) systems for engagements.

3.3 Autonomous without Man-in-Loop Operations

Human operators in the engagement cycle would introduce large delays. Acquisition, identification and engagement tasks during the UAV swarm attack could be assisted by AI-enabled automated operations.

3.4 Modular and Open Architecture

Modular configuration with the option of scaling up its sensor or engagement capabilities on the fly with a network of additional assets would be required to rapidly reconfigure an AD network to handle UAV swarms as the need arises.

3.5 Higher Rate of Engagement

C-UAV swarm systems need to provide a higher rate of engagement to handle a large number of threats during swarm attacks. A system with faster azimuth & elevation angle spanning, rapid rate of fire and rapid reloading capabilities would be ideal.

3.6 Lower Cost of Engagement

As the UAVs and loitering munitions would be produced in bulk and are comparatively inexpensive compared to other conventional aerial threats, their low-cost engagement would enable deployment in large numbers and cost-effectively handling of a larger number of swarming UAVs.

4. DETECTION AND ACQUISITION ASPECTS OF AN OPERATIONAL C-UAV SWARM SYSTEM

Smaller size, slower speed and low-altitude flights make UAVs extremely difficult to be differentiated from the birds or background environment, limiting their reliable long-range detection by any sensor[16,6]. The detection systems should have the capabilities of passive and active detection, which mean that detection from the UAV's emissions of RF signals, IR radiation or sound produced, along with the capability of illuminating the targets for detection.

The maximum range of detection should provide the required time for the system to identify and prioritize the threat for engagement for the system to neutralize more threats in a time-multiplexed manner. The threats are required to be detected from a larger range of about 8 km for smaller UAVs (Class-I and Class-II) and 20 km to 50 km for Class-III UAVs. The capability of the maximum number of targets detected and tracked simultaneously by the sensor will decide its capability to handle swarm attacks. As 48 UAV swarm is already demonstrated, therefore at least simultaneous handling of 50 targets or more capacity is expected[17].

Additionally, the system should effectively detect and acquire heterogeneous threats in a complex environment. The actual target is required to be detected and reported within the minimum accuracy requirements of the weapon system or its dedicated tracking sensor. The accuracy requirement will considerably increase with the increase in range. Since tactics adopted will be of surprise in nature, all-weather conditions detection capability is desirable. Performance is expected to be maintained in all types of precipitation and environment consisting of heavy clutter from the background. Capabilities of discriminating UAVs from birds and vehicular traffic, as well as identifying the type or class of UAV to further aid its tracking and neutralization is desired.

4.1 Radar-Based Detection

For C-UAV swarm systems the important radar features for the detection of swarms are as follows.

4.1.1 Relatively Shorter-Range and Elevated Deployment

Due to Line of sight non-availability at longer ranges to detect low altitude targets, a relatively shorter range distributed radar sensors configuration is best suited. Elevated radar deployment with at least an 8 km detection range for Class-I & II UAVs and at least a 40 km detection range for Class-III UAVs would be optimum.

4.1.2 Higher Frequencies

Due to the low velocity and low altitude flight of UAVs, their discrimination against background clutter would require higher Doppler and angular resolutions. Higher frequencies improve these parameters for the given dwell durations and antenna sizes.

4.1.3 Static Multi-Faced Antennas

The longer dwell time requirement for higher Doppler resolutions and micro-Doppler analysis[18] can be provided by the static multi-faced antenna-based radar system. This configuration can also provide higher update rates on the targets being engaged while performing surveillance.

4.1.4 Micro Doppler Analysis & AI Assistance

Micro Doppler extraction and AI-based analysis can aid in the target classification and discrimination against birds. This mode is desired to identify the UAV class and engagement type selection thereafter.

Ku-band phased array radar providing a smaller system and short dwell times to get the required Doppler resolutions, aiding in the clutter discrimination and target identification would be best suited[19]. Four-panelled phased array radar with simultaneous or independent operations of individual panels is an optimum deployment configuration. The incorporation of UAV target identification based on imaging or time-frequency analysis techniques exploiting the micro-Doppler radar return signals is useful.

4.2 Radio Frequency Sensing

UAV operations rely on the Radio communication link between the operator and the UAV for control commands and data relay. Swarms rely on inter-UAV communication using RF links. RF control or surveillance signals emitted by the swarm elements can be detected. Multiple deployments would be required for geo-locating its exact position using triangulation algorithms. Multiple high-gain directional antennas which can be co-mounted to provide Omni-directional performance with high accuracy directional estimates[20]; wideband operations from a few kHz to 18 GHz frequency range[21]; high measurement accuracy and High IP3 of <40 dBm antenna; hoist-able lightweight antenna with algorithms to detect and mitigate multi-path signals; and stored library based received signal's correlation for UAV's identification of transmitting UAV are suggested.

4.3 Electro-Optical (EO) & Infrared (IR) Sensors

A combined optical, IR and Laser range finder configuration could provide day and night operational capabilities, high accuracies for engagement, identification of the class/model of multiple UAVs and instant damage assessment after an engagement is suggested. Two different configurations of EO/IR sensors for surveillance and engagement assistance functions could provide performance improvements. A high update rate rotating EO/IR sensor with laser range finder-based surveillance will provide 360 deg azimuth coverage. Multiple co-mounted sensors for different elevation angle coverage can be considered[22]. A gimbal-mounted or weapon-aligned EO/IR sensor with a laser range finder can provide engagement assistance by providing the fine tracking parameters and identification of the acquired UAV threat. After the engagement, the weapon can move on to engage the next threat and the damage assessment can be done by the surveillance sensor or another dedicated IR sensor. AI-enabled image processing based on robust detection and identification of the UAV's class could assist in the ideal engagement weapons employment[23].

4.4 Acoustic Sensors

Acoustic sensors unlike EO/IR sensors are not limited by line-of-sight or the size of targets for detection. Distributed short-range acoustic sensors with directional acoustic scanning capability could provide effective coverage for a larger area[24-25]. The Library of acoustic signatures of different UAVs could be used to correlate with the input signal for detection and identification. Algorithms and array microphone system characteristics could be studied to provide background noise mitigation and performance enhancement.

An array of high-gain microphones with wider coverage using multi-beam/electronic scanning would be best suited[23-25]. Adaptive noise mitigation techniques; acoustic signature correlation algorithms; network of distributed sensors would be an ideal configuration.

4.5 LiDAR Sensors

Laser-based detection and ranging (LiDAR) are being used to detect small moving objects like drones[26]. Distributed short-range LiDAR sensors with scanning capability; background information correlation and Doppler processing could be used for improving UAV's detection performance; algorithms to distinguish UAVs from birds, and highly eye-safe lasers are

Table 1. Merits and limitations of different acquisition techniques

Techniques	Merits	Limitations
Radars	• Well-established technology with all weather operations • Target identification/ classification capability • A large number of targets detection and tracking capabilities	• Limited LOS for low-altitude UAVs • Low RCS of UAVs due to smaller non-metallic bodies • Challenging to distinguish from large background clutter or birds due to lower speeds
Radio Frequency (RF) Sensing	• Low complexity & established technology • Longer distance operations possible • All weather robust operations without performance degradation from clutter or other flying objects like birds.	• Not effective against autonomous UAVs • Multi-path reflections can degrade measurement accuracies • Prior knowledge and a library of emissions required
Electro-Optical (EO) & Infrared (IR) Sensors	• Target identification/classification capability • A large number of targets detection and tracking capabilities • Laser range-finding equipment for range detection fails in a highly dense environment	• Provides 2D images • Limited by weather conditions/background temperature • Susceptible to positions of objects (horizon) • LOS is required
Acoustic Sensor	• Not dependent on LoS or the target's size, orientation or flight profile • Supports day and night operations	• Range is limited • Vulnerable to ambient noise • Capacity limits and updating of libraries
LiDAR	• Provides 3D representation • Detecting an object in a complex background. i.e. high-resolution detection is possible • Provides targets Doppler information	• Highly limited by weather conditions • LOS is required and the detection range is short • Expensive technology

some of the suggested ideal LiDAR system configurations. A comparison of different acquisition techniques is tabulated in Table 1.

5. ENGAGEMENT ASPECTS OF AN OPERATIONAL C-UAV SWARM SYSTEM

C-UAV systems will be deployed in the proximity of their assets, operation to counter UAVs should cause the least collateral damage to the protected assets. The engagement system is desired to have the capabilities like soft neutralization capability, i.e., neutralising the UAV using non-kinetic means by navigation or controls spoofing, jamming or sensor interference; hard-kill neutralization capability, i.e. neutralizing the UAV using kinetic or directed energy means ensuring partial or complete damage; capability to handle swarm attacks by acquiring and neutralizing a large number of targets within reasonable cost; faster loading, faster firing/launching capabilities; and availability of a large number of projectiles/missiles in ready to fire configuration and increase in engagement range considerably increases the accuracies requirements of the sensors and weapons systems.

Therefore, to reduce the complexity of the system, Class-I and II UAVs can be engaged at much shorter ranges (approx. < 4 km), but Class-III UAVs must be engaged before they can deploy the secondary weapons (approx. > 6 km).

As distributed attack from multiple directions is part of the swarming tactics system should cover 360deg azimuth, with an option to operate in sector mode. Further, at the shorter range, the low-altitude UAVs project large elevation angles. Deployment on a raised platform with at least -10 deg to ~90 deg elevation coverage would be ideal.

UAVs and Loitering munitions are comparatively smaller and much slower in their velocities; engagement of small and slow-moving targets with velocity coverage for 80 km/hr to a max of 500 km/hr would be desirable. Network Centric Warfare capabilities utilising other networked weapon systems to increase the available engagement resources is desirable. Due to the higher engagement rate required, autonomous operations weapon steering for target engagements and damage assessment would be required with human operators in the loop for one-touch approval of the engagements.

5.1 Engagement Techniques

UAV engagement can be broadly divided into soft kill and hard kill techniques. RF/GNSS jamming, spoofing, dazzling, nets and fog bombs are a few soft kill techniques. High-energy lasers, high-power microwaves, projectiles, counter UAVs and very short-range SAMs etc are a few hard kill techniques. UAV performance can be degraded by disrupting the RF link between the UAV and its operator by generating large volumes of RF interference or disrupting the UAV's satellite-based navigation link such as GPS or GLONASS[27]. Once the RF link is denied, UAVs will usually either descend to the ground or initiate a "return to home" manoeuvre. If GPS is required to return to the home path, then it will paralyze the system.

5.2 RF/GNSS Jamming

RF jamming methods have a small footprint and require minimal processing. A reactive jammer sub-system which transmits signals only when it detects monitored spectrum/channels are occupied by unknown signals similar to UAVs is useful with scenarios. GNSS signal jamming along with a 360 deg coverage antenna which can transmit in multiple selected directions without moving the antennas could be used. RF engagement system for identifying the mother ship and breaking its link with other UAVs in the swarm, avoiding their coordinated attack on the targets can be developed. RF Jammer-based soft engagements capabilities need to be linked to the surveillance system for an autonomous response to the detection and identification of threats. Wideband operations from a few kHz to 18 GHz frequency coverage and hoisted light-weight multiple directional antennas providing Omnidirectional coverage will be best suited.

5.3 Spoofing

Allows one to take control of or misdirect the targeted UAV by feeding it spurious communication or navigation links, such as cyber-attacks, protocol manipulation, and RF/GNSS deception. An intelligent system which can automatically identify, stop, redirect, land, or take total control of the targeted drone or other radio-controlled devices will be useful. Systems shall be capable of operating in wideband (even with different antennas) providing Omni-direction coverage and capable of handling multiple UAVs at a time. Communication and navigation protocols need to be identified and need to be developed into a database for all the available UAVs. Identification of loopholes in the UAV system for navigation and controls spoofing and development of a static Omni-directional coverage system with multiple targets engagement capabilities will be best suited.

5.4 Air-burst Anti-Aircraft (AA) Gun

Air-Burst ammunitions when fired are programmed with the exact time delay at which they would reach the target location, where they burst and release high-speed tungsten pellets at the target in a narrow forward cone. Multiple rounds create a dense fragment field achieving a high kill probability even for small targets, considerably easing the accuracy requirements[28]. AA guns provide a high rate of fire with some lag between engagements due to the movement of high-inertia guns. AA guns when paired with robust and accurate UAV acquisition systems can provide a low-cost counter UAV weapon capable of engaging a large number of UAVs.

Smart ammunition based on a programmable delay fuse with >1m distance accuracy; setback generator-based power generation; multiple safeguards such as self-destruction on max delay, high G safety unlocking and read back of programmed delay can provide high reliability[27]. Multiple high rates of fire guns (480 rounds per min) usage on load sharing basis can provide the required high engagement. Muzzle velocity correction could further bring improvements in the accuracies[27]. Fast steering and movement mechanism for the gun assembly with -10 de/g to >90 de/g elevation to meet the steering can be developed for this application.

5.5 High Energy LASER (HEL)

The HEL-based system can destroy vital segments of the UAV's airframe using directed energy, causing it to crash to the ground. HEL systems can engage the next target without much delay providing a higher rate of engagement and a wider coverage area. However, HEL weapon with a 4km range is challenging even with the technology maturity in the coming years[28]. Thus a cost-benefit analysis could be done in depth to consider the HEL system for this application. In times to come network integrate-able HEL units to augment engagements are recommended for C-UAV systems.

5.6 High Power Microwave (HPM)

Microwave can produce different damage effects when it strikes different kinds of UAV swarm systems, varying from slight damage to the enemy's hardware that causes the enemy's system to lose its ability of communication or navigation or its combat capability, to complete damage to the hardware system or detonating missile or warhead instantly destroying the UAV[29]. The technologies related to high-power microwave generation, its directional antenna and shielding of control and generation circuit against such high power can be considered for development.

The coverage of HPM systems due to their short-range operations is very less, due to this it may be able to fill coverage gaps or provide high-importance point protection in an overall C-UAV swarm system configuration[30].

5.7 Intercepting UAVs

UAVs or loitering ammunitions can be fitted with an advanced target seeker and a warhead to destroy UAVs in kamikaze fashion by deploying explosives or EM disruptions.

This can be used both for Class-I, & II and Class-III UAV targets[32-33]. However, they would take a longer time to reach the threat compared to other means and their ability to gain or reduce altitude is limited due to their aerodynamic structure to fly. Self-destructing UAVs can be designed to intercept incoming threats and neutralize them. High-endurance intercepting drones can be designed to use secondary means for destruction or soft kill in intercepting multiple drones[32]. Terminal homing and guidance sensors for wider coverage in the required form factors will have to be configured. A miniaturised, low-cost, expendable drone deployed by hand or launcher tube[34] can

Table 2. Comparative table listing merits and limitations of different engagement techniques

Techniques	Merits	Limitations
RF/GNSS Jamming	• Independent of UAVs size or dynamic parameters • Can be easily scaled up to increase the effective range	• Ineffective against • autonomous UAVs with visual navigation • GNSS-Robust UAVs with IMU sensors • Encrypted GPS in UAVs
Spoofing	• Low-cost solution with no collateral damage. • Effective against almost all of the UAVs requiring RF links for control & navigation • Highly effective in disrupting the coordination mechanism of the swarm.	• Ineffective against autonomous visual navigation UAVs. • Information on complete communication protocols information about various UAVs • Communication protocols can be changed in a shorter intervals by the adversaries
Air-Burst Anti-Aircraft Gun	• Lower cost of engagement • Established anti-aircraft guns and fire control mechanism	• Precise aiming is required considering gravity/wind • Requires muzzle velocity corrections and other safeguards
High Energy Laser (HEL)	• Provides Instant damage delivery and kill assessments • Higher rate of engagement • Independent of ammunition limitations	• Performance sensitive to adverse weather conditions • Requires longer pointing of laser on the target to deliver the damaging energy • Cost-effective and longer-range mobile deployment technology not matured • Deployment in large numbers would be very expensive
High Power Microwave (HPM)	• Can engage multiple targets within the coverage • Provides a very high engagement rate • Effective against autonomous UAVs • No limitation on ammunition	• Higher collateral damage in absence of proper safeguards • Shielding against EM interference can make UAVs robust[30-31] • Kill assessment may not be possible • Shorter operational range
Intercepting UAVs	• Provides great manoeuvrability at comparatively slower speeds • Offers better control of the engagement • The capability of engaging multiple targets	• Engagement time is larger as it takes time to reach the targets • The rate of altitude climb is slow in normal UAVs
Low-Cost Very Short Range Surface to Air Missiles (SAM)	• Lower engagement time due to quick launches and faster speeds • Reliable engagements	• Comparatively higher cost • Robust homing and guidance requirement due to lack of high IR signatures and non-metallic bodies

also be developed and explored for C-UAV swarm operations. Grenades with different and innovative ammunition like integrating threads can be designed for countering swarms as shown in Table 2.

5.8 Low-Cost Very-Short Range Surface to Air Missiles (SAM)

A low cost simpler version of SAMs can be realized for the target speed and profile of UAVs. These missiles will offer robust and reliable means of engagement for the protection of high-value targets[35]. SAMs for the very short range of about 4 km~6 km which can be quickly launched and could be packed in high-density launchers of around 24-32 missiles could be used for C-UAV swarm application. As the UAVs don't produce as much IR radiation as other aerial threats, these missiles could use the Semi-Active Laser (SAL) guidance as used in Thales Starstreak or LMM missiles and terminal proximity sensor-based detonation. These could also be used in a modular network to integrate with conventional AD systems to provide additional engagement capabilities.

5.9 Very Short-Range Surface-to-Air Missile (VSRSAM)

Based on the suggested approach of the common AD system, using a universal VSRSAM for all the threats, similar to the ones used in the Pantsir-S1 AD system of Russia[36] can be considered for this application. The VSRSAM can be highly effective if used for the engagement of Class-III UAVs at ranges greater than their secondary weapons launching ranges. IR-guided or active radar-guided VSRSAM missiles used for approximately 1 km to 10 km ranges and 3.5 km altitudes are optimal requirements. Providing a suitable number of missiles on the system for engagements and a network integral high-density launcher can provide a high density of firepower.

6. ILLUSTRATIVE C-UAV SWARM SYSTEM

Based on the assessment of the available technologies a feasible conceptual system is configured to provide point protection to vital assets within the 1 km radius protected area. Considering, a scenario of 50 UAVs attacking uniformly from 360 de/g Azimuth in a synchronised manner. C-UAV Swarm system would require engaging and neutralizing all of them before they reach the 1km radius protected area.

RF/GNSS jammer with spoofing system with Omni-directional coverage with more than 4kms range could be used effectively against commercial drones, with autonomous navigation and encrypted communications likely to be used in military drones these techniques would be less effective as a generic solution. Therefore, further, in the paper hard kill options are being explored and proposed.

A max speed of 150 km/hr of the incoming threat is assumed such that the swarm will take approx. 72 sec to travel the 3 km distance. Suppose an engagement weapon has a kill probability of 90 %, then for this scenario, 55 times target engagement (considering the 10 % miss rate) is required. To execute 55 engagements in 72 sec, an engagement rate of 1.3 sec is required for the overall system. This would require multiple engagement weapon stations and autonomous target acquisitions to achieve a reasonable engagement rate.

6.1 Detection and Acquisition Function

A combination of sensor functionalities will be required to cover most of the UAVs detection and acquisition

- As mentioned earlier in section 4, higher frequency of operation provides performance improvement in C-UAV applications and as Ku-band technology has also fairly matured, a Ku-band multi-paneled phased array radar with micro-Doppler-based target identification capabilities is being proposed; wide spectrum Omni-directional RF sensing provides the acquisition at long ranges (about 50 km ranges); and
- Two configurations of EO/IR sensors, i.e. 30 rpm rotating EO/IR sensor for acquisition and gimbal-mounted 360 deg steerable EO/IR sensor for engagement assistance functions at shorter ranges (> 4 km).

This configuration provides a robust acquisition system for longer acquisition as well as multi-sensor assistance for engagement. The sensors can be co-mounted or located on different platforms as per requirement.

6.2 Engagement Function

6.2.1 Engagement for Class-I & II UAVs Swarms

Due to their higher probability to hit smaller UAV targets[37] (in comparison to conventional AA guns) multiple networked anti-aircraft guns using smart programmable air-burst ammunition with a max engagement range of 4kms controlled by a central command & control centre is suggested for engagement of Class-I and II UAV swarms. An engagement rate of 1.3 sec (derived earlier) can be achieved by using target load sharing of 3 networked AD artillery gun stations providing approx 4secs of average engagement time per target. Considering the smaller +/- 60degs azimuth coverage by each gun, automated target acquisition and engagement are a must. With 19 engagements per gun and 6 rounds per engagement, it requires at least 114 rounds of live munitions storage and with 1sec for firing and the rest of the time for gun pointing and stabilizing; it would require a min of 360 rounds per minute firing rate from these guns which is achievable.

6.2.2 Primary Weapon of Engagement for Class-III UAVs Swarm

Universal Very Short-range Air Defence Surface to Air Missiles and short-range SAM missiles could be used as the

Table 3. Comparative performance for 50 UAV Swarm at 4 kms distance

No. of guns	Azimuth sector	Engagement/Gun (10% miss rate)	Munitions /Gun	Engagement rate
One gun	360 deg	55 engagements	330	1.3 secs
Three guns	60 deg	~19 engagements	114	3.9 secs

primary weapon for Class-III UAVs engagements at longer ranges (10 km max) or UAVs attacking from altitudes great than 3.5 km which is AD Artillery gun's limitation as shown in Table 3.

This is a basic combination based on given assumptions and estimates. Secondary additional firepower capability addition can be considered based on the intelligence inputs. Stems like low-cost SAM missiles, 24-32 missiles launchers, HPM weapons, HEL weapons, Intercepting UAV launchers, RF jammers and spoofing systems, and distributed addition Air-burst anti-aircraft gun stations can be added to the system over the network to augment the capabilities.

7. CONCLUSION

Considering countering UAV swarms as an additional requirement for any new AD system development, the ideal system characteristic of a C-UAV swarm system and the challenges of countering the swarms are identified. An assessment of available C-UAV acquisition & engagement techniques is carried out by discussing multiple acquisition techniques of radar, RF sensing, EO/IR sensors; and layered engagement techniques of networked air-burst AA guns, low-cost short-range SAMs and RF/GNSS jamming. A thought experiment is done to outline as acquisition and engagement of a C-UAV swarm of certain capabilities. This gives a direction for configuring the UAV Swarm systems. Wherever needed, multiple systems need to be integrated dynamically to scale up the swarm handling capabilities.

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