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The Small and Silent Force Multiplier: A Swarm UAV—Electronic Attack

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Abstract At the last two decades, according to UAVs concepts and technological advances, there have been lots of unimagined improvements. Nowadays there are serious works and researches about the usage of UAVs in military operations at electronic warfare (EW) missions. But most of the work on UAV platforms is based upon the advantages of a single, big, expensive, and non-expendable platform. In this study, to get rid off the disadvantages of a stand alone platform a new concept is developed consisting of multiple UAVs with smaller dimensions, at a cheaper price and a wider coverage. According to clarify the study, firstly the EW and RADAR systems and then the swarm UAV concepts are explained. In this manner the current and previous works are pointed out and then the use of the swarm UAVs for EA in military operations is stated. Objectively, the swarm UAV concept's advantages and some outstanding challenges to the intra-theater space have been put forward regarding the information mentioned above. As a result it is considered that the swarm UAV systems will be tasked important EW missions in the future operation theatres, as soon as the technical handicaps are solved.

Keywords UAV · UAS · Unmanned aerial vehicle · Unmanned Aircraft Systems · Swarm UAV · Electronic attack · Electronic warfare

1 Introduction

The idea of using unmanned aerial vehicles (UAVs) in the battlefield is not new. From U.S. civil war's balloons to Afghanistan's modern and capable unmanned aerial systems, UAVs were used for various purposes ranging from ammunition depot attacks or to intelligence, surveillance and reconnaissance (ISR) platforms or tactical attack platforms. Today, UAVs are undertaken a very important and big role that they are sine qua non players of the battlefield. By the recent advances in aviation and electronics industry, UAVs gained power, better communication capabilities and better maneuverability. Conversely, the way does not seem to be over for UAVs.

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These advances have complicated the structure of unmanned aerial systems adding important ground facilities. Thus, in many formal documents and literature, "Unmanned Aircraft Systems" or UAS is mostly used instead of the conventional term UAV. However, this paper is mostly focused on the platform and thus "Unmanned Aerial Vehicle (UAV)" is preferred instead of UAS.

Actually, the use UAVs for electronic warfare purposes is not new. For example, the ADM-20 Quail drones are designed to be launched by the B-52 aircraft in 1950s might be considered among the first experiments [1]. In such drone applications the main purpose is the protection of the main platform via using an expendable drone as a fake target for adversary air defense systems and to penetrate air-defense systems. Within time, due to recent advances in electronic warfare expendable drones gained maneuverability and RF propagation capabilities.

These advances encouraged some countries to produce new designs which were also intended to support radar jamming, chaff-flare dispensing, and ELINT missions. Such as Tactical Air Launched Decoy (TALD), an improved version of the Samson that was part of the suite of countermeasures the Israelis used over the Bekaa Valley in Lebanon in 1982 against Syrian air defense. Other drone examples are Miniature Air Launched Decoy (MALD) and MALD-J which is the RF jammer version of MALD [2–4]. And some jammer applications by UAVs such as Aerosonde UAV [5], came out. Those show that, UAVs have been used for electronic warfare purposes for a considerable time. Nevertheless, swarm UAV concept is quite new and does not have any publicly declared operational application. In this paper, it is projected that the use of swarm UAVs in electronic attack missions is very critical to yield important advantages such as survivability, flexibility and cost effectiveness. And it is pointed that wireless beam forming in a swarm UAV network has many advantages over conventional beam forming techniques and may inspire some innovative battlefield applications. Operational advantages and outstanding challenges of swarm UAVs in EA, is also mentioned in this paper.

2 The Basic Principles of Radar and Integrated Air Defense Systems

Generally the basic logic underlying of the operation of RADAR systems is sending out radio frequency electromagnetic radiation and then catching the reflected signals from distant objects. By this way radars can detect objects and determine their ranges.

A simple radar consists of five basic parts namely, a radio transmitter, a radio receiver, two antennas, and a display screen. However, same antenna is used for both receiver and transmitter in common (Fig. 1) while the transmitter sends out radio waves, the receiver searches for echoes. If any object is detected, an indicator comes up on the display screen.

For the radar to function properly there should not be any obstacle in between the radar's line of sight and the potential target [6].

A radar transmitter transmits its waves in two forms. The main form is called "main beam or main lobe" and the second form is "side lobe" with a weaker transmission power than the main lobe. The main lobes' direction shows the target as shown in Fig. 2 [7].

The target's range can be determined from the intervals between the transmitted signal and received signal. The radius, given as Burn through Radius in Fig. 2, means main lobe's motion region radius border and is also known as "Threat Circle" [7]. However, the range of received signal's power depends on many agents such as "the power of

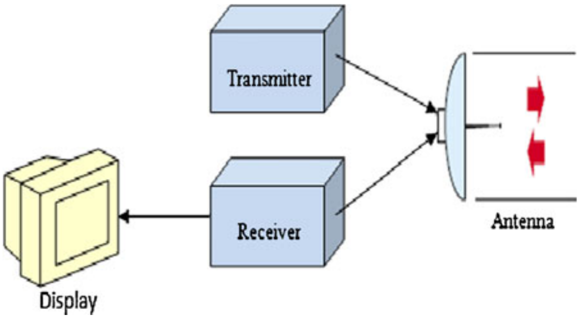


Fig. 1 Scheme of a simple radar system

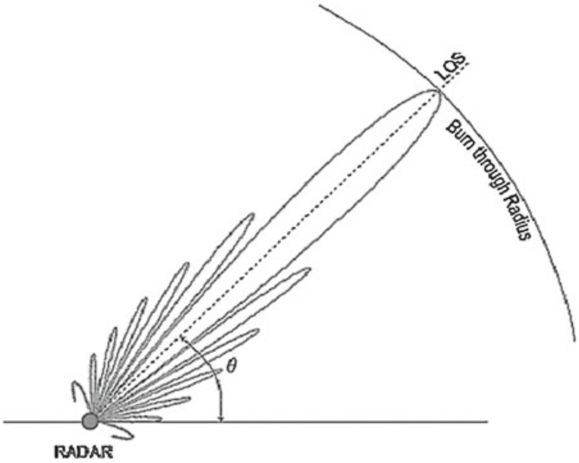


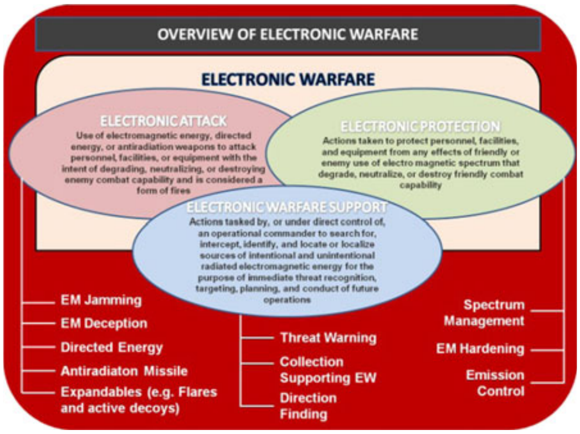
Fig. 2 Radar lobe structure

transmitted signals, size of the antenna, reflecting characteristics of the target, number of search scans in which the target appears" and etc [6].

3 Electronic Warfare

Today's battlefield is electronically more complex and requires more electronic capabilities than simply detecting enemy transmissions. Military operations are planned and executed in a complicated electromagnetic environment (EME) [9]. So much so, the electromagnetic environment can be used for both military and civilian purposes such as navigation, communication, information storage & processing, sensing and intelligence. The use and exploitation of the electromagnetic spectrum has become crucial for military units [8]. This extensive use of the EM spectrum (EMS) made electronic warfare a key parameter to mission success. Besides changing military tactics, the concept of EW itself has also evolved.

Electronic Warfare (EW) is one of the five core capabilities of information operations (IO) which is defined as "Any military action involving the use of EM and directed energy (DE) to control the EMS or to attack the enemy". Figure 3, presents an overview of EW and its relationships with the subdivisions. Also reference [8] divided the EW missions into following major subdivisions:



Use of electromagnetic energy, directed energy, or antiradiation weapons to attack personnel, facilities, or equipment with the intent of degrading, neutralizing, or destroying enemy combat capability and is considered a form of fires

Actions taken to protect personnel, facilities, and equipment from any effects of friendly or enemy use of electro magnetic spectrum that degrade, neutralize, or destroy friendly combat capability

Actions tasked by, or under direct control of, an operational commander to search for, intercept, identify, and locate or localize sources of intentional and unintentional radiated electromagnetic energy for the purpose of immediate threat recognition, targeting, planning, and conduct of future operations

Fig. 3 An overview of EW

3.1 Electronic Attack (EA)

The division of EW involving the use of EM energy, DE, or anti-radiation weapons to attack personnel, facilities, or equipment with the intent of degrading, neutralizing, or destroying enemy combat capability. Electronic attack is considered a form of fires [10]. EA consist of two main parts as offensive and defensive activities to include countermeasures (CMs).

3.2 Electronic Protection (EP)

EP involves protection activities for personnel, facilities, and equipments from any effects of friendly or enemy use of the EMS.

3.3 Electronic Support (ES) or EW Support

ES involves actions tasked by, or under direct control of an operational commander to search for, intercept, identify, and locate or localize sources of intentional and unintentional radiated electromagnetic energy for the purpose of immediate threat recognition, targeting, planning, and conduct of future operations.

The EA applications and systems began to be utilized in today's military operations more than in the past, to handle the emerging and known targets or threats on the battlefield. Moreover, forces generally use large EA platforms, mostly an aircraft assigned, for jamming or other facilities for EA. However, there is another option also that to use any micro, mini or tactical UAVs in EA missions.

Both of these choices have their own trade-offs. While large platforms are able to carry much higher jamming power than the relatively small UAVs, their large structure leaves a much bigger radar signature than that of UAVs. Another great challenge to be addressed over the battlefield is the threat. The threat over the battlefield includes all types of adversary defensive units and activities. The availability of the technological advancements in the missile industry has also made asymmetric threats very capable against conventional military tactics. So, the major advantage of UAVs over larger single platforms is that, due to their small sizes, UAVs are less vulnerable to threats and thus require less self-defense precautions. Last but not least UAVs are cheaper and in some cases to be expendable.

4 The Concept of Swarm UAV

Several concepts are defined and many missions are executed in the unmanned aviation world. The concept of this study is based on UAV swarming for jamming in EA missions. Because, it is clear to presents that by using multiple micro/mini UAVs rather than a single large one, many missions can be performed with greater efficiency due to cheapness of a swarm. In addition, if one member of the swarm is lost in an operation, the rest of the swarm can complete the mission. Furthermore, there are so many studies on autonomous, coordinated and cooperatively flights which put forth that a swarm UAVs could have a synergistic effect in the battlefield than a single one.

In this concept, UAV systems and EA applications are examined within a larger framework than concepts and tactics already performing EA by aircrafts acting individually. This means that this paper broadens the variety of EA works. A flock of mini UAVs can stand-in jamming applications in close to the threat radars that could be very effective. in the beginning, it seems like the frequency options, and the ability to direct EM will likely be much less than conventional manned platforms. But if the quadratic benefit of range is thought, jamming with a group of UAV may be of greater importance.

On the other hand, using UAVs in EA missions has some important challenges for countries. The primary challenge is the price. It needs to be expendable. Another important challenge is the payload capability. EA technology needs big volume units and UAVs cannot respond to the needs like that. A single UAV platform is obviously not capable of carrying an EA jammer kit that matches the range capability and jammer power of a larger jammer aircraft. But similar to the extension from a single antenna to an antenna array, a swarm of UAVs acting collectively can match the parameters of a manned jammer platform. In order to achieve the anticipated gain and range enhancements, the concepts of opportunistic arrays and wireless beam forming can be utilized for a swarm of UAVs.

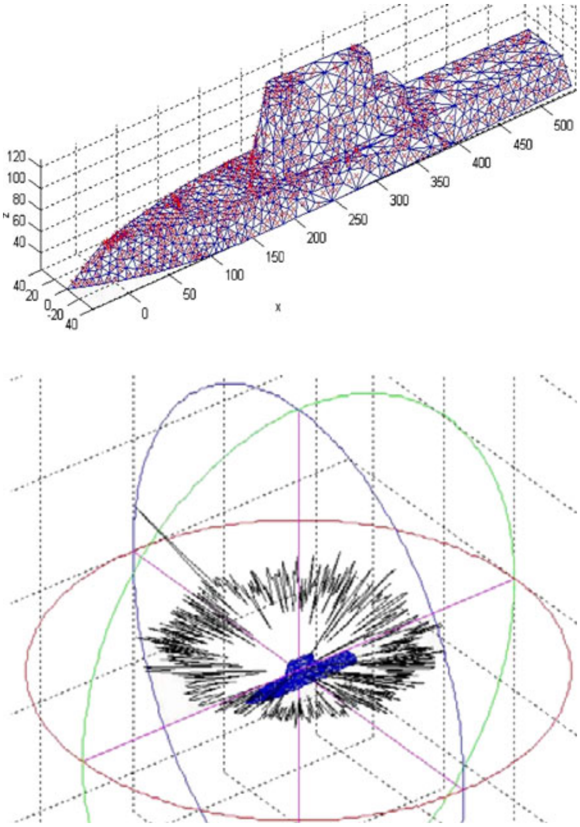


Fig. 4 Example of an array of sensors or antennas distributed over a ship and a coherent radiation pattern [11]

An opportunistic array is a distributed array where the elements are placed at available open locations, rather than in a rigid periodic arrangement. Figures 4 and 5 shows some examples of opportunistic arrays.

Wireless beam forming has also been an area of interest over the last several decades. Beam forming is a signal processing technique that is used to increase efficiency in sensor networks. In conventional phased arrays, a beam former circuitry is used to achieve the desired radiation characteristics such as beam direction, side lobe level and gain. When the beam former circuitry is replaced with a wireless network, the technique is often referred as wireless beam forming or distributed beam forming [1, 2].

Given that the concept has a biological inspiration from the flock of animals such as birds and insects, the term "swarm" is preferred in order to imply that the cluster of UAVs have the same flight pattern. In this sense, swarming concept utilizes the distributed control technology [12]. Swarm UAV concept is defined as the cluster of wirelessly networked mini or micro-UAVs which fly within the same flight pattern and employed for the same or similar purpose. Swarm UAV concept may introduce new advances to air warfare. These advances are mostly related to the possible payloads on the swarm elements. The technical necessities and restrictions on the flight patterns of the swarm UAV networks is beyond the scope of this study, however there is enough research to be convinced that a flying cluster of UAVs is viable [12–14].

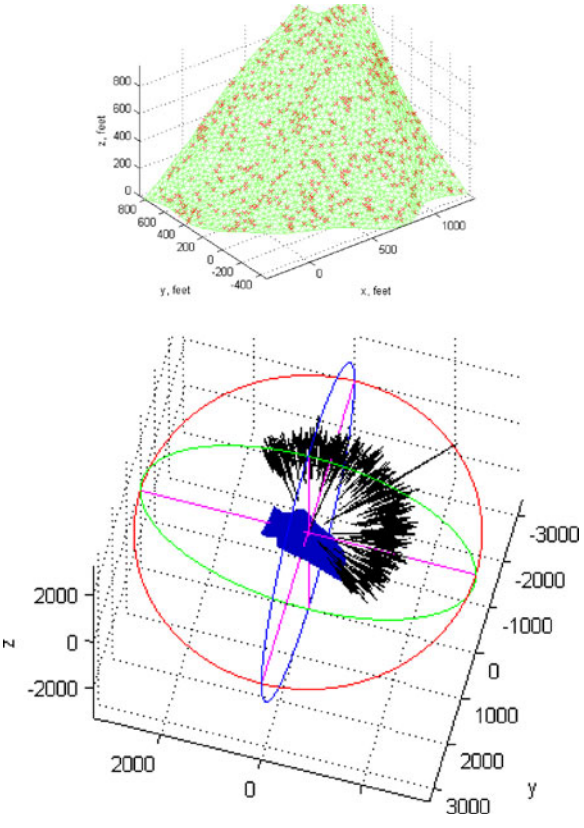


Fig. 5 Example of an array of sensors or antennas distributed over a hillside and a coherent radiation pattern [11]

There are various classifications of UAVs in the literature [15, 16]. Swarm UAV concept mostly involves mini and/or micro class UAVs. And this paper regards mini-UAVs as platforms that have wingspans up to 3 m and up to 20 kilograms of weight following [16] and micro-UAVs as platforms shorter than 15 cm in any dimensions and lighter than 500 g following [15].

Military systems around the world have been using UAVs in accordance with their war fighting concepts for decades. The use of UAVs on the battlefield has gradually increased by quantity and diversity of the applications [8]. Moreover, the use of UAVs for civilian and commercial application has increased for the last two decades. The use of UAVs changes from monitoring carbon footprint, to meteorological events, irrigation, education and commerce etc. However, the concept of using so many small UAVs as a unique body is not used too much especially in electronic warfare.

5 Previous Works

A swarm has been defined, as in [17], as "Modeled flight that is biologically inspired by the flights of flocking birds and swarming insects." First multiple-UAV studies started in early 1990s. In early studies, researchers had the conviction that using a swarm of UAVs can work like a network that means those UAVs can behave like both an individual UAV and together. By this way a swarm of UAVs can provide information about operation area and/or perform other missions that have been completed by larger UAVs.

There are many studies and completed projects about swarming or grouping micro, mini or larger UAVs. Although these studies are usually seen in countries like Australia, Germany, Israel, the Netherlands, the United Kingdom, and the United States intensity, seen in China or South Korea. Generally, these studies and designed theories were on to flying UAVs together as a flock to a target, and return to their bases [18].

From "Collision Avoidance" perspective, a successful swarm of UAVs must be able to fly without colliding each other. Some researches on anti-collision applications are presented below:

5.1 Korea Advanced Institute of Science and Technology (KAIST)

In 2003 researchers in the KAIST, studied and made some experiments on coordinating a swarm UAVs flights individually. As a result of this study, they expected to get a way of to avoid collision with other UAVs in the swarm where each individual UAV cannot see whole swarm. This was one of the several experiments for coordinating individual UAV movements within a swarm. In this study, researchers considered a swarm a decentralized group where each individual, without seeing the entire swarm, performs simple maneuvers to avoid colliding with other members of the swarm. This concept is similar to that of an individual driving on a crowded highway [19].

In 2004 another proposal on preventing UAVs from collision was proposed by a group of researchers at KAIST. By Proportional Navigation (PN), the researchers using mathematical equations, defined a collision-avoidance vector and also found out an appropriate condition for collision avoidance. In this experiment, researchers found that, upon encountering an obstacle, the UAV used an equation to plot acceleration, relative velocity, and the direction of a collision-avoidance vector [21].

5.2 University of Padua, Italy

One experiment based on the theory of birds' vision in a flock. Between 2003 and 2004 the researchers at the University of Padua, Italy, studied a geometric model for a vision system that uses cameras mounted in UAVs to enable each individual UAV to avoid collisions in a swarm by maintaining their position [20].

5.3 Technion, Israel

The Israel Institute of Technology in Haifa in 2004, studied on a simple mission execution performance without the computational complexity that bring more loadings on processors. They proposed to develop a heuristic algorithm that was capable of incorporating target and group property changes without the computational complexity that such missions normally require [22].

In 2005, a study of two algorithms on searching areas for targets is presented. These algorithms were for programming UAVs to search operational areas for their assigned targets and produced flying patterns "designed for scanning a rectangular area in such a way that the targets cannot reenter subareas which were already scanned" [26].

5.4 In 2005 The Shaanxi Engine Design Institute in Xian

The Hebei Electric Power Reconnaissance Design Academy, and the Aircraft Engineering Department of Northwestern Polytechnical University hosted studies on UAVs' search patterns theory that based on ant colony coordination characteristics. Researchers developed algorithms for leading UAVs on optimal paths to targets [23].

5.5 In 2005 Delft University

One experiment for optimal path planning in a swarm was offered by researchers from Netherland at Delft University. In this study, researchers used basic mathematical formulas, rules, and approximation (a heuristic method) to design routing for a simulated, autonomous swarming mission of large UCAVs to suppress enemy air-defense (SEAD) missions [24].

5.6 The Indian Institute of Science in Bangalore

In another experiment in 2005, researchers at the Indian Institute of Science in Bangalore studied time constraints in an optimal search route decisions. They pursued “a game theoretical approach to route decision-making that takes into account various levels of communication capabilities possessed by UAVs while taking the flight time (or refueling) constraint into account” [25].

5.7 Just in Time Strike Augmentation (JITSA)

In 2006 one of the earliest swarm UAV concepts is “Just in Time Strike Augmentation (JITSA)”. The main idea of this concept depends on striking to the fleeting targets on the modern battlefield which appear briefly and are gone. So the vision purposes a networked battle space with unmanned aircraft maintaining continuous surveillance over a wide area.

As shown in the Fig. 6, Boeing researchers experimented the JITSA scheme that the Dominators (mini UAVs) were packed in pallets of twenty on a C-17 transport plane, with thirty pallets in all that’s a total of six hundred drones. And a loadmaster would handle the individual release of as many as needed. Once in position in the operation area, the swarm would maintain air dominance over a wide area, providing both of continuous surveillance and instant reaction. This concept estimates that any target in the kill zone could be hit within 2–4 minutes maximum. None of those fleeting targets would escape (http://defensetech.org/2006/04/10/drone-swarm-for-maximum-harm/).

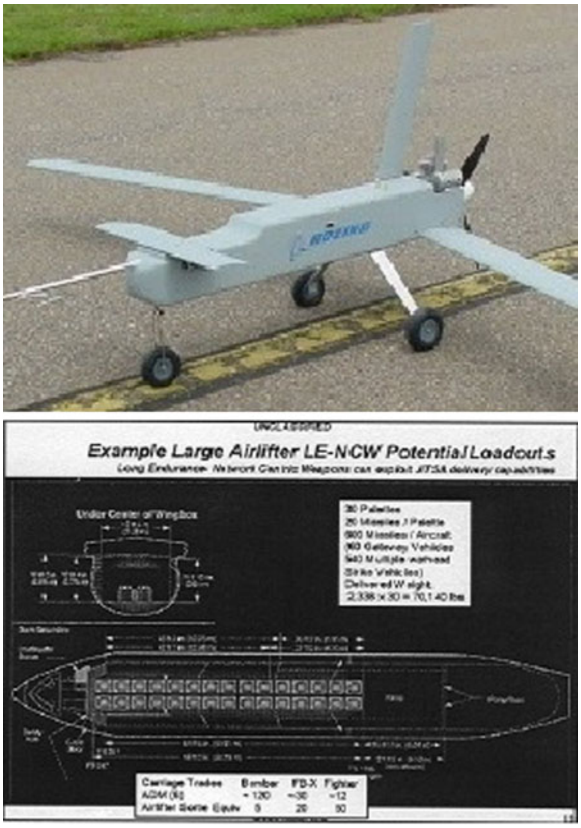


Fig. 6 A Dominator and package scheme of dominators in C-17

5.8 SWARMS Project

In 2009 one of the swarm UAV application is called SWARMS Project at the University of Pennsylvania was based on the assumption that future military missions will rely on large, networked groups of small unmanned vehicles and sensors. These researches propose to embark on a broad-based, cross-disciplinary research program in which we will develop and study a variety of biologically-inspired models of swarm behaviors which are appropriate to large networked groups of autonomous vehicles (http://www.swarms.org/). In Fig. 7, a Swarms Project Illustration is shown.

Fig. 7 SWARMS project illustration

5.9 SMAVNET

In 2010 Switzerland's Ecole Polytechnique Federale de Lausanne (EPFL) lab is demonstrated a Swarming Micro Air Vehicle Network (SMAVNET) that can create an instant, wireless communications network, similar to iRobot's Ember LANdroids swarm of small unmanned ground vehicles-UGVs (Fig. 8). For swarming, this project's UAVs react to wireless communication with neighboring robots or rescuers (communication-based behaviors). Flying Robots were specifically designed for safe, inexpensive and fast prototyping of aerial swarm experiments.

They are light weight (420 g, 80 cm wingspan) and built out of Expanded Polypropylene (EPP) with an electric motor mounted at the back and two control surfaces serving as *elevons* (combined ailerons and elevator). The robots run on a LiPo battery and have autonomy of 30 min. They are equipped with an autopilot for the control of altitude, airspeed and turn rate. Embedded in the autopilot is a micro-controller that runs a minimalist control strategy based on input from only 3 sensors: one gyroscope and two pressure sensors (http://lis.epfl.ch/smavs).

5.10 Boeing and Johns Hopkins University in 2011

One of the most recent autonomy concepts being demonstrated by Boeing and investigated by Johns Hopkins University Applied Physics Laboratory (JHU/APL) take the human out of the loop in terms of individual vehicle control. The UAVs communicated with each other by using a Mobile Ad Hoc Network developed by Boeing Phantom Works and swarm technology developed by JHU/APL. With these systems, the operators provides high-level goals, constraints, and resources, relying on the system itself to conflict, elaborate, and choose among alternative courses of action in mission execution. APL has been investigating several approaches to the coordinated behavior of UAV swarm members (Fig. 9).

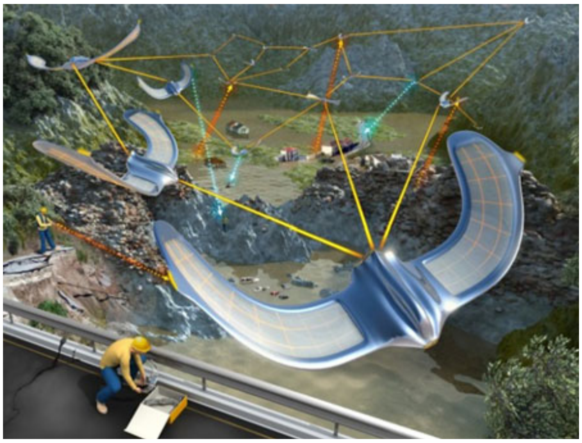
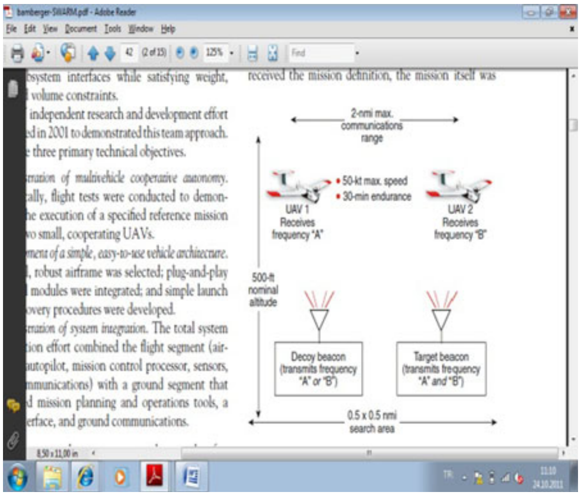


Fig. 8 Illustration of EPFL's SMAVNET in action

These concepts include a simple teaming arrangement, the use of consensus variables, and the use of *stigmergic* (i.e., biologically inspired) potential fields.

5.11 Augusta Systems

In 2008–2009 Augusta Systems in Morgantown, has started a new study to test and enhance a distributed, intelligent network capable of managing single and multiple swarms of unmanned air, ground and sea vehicles, unattended ground sensors, video cameras, and other devices for the U.S. Naval Air Systems Command (NAVAIR) (http://www.augustasystems.com/pressreleases/navair_demo.htm). As shown in Fig. 10, the intelligent network would enable the



bsystem interfaces while satisfying weight,
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independent research and development effort
d in 2001 to demonstrated this team approach.
e three primary technical objectives.
ration of multivehicle cooperative autonomy.
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he execution of a specified reference mission
wo small, cooperating UAVs.
ment of a simple, easy-to-use vehicle architecture.
, robust airframe was selected; plug-and-play
l modules were integrated; and simple launch
overy procedures were developed.
ration of system integration. The total system
ion effort combined the flight segment (air-
autopilot, mission control processor, sensors,
mmunications) with a ground segment that
d mission planning and operations tools, a
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received the mission definition, the mission itself was

Fig. 9 UAV, teaming approach flight demonstration

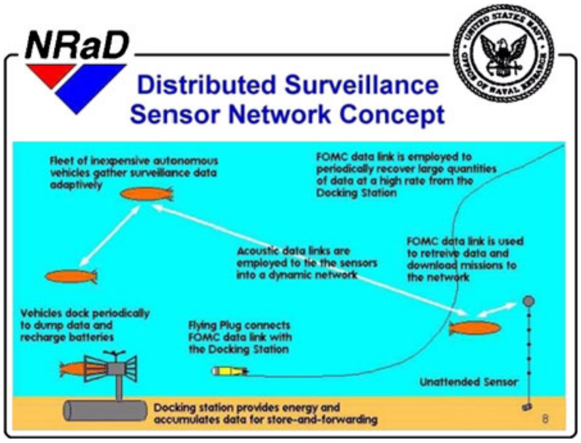

Fig. 10 Illustration of distributed surveillance sensor network concept

vehicles and devices to act on their own, in an autonomous manner, based upon data sent from their own swarm or other swarms. Edge Frontier products enable integration and normalization of data, events and control functions from diverse systems, as well as event processing and event and policy-based actions through a policy engine (http://www.augustasystems.com/pressreleases/navair_demo.htm).

5.12 Opportunistic Array Concept

In 2007 Y. Loke undertook an opportunistic array concept. Loke, defines an opportunistic array as an integrated platform wide digital phased array, where the array elements are placed at available open areas over the entire surface of the platform (Fig. 11). Element localization and synchronization signals, beam control data, and digitized target return signals and all others associated with beamforming are passed wirelessly between the elements and a central signal processor [27].

The most frequent application is distributed beamforming in an array distributed over a platform surface, such as a ship. Loke proposed possible solutions to element geolocation and synchronization problems for such an array. Loke's study compares the performance of "brute force" and "beam tagging" synchronization techniques and presents a survey of position location techniques [27].

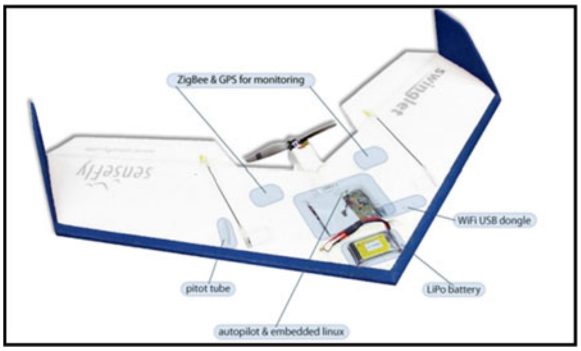

Fig. 11 An example micro UAV and electronics for EA

5.13 Personal Role Radio (PRR)

Another application examines distributed beamforming in man portable communication Networks [18]. Chan's study, which considers a Personal Role Radio (PRR) system as a man portable communication network, is among the few to model mobile network elements for distributed beamforming.

5.14 UAV Network Sample

Considering the information transmission from a cluster of adjacent antennas to a distant stationary antenna, Tu and Pottie have analyzed two network synchronization approaches: Mutual synchronization and master-slave synchronization. The master-slave synchronization fits the objectives of beamforming in a swarm UAV network better than the mutual synchronization approach.

The researches mentioned above have no direct link to EA, they just focus on similar optimization problems. Our motivation is to develop a new technology that could, with considerable additional development, be used on existing and future UAVs. More specifically, existing algorithms, studies and experiments could be used and new ones could be developed for generic and real scenarios involving teams of unmanned Electronic Attack Air Vehicles systems.

6 UAV Swarm as an Electronic Attack (EA) Component

In this study, as a swarm jammer application, wireless beamforming and UAV swarming concepts are merged in order to get an EA component. The network of swarmed UAVs is defined as the problem domain and each single UAV node is modeled as an antenna array. The resulting design is a phased array radar antenna which is often called as an opportunistic array [8]. In swarm jammer application, considering the operational scenario which is shown below, [8] discusses the relation of jamming parameters such as burn-through range and jamming-to-signal ratio (JSR). He concludes that the signal power emitted from each UAV antenna and the number of swarm elements has the greatest effect on the jamming parameters. The jamming scenario in Fig. 10 includes a UAV swarm of N elements tasked to carry out RF electronic attack against SA-2 FAN SONG search radar in order to screen a friendly fighter aircraft which has a radar cross section (RCS) of 2 m^2 (Fig. 12).

In order to task a swarm of UAVs as a jammer, it should be provided that the swarm electronically behaves as a single node. In other words, it should be provided that the nodes within the swarm network contribute to the same RF beam. Here comes the wireless beamforming concept. Wireless beamforming is a signal processing technique that is used to increase efficiency in sensor networks [8, 28].

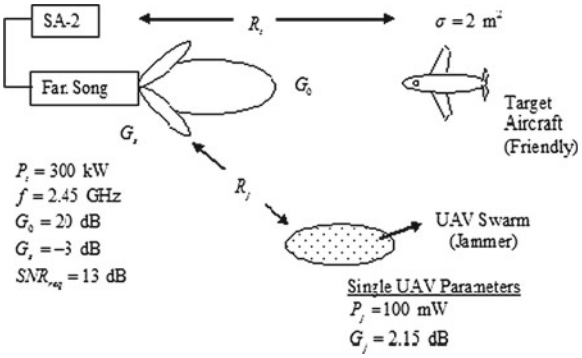

Fig. 12 Jamming of SA-2 FAN SONG search radar by a UAV swarm [8]

The burn-through range for a jammer is mostly accepted as the range at which the signal strength of target return at the victim radar equals the jamming signal level. This means that if the screened friendly aircraft is within the burn-through range of the victim radar, the jamming is no longer successful. Following [29], a signal-to-noise ratio (SNRreq) of 13 dB is required for an effective detection at the air defense radar. Thus, a threshold value of 13 dB for signal-to-jam ratio (SJRreq) at the victim radar is accepted for detection of the target. In other words, the necessary jamming-to-signal ratio (JSRreq) for effective screening of the friendly aircraft in the scenario above is 0.05.

From [8] R_{BT} can be expressed as follows:

$$R_{BT} = \{JSR_{req} P_t G_0 \ldots..\},$$

From this equation, a single jammer UAV at $R_j = 500$ m gives a burn-through range of $R_{BT} = 3473$ m while at $R_j = 1000$ m gives $R_{BT} = 4912$ m. Using this equation, the detection characteristics of SA-2 Fan Song radar vs. single jammer UAV is depicted in the Fig. 13.

To understand what the Fig. 13 expressions, it may be assessed as follows:

- The green straight line shows the burn-through range line which means SA-2 radar detects the target aircraft below this line and it can be called as Detection Area, under the green line.

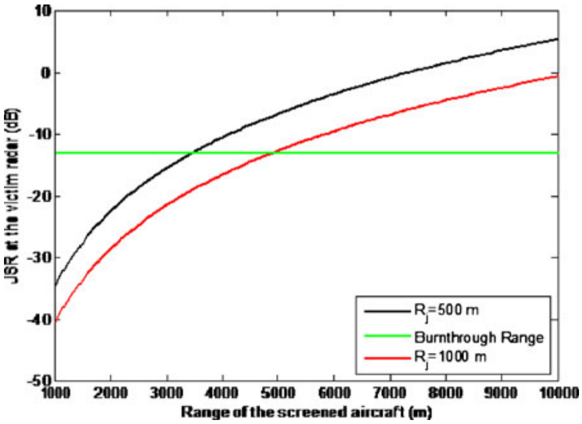

Fig. 13 Detection characteristics of SA-2 Fan Song radar vs. single jammer UAV [8]

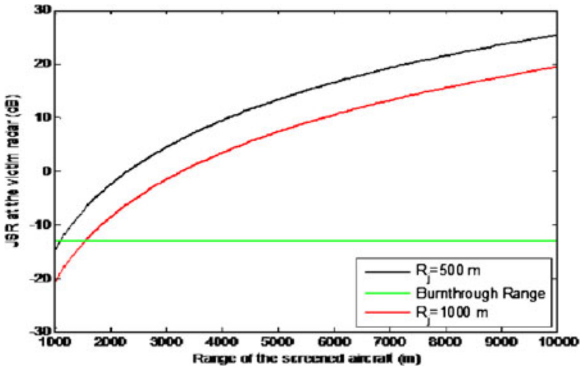

Fig. 14 Detection characteristics of SA-2 Fan Song radar vs. 10 coherent jammer UAVs [8]

- So that means SA-2 radar cannot detect the target aircraft above the green line (burn-through line), where jamming is successful. And it can be called as Jamming Area, above the green line.

Assuming that the UAVs are concentrated at a long range, jamming power received at the victim radar antenna depends on the synchronization which is defined coherent or noncohorent transmission within UAV swarm elements. For comparison perfect and imperfect synchronization within UAV swarm elements respectively, are considered. Detection characteristics of SA-2 FAN SONG radar against a swarm of 10 UAV elements coherent (perfectly synchronized) UAV jammers and non-coherent UAV jammers are shown in Figs. 14 and 15 respectively.

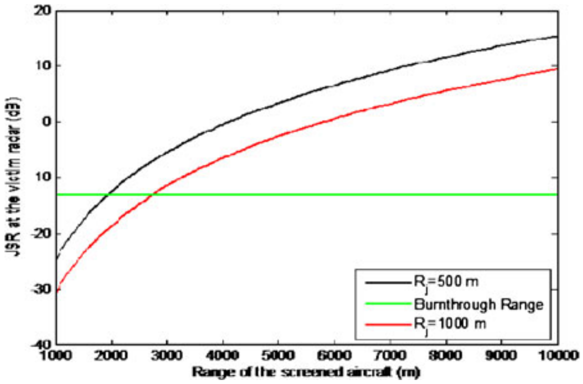

Fig. 15 Detection characteristics of SA-2 Fan Song radar vs. 10 non-coherent jammer UAVs [8]

Figures 14 and 15 reveals that using a swarm of jammer UAVs instead of a single jammer UAV increases the jamming area in which the friendly target aircraft is successfully screened.

This simulation results of swarm UAV jammer application show that when an air defense radar system is jammed using a swarm of UAVs, friendly aircraft may be screened until acceptable burn-through ranges. In comparison with the single platform jamming case, the UAV swarming case yields an important signal power advantage which means increased jamming range. In this scenario, a friendly platform with an RCS value within the range of 1–6 m^2 which includes the RCS value of many fighter aircraft such as F-4, MIG-29 and B-1B [29]. Thus the scenario clearly shows that many modern aircraft may be protected against adversary air defense radars utilizing wireless beamforming in a swarm UAV network. Even larger platforms with greater RCS values may be screened given that the output power at the UAV antennas in the swarm or the number of the swarm elements is raised.

7 Operational Advantages of Electronic Attack Using Swarm UAV Networks

UAVs have been used for various military purposes. They could be utilized within several kinds of warfare like reconnaissance, battle management, chemical-biological warfare, information warfare and etc. And UAVs may be included in other possible warfare such as command/control (C2), force protection, suppression of enemy air defenses (SEAD), mine counter measures (MCM) and psychological operations (PSYOP) or etc.

Today EA is vital to all types of military operations over the world. In the traditional approach, EA involved a large jammer platform—mostly a specially designed aircraft as a jammer—provides EA capability. Another option, which is proposed in this paper, is to use unmanned aerial vehicles (UAVs) in EA missions. Each choice has its own trade-offs. Large platforms carry much higher jamming power than the relatively small UAVs, however they are more vulnerable to adversary threat given that they have much greater

RCS values than that of UAVs. This paper discusses that tasking a cluster of small UAVs, which are swarmed and wirelessly interconnected, as a jammer component has many advantages over the choice of employing relatively larger manned platforms. A brief list of assessed advantages is presented below [8]:

7.1 Low Power Requirements

Conventionally, a jamming platform must stand off at a significant distance from a target. As it needs to stand off, it requires more power. By small-size swarm UAVs, it is able to stand in that means less power to jam a given target. And as shown in SA-2 jamming scenario in Fig. 1, using single UAV jamming antennas with an apparently low power level of 100 mW it is able to screen a friendly fighter aircraft. Same jamming performance would require a higher jamming power if a manned platform were to be used.

7.2 Low Observablity

Large EA platforms generally have RCS values within the range of 1–100 m^2 [29]. On the contrary, small UAVs that are proposed in this paper for swarm jammer application mostly have negligibly low RCS values. Coupled with abovementioned low output power levels, the negligible RCS means that single swarm elements can be regarded to be low observable to the adversary air defense systems. Moreover, these mini and/or micro class UAVs have an inherently small infrared, and acoustic signature, which, when coupled with their low cost and expendability, makes them the optimum candidate for EA mission.

7.3 Reduced Mission Risk

The aforementioned advantages "a" and "b" yield reduced mission risk for the UAV swarm. In case the swarm is targeted by adversary air defense, due to its flexible network topology the swarm may be distributed in order to neglect adversary threat. In addition, due to the stand in EA swarm UAVs closer to the target the potential for electro-magnetic fratricide is reduced.

7.4 High Operational Flexibility

Flexibility is the key to air power effectiveness, though many might claim it is a cliché. At first glance, it looks likes to lake the inherent flexibility of manned platforms because of the single role of swarm UAVs. However, by the utilization of swarm UAVs in EA, EW or SEAD roles, the manned platforms, personals, time and money can be directed to other issues and roles. Furthermore, instead of high-cost stand off missiles, cheaper missiles can be used. In addition, a swarm of inexpensive mini and micro UAVs owns an important advantage, which is, if one member of the swarm is lost in operation, the rest of the swarm can carry out the mission. Finally, this concept allows tasks to be performed by military or civilian specialist outside the operation zone.

7.5 Mission Sustainability

The risk of losing the whole EA component is reduced because even if a considerable percentage of the swarm elements are downed, the remainder may be re-grouped in order to form a new swarm. In this case, the jamming power of the new swarm network will obviously be lower; however the EA mission will be sustained.

7.6 Cost Effectiveness

Given that mini and/or micro class UAVs are proposed in this paper, generally they are far cheaper than larger manned jammer platforms. A moderate mini or micro-UAV can cost a few thousand US dollars while larger platforms cost millions. Thus, a jammer application of a swarm UAV network formed by hundreds of such UAVs will be cheaper in comparison with any manned jamming platform.

7.7 Psychological Effectiveness

The effects of EA swarm UAVs are not physical alone but also have a psychological impact in the battlefield. These impacts are double-sided; means affect both friend and foe. However, the negative impact of having a big force multiplier as EA swarm UAVs on the enemy will be more severe than the positive effect on the friend. Because, for friend side perhaps it will only increase the sense of confidence but for enemy side to know the trustful defense system will lose some functionality by not knowing where a swarm UAVs come from, brings with it concern, fear, insecurity, and hopelessness. Consequently, due to stressful psychological effects the enemy side can have wrong decisions and make bad conflict planning.

8 Outstanding Challenges

8.1 Geolocalization Problem of the Swarm Elements

Element localization is crucial to the beam forming performance. Geolocalization or referenced locations of the array elements may consists a problem in a UAV network given that each node is highly mobile and their positions will be continuously changing. If available, every single UAV element is required to send a position information signal to the master or beam former UAV within predetermined time periods. Sufficient level of accuracy about the location information should also be achieved.

8.2 Synchronization Problems Between the UAV Antennas

Since each UAV antenna is to have a separate local oscillator, it is highly probable that important synchronization errors will occur between the swarm elements. Synchronization is important so as to ensure that the beam forming signal is converged coherently at the target in order to gain full advantage of beam forming and get increased signal-to-noise ratios. Thus, imperfect synchronization which can degrade beam forming performance is a major outstanding challenge to be addressed.

8.3 Complex and Crowded Air Space

Today proper management and control of air space is crucial to mission success. Frequent use of UAV swarms may introduce a crowded air space which might be a challenge to the battlefield air space controllers. In order to avoid fratricide, which is an air warfare term to describe losses by friendly fire, UAV swarms flying in crowded air spaces may increase the requirement for additional air space controlling procedures.

9 Conclusion

In this paper, the feasibility of merging wireless beam forming and UAV swarming concepts is analyzed. An electronic attack application of swarmed UAVs is proposed and the operational advantages of such a design over conventional manned jamming platforms are assessed. The outstanding difficulties and restrictions of beam forming in a swarm UAV network are pointed out. It was concluded that beam forming in a swarm of wirelessly networked UAVs is feasible despite the outstanding challenges. It was also concluded that employing a swarm of UAVs carrying EA payloads as a jammer component instead of conventional larger manned platforms yields many operational advantages such as reduced risk, low power requirements, mission sustainability and cost effectiveness etc.

Furthermore, the micro and small UAVs will increasingly execute SEAD/EW missions in the next decades. Projects, by 2035, include the swarm UAVs which will have fully autonomous capability, giving them unprecedented capabilities throughout the full spectrum of conflict. By using multiple-mini/micro UAVs as swarm EA platforms, greater efficiency will be gained in operations. Indeed, different sized UAVs, such as a combination of mini and micro UAVs, can be used in a swarm UAVs operation.

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