PROBLEMY MECHATRONIKI
UZBROJENIE, LOTNICTWO, INŻYNIERIA BEZPIECZEŃSTWA

ISSN 2081-5891 **8, 4 (30), 2017, 79-94**

PROBLEMS OF MECHATRONICS
ARMAMENT, AVIATION, SAFETY ENGINEERING

SAN: an Integrated Unmanned Air Vehicles Interdictor System Concept

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Received by the editorial staff on 1 June 2016.
Reviewed and verified version received on 9 August 2017.

DOI 10.5604/01.3001.0010.7319

Abstract. The development of unmanned air vehicles (UAVs) has been very rapid recently. The wide accessibility of UAVs has unlocked a great potential for the malicious or accidental damage or destruction of property or other aircraft in flight. UAVs can be used for espionage, contraband, and the trafficking or transport of arms and hazardous materials. Every month sees a growing number of reports of incidents that involve remote-controlled UAVs operated for aerial video recording. These incidents justify undertaking research into minimizing the hazards which UAVs may potentially cause. A concept was developed for a solution dedicated to this problem and comprising an integrated modular anti-UAV system for application in commercial (civilian) markets in the areas of security of mass events, strategic enterprises, and critical strategic infrastructure in Poland.

This work has been compiled from the paper presented during the 11th International Armament Conference on *Scientific Aspects of Armament and Safety Technology*, Ryn, Poland, 19 - 22 September 2016.

The proposed system is intended to incapacitate any UAVs that breach a predefined air space and bring the incapacitated UAVs safely to the ground. The project is developed jointly by the Institute of Armament Technology at the Military University of Technology (Warsaw, Poland) and Polish company Ellipsis Sp. z o.o.
Keywords: unmanned air vehicle systems, drone, anti-terrorist security, air defence

1. BACKGROUND

The development of technologies related to unmanned air vehicles (UAVs) has been very rapid in recent years. As UAV technologies become increasingly popular, the market prices of UAVs reduce. Various types of UAVs can be equipped with sophisticated control systems that allow operation by virtually anyone, without extensive or time-consuming training. Moreover, some UAVs feature RC FPV (Remote Controlled First Person View) systems to allow aerial operations outside the operator's line of sight and at distances of up to several kilometres. Many modern UAV systems available on the civilian/commercial market can easily reach an altitude of 1000 m and a cruising speed of 60 m/s. UAV systems also exist which can operate independently from a human operator by performing pre-programmed flight patterns, guided by various on-board systems, including GPS, inertia sensors, video cameras, etc. Given the relatively small sizes and the ability to fly at low altitudes, to hide or be hidden from sight behind terrain obstacles, to land in virtually any location, and to undertake extreme manoeuvres, UAVs are very difficult to detect and track.

The widespread availability of UAV technologies has unlocked great potential for creative applications of this aircraft type, and in many different fields. There are UAVs now available in the civilian market that are capable of commercial passenger flights. Law enforcement services have begun operating UAVs to look for lost persons, in daily field operations, to monitor road traffic, and to secure mass events. A number of private enterprises (including Amazon) has been studying the feasibility of operating multirotor UAVs for shipping goods purchased by their customers. UAVs are also used in industrial research projects, to monitor engineering structures or manufacturing facilities. The great number of UAV applications may also result in abuse of this technology through malicious or unintentional use in criminal ways. The potential hazards of UAV operation include:

– damage to or destruction of other manned or unmanned aircraft;
– damage or destruction of property;
– carriage of arms, hazardous materials or explosives;
– injury or death;
– espionage;
– smuggling of contraband.

The number of incidents involving UAVs has been growing in recent years. A report published by the U.S. Federal Aviation Administration states that in 2015 there were 770 incidents involving UAVs, 27 of which could be qualified as close encounters.

Similar incidents have happened in Poland, too. In 2014, a remote-controlled aircraft replica dropped a flare into the military area at Balice Airport in Kraków (Poland). Over a dozen UAV-related incidents were reported in Poland in 2015. The most prominent incidents involving UAVs include a collision between an unidentified UAV and an F-16 fighter aircraft over the Krzesiny Polish Air Force Base. The incident damaged the fighter's skin. In July 2015, a remote-controlled multirotor came into dangerously close proximity to an Embraer 195 passenger plane, which was landing at Okęcie Airport (Warsaw, Poland). In April 2016, the first-ever collision between a landing passenger plane and a radio-controlled UAV filming the aircraft happened at Heathrow Airport. In the same month, a military UAV weaponized with explosives was used for the first time in a combat situation as a 'hunter-killer missile' during one of the battles of Nagorno-Karabakh.

Terrorists have for some time now been interested in the weaponization of UAVs to carry out attacks [1]. The use of UAVs by terrorist organizations has great potential, which comes from certain advantages unmanned air vehicles have over conventional forms of terror attacks [2]:

– UAVs can strike targets inaccessible by land (e.g. to bomb a car or a suicide bomber operating on foot);
– UAVs can strike on a large scale, mainly with biological or chemical weapons;
– an attack with a UAV is hard to detect, and the take-off location of a weaponized UAV can be virtually anywhere;
– UAVs combine a relatively long striking distance with high accuracy at low cost, all with a widely available technology;
– current air defence systems are rather poor at detecting and engaging small, low-altitude UAVs;
– good performance to cost ratio;
– ability to achieve a strong psychological effect.

Terrorist organizations highly value a strong message and good media coverage for their attacks, which helps them stir unrest, anxiety and panic among the global community. Should it be successful, a terror attack with a UAV would largely undermine the public sense of security and expose the impotence of law enforcement agencies at preventing such incidents.

Although no terror attack with a UAV has been reported yet, there are media reports which implicate that various terrorists are proactively investigating the weaponization and application of UAVs for terror. There have been several recorded failed attempts at UAV terror attacks.

In 2001, Al-Qaeda, led by Osama bin Laden, considered using remote-controlled aircraft weaponized with explosives to assassinate the G8 leaders during a convention in Genoa, Italy; in 2003, the same organisation schemed to acquire a nondescript UAV type and strike the British House of Commons. Similar attacks on Israeli settlements were planned by Palestinian extremist factions in 2002 and 2004.

The threat level related to the illegal use of UAVs will continue to rise, as this technology is becoming increasingly popular. It is then indispensable to develop a civilian-market defence solution capable of identifying and effectively countering risks posed by unauthorized UAV operation. The problem has been considered by Polish Armaments Group and the Polish Ministry of Defence. The priorities of the 2019 Polish Armed Forces Technical Modernization Plan include general upgrades for the Polish armoured and mechanized forces, marine threat enforcement, cybersecurity, and, last but not least, air defence. Moreover, the air defence upgrade priority measure follows the framework established in the document: "Years 2013 to 2022 Priority Research Vectors for National Defence", with Section 4.4 concerning defence against unmanned military system platforms.

2. REVIEW OF CURRENT SOLUTIONS

Air defence against small UAVs is a relatively novel problem. This is because to date there have been very few anti-UAV (or UAV interdictor) technologies to see successful use in real-world scenarios. The anti-UAV solutions implemented so far function largely by the principle of interfering with the UAV's electronic control systems. The embodiment of this principle depends on the manufacturers of specific solutions. Broadcasting high-power RF signals in the UAV remote control band (typically 2.4 GHz) jams the transmission of command and feedback signals to and from an UAV, forcing the UAV to react in a way designed by its developer for those circumstances. The exact reaction to the loss of remote control connection with the UAV operator may vary according to the sophistication and complexity of the UAV on-board systems. Some models and types of UAVs can initiate automatic return to the take-off location or land immediately and safely. Other UAVs may continue to fly along the last heading. The least sophisticated UAV models may simply shut down and crash into the ground. Unfortunately, the latter case is dangerous to the people and property forming the crash site of the UAV, which prevents any safe use of UAV interdiction technologies for mass event security.

Airbus Defence and Space suggested an anti-UAV solution (Fig. 1) called the Airbus Counter-UAV System. It is capable of the long-range detection of UAVs trespassing in secured areas, jamming the controls of the UAVs, and locating the UAV operators.

The Counter-UAV System comprises monitoring equipment, RF locators, RF signal data analysis and processing systems, and directional electronic jammers. The Counter-UAV System can detect UAVs 5 to 10 kilometres away and rate their threat level. The RF signal data analysis and processing system runs in real time to enable the complete jamming of the RF communication between the targeted UAV and its operator on the ground (to deprive the latter of control over the UAV) and jam the UAV navigation systems to prevent further flight.

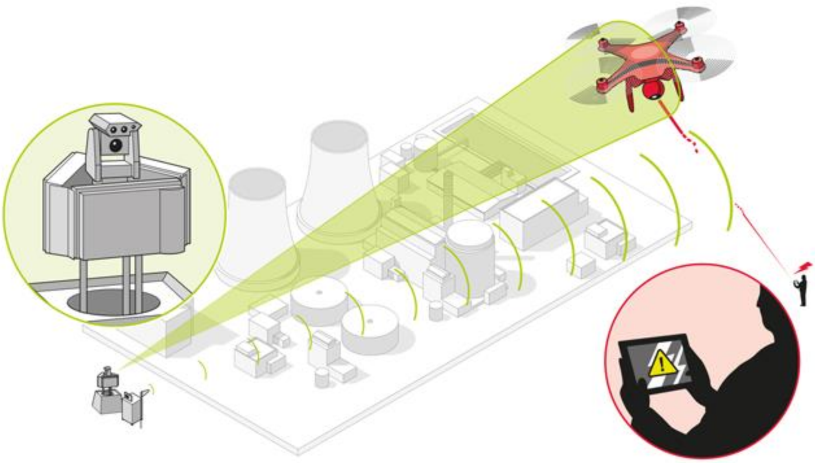

Fig. 1. Airbus Counter-UAV System

A similar anti-UAV solution has been showcased by an Italian company, Selex ES. Selex ES proposed an anti-UAV system called “Falcon Shield” which, unlike the Airbus Counter-UAV System, has a modular architecture; hence, it allows customizing of the detection and jamming components.

A similar anti-UAV solution by control communication jamming is the AUDS, or Anti-UAV Defence System (Fig. 2) proposed by a consortium of Blighter, CHESS Dynamics, and Enterprise Control System.

The AUDS comprises a threat detection radar (Blighter A400), an optoelectronic UAV tracking and identification subsystem (CHESS Dynamics Hawkeye/DS/EO), and a GPS and RF communication jamming application (Enterprise Control System).

These three systems are stationary and very complex, making them high expenditure projects with poor mobility and impractical to apply as mass event security, which requires the deployment of an anti-UAV system in virtually any location.

Fig. 2. AUDS (Anti-UAV Defence System)

The challenge of tackling these issues has been taken up by Battelle, an R&D organisation, which has developed a device called DroneDefender (Fig. 3): a low-budget, easy to use anti-UAV system with an effective range of 400 m. The DroneDefender broadcasts RF signals at the frequency band required to interrupt remote control of the targeted UAV. The DroneDefender can be operated in stationary and portable modes. The operating time, dictated by the battery, is 5 hours at best, with a total weight of the DroneDefender of approximately 4.5 kg.


Fig. 3. DroneDefender

Another approach to the UAV threat involves UAV-safe defence systems, which employ nets to catch illegally operated UAVs. This approach is currently under development by a number of companies.

OpenWorks Engineering has presented SkyWall, a system comprising a compressed gas-powered smart launcher and an intelligent programmable projectile, which deploys a net in mid-air (Fig. 4).

Fig. 4. The SkyWall projectile launcher

The SkyWall launcher shoots a projectile by compressed air; the projectile breaks apart at an optimum distance from the UAV to deploy a net with a parachute. When the net engages the UAV, the parachute brings both safely to the ground. The SkyWall projectile launcher weighs 10 kg and boasts a striking distance of 100 m.

The projectile muzzle velocity and elevation angle of the shot are determined by a tracking computer in the launcher to help the SkyWall operator choose when it is best to fire. Once launched, the SkyWall projectile exchanges data mid-flight with the projectile launcher to determine the exact moment at which the projectile should deploy the net.

Aside from manned ground anti-drone weaponry, there is a growing interest in operating what can be called counter-drones, counter-UAVs or hunter-UAVs/drones, which are UAVs simply designed to intercept illegally operated UAVs. The first counter-drone was used in 2015 by the Tokyo Metropolitan Police; their solution was to hoist a net under a multirotor UAV.

The scientists at the Michigan Tech University Human-Interactive Robotics Lab have built an octocopter-based UAV with a net launcher. This multirotor "hunter" (Fig. 5) can intercept and catch other UAVs.

The striking distance of the net is approximately 12 m. Once deployed, the drone-catching net remains connected to the “hunter”, so the latter can bring the “prey” to any location. The multirotor “hunter” can be controlled by a human operator or operate autonomously.

Fig. 5. Counter-UAV built at the Michigan Tech University

A similar solution has been proposed by Delft Dynamic of the Netherlands; the difference is that the “hunter” UAV shoots nets with parachutes. Once a trespassing UAV is incapacitated with the net, it lands safely thanks to the parachute.

There has been research into the application of high-power electromagnetic pulses intended to destroy the electronic control systems of illicit UAVs.

It is evident that there are few engineering measures currently existing to protect sensitive air space and mass events from trespassing UAVs. See Table 1 for a list of systems, complete with pros and cons.

Most of these systems embody the concept of RF control line jamming or destruction of UAV on-board electronic systems, which may cause the targeted UAV to crash and (a) release hazardous materials (if any), (b) cause personal injury and/or (c) damage property.

Only three anti-UAV systems are known to safely incapacitate and land the targeted UAV on the ground, with two embodying the principle of counter-drones or hunter-drones. Given the current geopolitical makeup, it can be concluded that development of these systems will continue in the foreseeable future. It is then prudent to carry out research to develop an advanced, integrated platform to interdict UAVs.

Table 1. List of anti-UAV systems

Manufacturer	**Name**	**Target market**	**Pros**	**Cons**
Airbus Defence and Space	Counter-UAV System	Military	- long range - directional - selective RF jamming	- very high costs - stationary - unforeseeable UAV response
Selex ES	Falcon Shield	Military	- long range - may take over the UAV - modular	- very high costs - stationary - unforeseeable UAV response
Blighter, CHESS Dynamics, Enterprise Control System	AUDS (Anti-UAV Defence System)	Military	- long range - selective RF jamming	- very high costs - stationary - unforeseeable UAV response
Battelle	DroneDefender	Commercial	- mobile	- unforeseeable UAV response
OpenWorks Engineering	SkyWall	Commercial	- safe UAV landing - high rate of fire - low cost	- short range
Michigan Tech University's Human-Interactive Robotics Lab	-	Commercial	- counter-UAV-dependent operating range - safe UAV landing - low cost - mobile	- one-shot capability
Delft Dynamic	-	Commercial	- counter-UAV-dependent operating range - safe UAV landing - low cost - mobile	- one-shot capability

3. THE PROPOSED SOLUTION

The subject of the project proposed herein is a comprehensive UAV interdictor system, codename SAN. The SAN will be based on state of the art technologies and a wide spectrum of target detection, tracking and incapacitation methods. The SAN is designed for protection of mass events, strategic enterprises and strategic infrastructure in Poland. The SAN will provide an end-to-end solution with significantly improved security against the growing threat of 'rogue UAVs'.

Based on a complete audit, conceptual design work and testing phases, it was found that the SAN could feature resources to enable the identification and incapacitation of UAV-related threats.

Given that the drone/UAV defence sector is still in the initial stages of development and growth in Poland, the technological solutions offered under SAN will be developed gradually by implementing successive modules to improve the level of security and protection. The ultimate SAN evolution will include the following components (Tables 2 and 3):

– Short range defence systems: to eliminate low-altitude UAVs that pose an imminent threat to personnel or property;
– Target identification systems: medium-range target identification based on thermal imaging and remote control signal sniffing;
– Electronic disabling system: a microwave radiation system for targeted medium-range incapacitation of UAVs.

The cornerstone of SAN is a developed projectile launcher and smooth-bore firearm projectiles which deploy nets to entangle the UAV. The net will incapacitate the rotor(s) of the UAV. The ultimate SAN evolution will feature projectiles with modules to slow down the descent of the incapacitated UAV with a parachute formed by purpose-designed ribbons with a high aerodynamic drag.

Most importantly, the incapacitated UAV will have the rotor(s) disabled when descending to the ground; this will prevent injury and property damage, while the ribbon parachute deployed by the projectile with the net will greatly reduce the descent rate.

Table 2. SAN safe UAV interception modules

	Short range defence	**Medium range defence**	**Long range defence**
Tracking and acquisition	Manual and aided by visual optics	Automatic: visual and thermal	Automatic: visual, thermal and radar
Incapacitation	An entanglement net projectile for smooth bore firearms	An entanglement net module launcher	A system of remote-controlled Interdictor UAVs
Grounding	Free fall	Ribbon parachute	Ribbon parachute and Interdictor UAV rotor thrust
Optional	-	Electronic system destruction system	Electronic system destruction system

In the target evolution of the SAN, the entanglement net launchers will be installed on the Interdictor UAVs. According to this concept, rogue UAVs will be intercepted by a high-speed UAV.

Table 3. Incapacitation system types

	Smooth-bore firearm system	**Medium range anti-air guns (launchers)**	**Interdictor UAVs**
Rotor entanglement net module	+	+	+
Ribbon parachute module	-	+	+
Multiple hits	+	+	-
Flight manoeuvring	-	-	+
Automatic targeting	-	+	+

This Interdictor UAV will feature a digital-assisted acquisition and tracking system to approach the target, shoot the entanglement nets and, upon a successful hit, use the ribbon parachute and its own engines to slow the descent of the rogue UAV to the ground.

3.1. Conditions for the tracking and acquisition system

The tracking and acquisition system is to be a budget-friendly solution. It was decided to build it with commercially available components for the initial stages of SAN evolution. The SAN system will feature components to help the SAN operator identify, track and intercept the rogue UAVs in the restricted air space. The key features to base the automatic target detection and tracking on include:

- Thermal traces generated by electric motors and high-density batteries, including:
  - Generated heat intensity
  - Hot spot shape
- UAV control transmitter signals to track down the rogue UAV and its operator;
- Visible-light optical system data.

The tracking and acquisition system will combine a number of different sensor outputs to enable explicit identification of the target. It will be necessary to implement the following modules:

- A data aggregation system: the module will communicate with specific SAN subsystems which will use different physical phenomena (i.e. thermal imaging, RF, and machine vision) to collect the data required to identify and track targets;
- A data processing system: a central subsystem which will synchronize and correlate the aggregated data to identify the detected UAVs;

- An identification verification system: to communicate with the SAN operator(s) who will make the final call to confirm or reject the threat. The identification and incapacitation process will not be fully automatic.
- An automatic response procedure system: to respond to each confirmed threat.

A system is also planned for auditing and reporting events and external communication with third-party security systems operated in parallel with the SAN.

3.2. Conditions for the entanglement net module launcher system

The launcher system being developed for the entanglement net to intercept rogue UAVs is an innovation among similar designs (Fig. 6). The entanglement net launcher system is designed as an integral part of the Interdictor UAVs.

The system comprises a projectile launcher and an entanglement net-deploying projectile head, i.e. the module. The entanglement net is square and with a total surface area of 1 m^2. The corners of the entanglement net have weights attached to endow it with an optimum speed and direction after deployment from the projectile. The weights are housed in guidance tubes inside the projectile before deployment. The projectile launcher has a gunpowder-based two-chamber propellant system. The propellant system largely reduces the G-forces generated upon firing the entanglement net module (the projectile) by significantly reducing the maximum pressure in the expansion chamber and retaining a sufficient pressure pulse. This allows the use of light-weight structural materials in this project, such as aluminium and high-strength plastics. In comparison to similar, compressed-air propelled projectile launchers, the overall projectile launcher system is lighter, and eliminates any need for compressed air (or other gas) canisters or bottles.

The solution for the primary problem of internal ballistics was developed using a mathematical model of the gunpowder-based two-chamber propellant system [3], with suitable modifications to consider the specific nature of the intended structure of the SAN components. The solution calculations showed that the maximum pressure in the expansion chamber will be approximately 3±0.15 MPa. Given this, the module (projectile) head in which the entanglement net will be stored can be manufactured from a high-strength plastic by 3D printing. 3D printing allows the manufacture of geometrically complex objects with the optimum use of volume and an optimum dispersion angle of the weights used to direct and propel the entanglement net.

The operating principle of the entanglement net projectile launcher is as follows: once the target UAV is identified, the entanglement net module/ projectile is initiated, with a firing pin initiating the gunpowder-based propellant.

When the combustion gas from the initiated propellant reaches a predefined shearing pressure, it cuts a diaphragm and proceeds via combustion gas ducts from the combustion chamber to the expansion chamber. The pressure of the combustion gas in the expansion chamber meets the rear ends of the entanglement net weights and propels them forward. When the weights leave the guidance tubes, they begin to drag and deploy the entanglement net in the air. The dispersion angle of the weights will fully deploy the entanglement net approximately 4 to 5 m in front of the launcher. The small gunpowder-based propellant charge propels the entanglement net weights to approximately 45 m/s; given that the entanglement net weighs 167 g, its muzzle velocity reaches approx. 7.5 m/s. The muzzle velocity can be easily modified by changing the small gunpowder-based propellant charge or the mass of the weights.

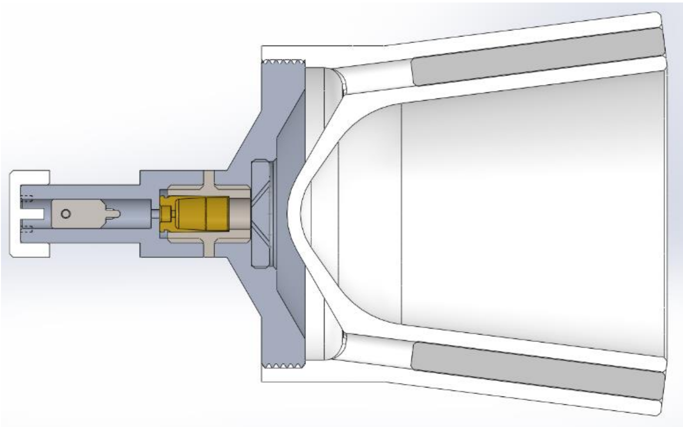

Fig. 6. Diagram of the entanglement net projectile/module launcher:
1 – breech bolt, 2 – firing pin, 3 – combustion chamber, 4 – baffle with diaphragm, 5 – expansion chamber, 6 – weight, 7 – entanglement net stowage compartment

The entanglement net behaviour in flight will be analysed at the next design stage of the SAN project. Based on [4], a conclusion can be made that along its flight trajectory, the entanglement net will form a paraboloid, which will reduce the effective intercepting surface area. It can also be concluded that a limit value exists for the muzzle velocity of the entanglement net weights.

A further increase in the muzzle velocity above the limit will not improve the deployment (spreading) of the entanglement net or its striking range. It will be necessary to develop a numerical model to map this phenomenon and select the optimum shape, size and mesh size of the entanglement net.

4. CONCLUSION

The SAN system being designed comprises an Interdictor UAV and an entanglement net module/projectile launcher, which require continued research to verify the design conditions, optimize the structural design, and improve the target tracking and interception efficiency.

A high number of experimental tests is necessitated by the difficulty of designing dedicated systems from scratch.

Work is currently under way to prove the effectiveness of the SAN projectile launcher and its ammunition, which function along with the designed tracking system, in order to incapacitate UAVs at short range. The research is carried out in cooperation with the Military University of Technology in Warsaw (Faculty of Mechatronics and Aerospace, Institute of Armament Technology). Installation of the entanglement net module/projectile launcher on a dedicated Interdictor UAV will extend the strike range significantly; this will improve the effectiveness of the entire SAN solution. To achieve this objective, it will be necessary to modify a projectile launcher solution to install it on a SAN-dedicated UAV. The designed SAN system will then be able to incapacitate rogue UAVs at a striking distance of 300 m, while the ribbon parachute system will reduce the descent rate and bring the incapacitated UAVs safely to the ground.

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Koncepcja Zintegrowanego Systemu Antydronowego – SAN

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Streszczenie. W ostatnich latach można zaobserwować szybki rozwój technologiczny bezzałogowych statków latających. Szeroki dostęp do bezzałogowych statków powietrznych (BSP) otwiera drogę do nadużyć spowodowanych ich umyślnym lub niezamierzonym użyciem w celu doprowadzenia do uszkodzenia lub zniszczenia innych statków powietrznych, innego mienia. BSP mogą być wykorzystywane do szpiegostwa, przemytu, przenoszenia broni i substancji niebezpiecznych. Z miesiąca na miesiąc wzrasta liczba doniesień odnośnie incydentów z udziałem głównie modeli zdalnie sterowanych wykorzystywanych do filmowania z powietrza. Uzasadnia to podjęcie prac zmierzających do zminimalizowania zagrożeń, jakie mogą być spowodowane przez bezzałogowe statki powietrzne. Opracowana została koncepcja dedykowanego rozwiązania w postaci zintegrowanego, modułowego systemu do ochrony przeciw BSP, który może zostać zastosowany w rynku cywilnym do ochrony imprez masowych, strategicznych przedsiębiorstw oraz infrastruktury krytycznej w Polsce. Proponowany system ma na celu unieruchomienie BSP, które naruszyły zastrzeżoną przestrzeń powietrzną i bezpieczne sprowadzenie ich na ziemię. Projekt powstaje we współpracy Instytutu Techniki Uzbrojenia Wojskowej Akademii Technicznej z firmą Ellipsis Sp. z o.o.

Słowa kluczowe: bezzałogowe systemy latające, dron, ochrona antyterrorystyczna, obrona powietrzna