Countering UAVs – the Mover of Research in Military Technology

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ABSTRACT

Unmanned aerial vehicles (UAVs) are massively seeping into a wide range of human activities. Along with other remotely controlled or automatic devices, they have entered many aspects of human activities and industry. While the majority of researchers have been working on the construction, deployment and non-military use of UAVs, the protection against UAVs remained on the edge of their interest. Nowadays, the situation is rapidly changing. The risk of misuse of UAVs by criminals, guerrillas or terrorists has compelled authorities, scientists and defence industry to face this threat. Organisations have launched crucial infrastructure defence programs to cope with UAV threat. To solve this problem, it is necessary to develop disciplines improving the air space surveillance and UAVs elimination techniques. The substantial aspects of the UAVs detection and elimination were analysed, being supported by a number of conferences, workshops and journals articles. The contribution of the study in the Counter–UAV area consists particularly in generalisation and evaluation of the main technical issues. The aim of this paper is to emphasise the importance of developing new scientific fields for countering UAVs, and hence it is directed firstly on the scientific audience.

Keywords: Defence technology; Air defence; Unmanned aerial vehicles

1. INTRODUCTION

Unmanned aerial vehicles have already become an integral part of military, security and rescue services. They are commonly used even for leisure activities. However, due to lagging legislation, the UAVs have not yet officially joined the common airspace for piloted vehicles and hence they still cannot be deployed for wider commercial use – for example by logistic companies[1].

Scientific-research teams, students, professionals as well as amateur enthusiasts drive this aviation field forward. Groups of skilled (or less skilled) aircraft engineers, programmers, operators and UAV users are growing rapidly all over the Europe and the whole World as well[2]. As analysed and then stated[3], 'The world of unmanned aviation is a very impatient innovative world'. This generates new options for scientific development.

Due to the undisputable advantages, the UAV technologies are widely used for military purposes. Aside from regular military utilisation, they are being used with increasing frequency by paramilitary and guerrilla (criminal) organizations. It should be noted that the negative exploitation of the unique features of the UAVs is not happening in the criminal groups only. People trying to take an original selfie, tabloid journalists disturbing celebrities, or individuals capturing extreme adrenaline video shots can endanger e.g., aircraft take-off procedures. And even here – in the field of protection and defence against such exploratory and invasive

UAV activities – there is a wide range of scientific disciplines that could be driven forward by this phenomenon.

2. RESEARCH AREAS FOR UAVS DEVELOPMENT

Regarding the entire unmanned aerial system (UAS) of which the aircraft (UAV) itself is a one part, one can define research areas that can be approached from the technological or the operational point of view[4]. This issue, including a significant focus on military domain and its connection to NATO documents, has been thoroughly analysed[5].

As discussed by Demir[5], *et al.* it is also possible to identify weak, still lagging problems, requiring new technical solutions, and thus directing relevant R&D activities. For these reasons, the scientists and technicians are trying to scale the levels of maturity or the levels of sophistication presently achieved within scientific disciplines related to UAS construction and operation. Based on analyses, studies and experiments, the authors suggest the scaling of below stated levels.

The degree of sophistication presently achieved in the individual scientific disciplines related to UAS construction and operation can be evaluated. Based on analyses, studies and their own experiments, the authors suggest the evaluation to be conducted as follows:

- Performing a correlation between research areas (applying Czech Government resolution[7] and its enclosure[8]) and UAV configuration, or the legal and social aspects of their operation. In the first column of Table 1, this is collectively referred to as Aspect.

- Think-tank or expert evaluating the existing degree of sophistication.
- Evaluating the given R&D area in relation to UAS.
- Evaluating the need to achieve some considerable progress in the corresponding branch of knowledge.

Qualitative correlation, followed by an evaluation were carried out (inspired by methodology[5], Table N°5). A five-degree scale was created for the expert evaluation.

Low ....'L'
Bellow moderate ....'BMod'
Moderate ....'Mod'
Bellow mature ....'BMat'
Mature ....'Mat'

The grades in Table 1 were given from subject matter experts (SMEs) evaluation questionnaire. SMEs were chosen from the following branches – Ground Based Air Defence (Czech), Aircraft construction (Czech), Air Forces (Czech).

SMEs were not able to make a consensus of which aspect should have higher weight than the other, so all aspects have the same weight. Some aspects were not evaluated by SMEs. That was in case when most SMEs were not able to evaluate certain aspect according to the branch of knowledge. The final level of aspect maturity was given by stating the centre of gravity (while all aspects have the same weight considered). E.g. the platform aspect has two evaluated braches of knowledge (ICT and Geogr.). One has below mature preferences and the second moderate preferences. Than the final aspect maturity was stated as moderate in this case. That was because most of SMEs voted moderate decision in case of Materiel engineering branch, than below moderate decision in case of Mechanical engineering branch. The centre of gravity of opinions in case of material engineering branch was stronger (there were more the same opinions).

Analysis of the results in Table 1 and the subsequent evaluation show that, from a technical point of view, the unmanned system can be classified as 'Moderate mature'.

To conclude the above, the massive development of UAS technology is outgrowing user, legal, moral, and military-political frameworks. These facts indicate the direction of the future research, development and applications.

3. AIR THREATS AND AIR DEFENCE TECHNOLOGY

Scientific research organisations (both military and security) have started to investigate possible ways of protection against UAVs relatively recently. This mostly concerns the 'mini-UAV' and smaller categories[9].

The problem of defence is principally built on three fundamental pillars (the term 'pillar' as a supporting element of any logical framework is used according to NATO terminology):

(I) **Air Surveillance:** This includes: the detection, recognition, localisation, and identification of an aerial object;

(II) **Command and Control** (C2) of all resources included in an AD system;

(III) **Elimination** of the aerial object – if it poses an AT.

Logically, defence against larger UAVs (Class II and III according to NATO UAV classification) is associated with the defence against standard threat (an aircraft). With the

Table 1. UAS sophistication quantification

Branch of knowledge / Aspect ↓	ICT	Geogr.	Mech. Eng.	Mater. Eng.	Electr. Eng.	Civil, Social & Politics	Military	No. of branches included	Maturity of aspect
			Technical view			Operational view			
Platform			BMat	Mod				2	Mod
Propulsion			Mod	BMat	BMod			3	Mod
Avionics and control	BMat	BMat	BMat	Mod	BMat			5	BMat
Payload			BMat	Mod	BMat	Mod	Mod	5	Mod
Autonomy	Mod	Mod						2	Mod
Ground equipment	BMat	BMat	Mod	BMat	Mod			5	BMat
Ground H/M interface	Mod				Mod			2	Mod
Support elements	Mod		Mod		Mod			3	Mod
Operation - Higher levels						BMod	Mod	2	Mod
Operation - Tactical levels							BMod	1	BMod
Training						BMod	Mod	2	Mod
C2 and Communication	BMod				Mod		BMod	3	BMod
Certification						Low	BMod	2	BMod
Legal issues						Low	Low	2	Low
Moral and ethical issues						BMod	Mod	2	Mod
Number of aspects Included	6	3	6	5	7	6	8	**The whole maturity of UASs:**	**Mod**
Maturity of a single branch	Mod	BMat	BMat	Mod	Mod	BMod	BMod		
Maturity of the particular view	Mod					BMod			

introduction of completely new ways of using small UAVs (the 'mini' and lower categories) has led to a reassessment of the approach to Ground-Based Air Defence Asset technology and its operational use in the case of possible small UAV elimination. Table 2 shows a general comparison of distinctive AD-related characteristics of standard ATs, like a supersonic fighter[29] versus Mini UAVs 'Class I'[30].

Using principles of the expert evaluation methodology (like in[5]), a five-degree scale was devised: 1 - Small; 2 - Relevant; 3 - Significant; 4 - High; 5 - Crucial. This scale expresses the significance of a given parameter with regard to a given AD pillar. Qualitative assessment was chosen according to air defence SMEs' and authors' experience.

Table 3 reflects the degree of significance of the selected AT parameters with regard to the individual AD pillars.

In case of 'MTOW' and Platform robustness', the SMEs evaluation is 'Small', 'Small', 'Crucial', while the output (parameter significance) is 'Small' in case of 'MTOW' and 'Relevant' in case of 'Platform robustness'. That is because the evaluation 'Crucial' in case of 'Platform robustness' was more frequent (stronger).

Table 3 shows in fifth column, that from the AD realisation point of view, the key parameters (i.e. 'Crucial' and 'High') of aircraft are:
- Operational altitude during mission execution,
- Maximum speed during mission execution,
- The distance at which aircraft are able to affect defended object (operation radius),
- EW resistance,
- Attack distance.

4. RESEARCH DEVELOPMENT TO MEET THE C-UAV CAPABILITIES

The defence against UAVs through the implementation of measures in air surveillance, C2 and elimination domain assumes the creation of a complex system of sophisticated technological solutions. There is also a need for improvements in readiness (alert) system and adequate legal framework through most of command and control levels. When applied to CUAV issue, some of the measures require a completely new and specific approach. At the end of the air defence process, the chain of events must lead to such elimination of the UAV that the mission consequences, intended by the enemy, are completely neutralised or at least minimized.

The three AD pillars are further discussed in the context of defence against small UAVs.

4.1 Air Surveillance

Air surveillance and the information acquired about the aerial situation constitute the primary conditions for countermeasures. The gathered information is ideally without gaps in sensor coverage and distributed in real time. Nano, micro, mini and small UAVs have specific qualities with respect to their detectability – small physical dimensions, minimal effective radar cross-section (RCS), low emissions of thermal and

Table 2. Typical standard ATs and small UAVs characteristics comparison

Parameter, aspect	Standard AT (e.g. F-16 fighter)	Class I, Categories Mini and Micro
MTOW [kg]	up to # 1000	< 20
Dimensions [m]	5 +	< 2
Operation radius [km]	up to # 100	< 50
Maximum altitude AGL [m]	18 000 +	< 1500
Operation altitude AGL [m]	50 +	< 300
Useful payload [kg]	up to # 1000	< 10
Maximum speed [m.s^{-1}]	up to 700 +	< 60
Radar cross-section [m^{-2}]	1	< 0.2
Acoustic signature [dB]	> 100	# 10
IR signature/engine temperature [°C]	500 +	< 200
Platform robustness	middle - high	weak - low
EW resistance	high, active	none, minimum
Self-protection	active + passive	none
Take-off distance from attacked object [km]	up to # 100	up to # 1
Attack distance from an attacked object [km]	up to # 10	up to # 0.01
Max. cost [USD]	up to tens of millions	thousands

Note: The symbol '#' in Table 2 means 'several'.

Table 3. The significance of the AT parameters to the AD pillars

Pillar → / Parameter ↓	Reccon.	C2	Elimination	Parameter significance
MTOW	Small	Small	Crucial	Small
Dimensions	High	Relevant	High	Significant
Operation radius	High	High	Significant	High
Maximum altitude AGL	High	High	Relevant	Significant
Operation altitude AGL	Crucial	High	Crucial	Crucial
Useful payload	Small	High	High	Significant
Maximum speed	High	Crucial	Crucial	Crucial
Radar cross-section	Crucial	Relevant	Relevant	Significant
Acoustic signature	High	Small	Significant	Relevant
IR signature	High	Small	High	Significant
Platform robustness	Small	Small	Crucial	Relevant
EW resistance	High	High	Significant	High
Self-protection	Significant	Small	High	Relevant
Take-off distance	High	Crucial	Small	Significant
Attack distance	High	High	Crucial	High
Max. cost	Small	Small	High	Small

acoustic energy[10] and flight envelope (flight in low altitudes, relatively low speed, high manoeuvrability).

4.1.1 C-UAV Sensor Technology

Devices for small UAV detection must, therefore, include the widest possible range of the electromagnetic spectrum (and possibly the acoustic and optical). Their deployment must also be adapted to detection-influencing factors[11].

For the detection, localisation, and identification of small UAVs, the following technologies can be generally used:

- Active radars capable of detecting targets with a small RCS[12,13]
- Passive radar systems using various methods (such as passive coherent location (PCL))[14].
- Infrared sensors[15].
- Laser devices[16].
- Optical surveillance aids and devices[17,19].
- Equipment operating with image recognition technology.
- Acoustic devices[20].
- Devices capable of detecting and localising UAV remote control signals[18].
- A human air observer, possibly also equipped with any of the technology mentioned above.

The processing of initial information about the possible location of the UAV can often be highly challenging, since the size of signals containing this information is often only barely above (or even below) the threshold of a clutter[21]. The problems are especially in the urban area[22].

To increase detection probability during air surveillance, the deployment of a spatially distributed multispectral sensor framework is expected.

4.1.2 C-UAV Sensors

Based on the list of sensor types listed above and with respect to UAV categories, we can define tasks that need to be solved. Then, for each task, we have to define a clear research goal (or goals) in order to meet the desired final goal– elimination of the enemy UAV.

Among the most important tasks related to the detection, localisation and identification of small UAV are:

- Measuring RCS[23].
- Selecting proper radar frequency band.
- Optimising methods of suppressing the radar clutter[24].
- Optimising passive radiolocation methods[25].
- Selecting detection equipment parameters in the visible and infrared spectrum.
- Improving methods for range measurement[26] with optical rangefinders.
- Improving methods of selecting useful signals and suppressing acoustic clutter on the background of the UAV flight[28].
- Developing electromagnetic signal scanners in UAV remote control bands, including location identifiers.
- Developing automated (or even automatic) analysers and fusion algorithms for better UAV tracking.
- Optimising fields of sensors to detect UAVs in a given combat environments.

4.2 Command and Control

In principle, command and control systems suitable for the defence against small UAVs are similar to standard C2 systems, already used in the Air Forces.

For further analysis, let us assume that in the 'surveillance segment' (see 4.1.1), the true target is successfully isolated from the clutter, correctly localised and identified, and the C2 system receives already pre-processed information containing all necessary characteristics of the target.

4.2.1 Command and Control Technology for C-UAV

While countering the air threat, the task of the system is to acquire information from the sensors, fuse it, determine the (if possible) optimal task distribution for its effectors, assign a specific task, supervise its completion, and possibly take follow-up measures depending on the task assessment. Next task for C2 technology is the direct preparation of fire and fire control.

4.2.2 C-UAV Information and Communication Technology

The above-mentioned tasks and requirements of the C2 also lead to the other issues:

- Fusion of target data, which is often incomplete and being transmitted over a relatively short time.
- Optimising the decision-making process affected by:
  • Terrain configuration,
  • Sudden appearances of a UAV - often when it is no longer possible to effectively intervene,
  • Short period when the UAV is present in the Effector Kill Zone,
  • The complexity of decision-making process about target allocation to available effectors, such as anti-aircraft machine guns, cannons, directed energy weapons (DEWs) and electronic warfare (EW) devices,
  • Collateral damage, for example the impact zone of fired projectiles, where own troops or civilian population can be expected.
- Completing the often fragmented information about the results of tasks carried out by effectors, e.g. the need of the quick determination, if the UAV was hit or not.
- Data flow problems
  • Maximum data flow of effector control channels
  • Frequency compatibility of different sources of information
  • Compatibility of data links
- Minimising the number of elements (levels) in the fire control loop and the C2 chain itself.
- Assigning competencies and delegating them to the lowest degree (preferably to fire units).
- Information encryption and confidentiality.

4.3 Elimination

Several methods and corresponding means can be used to eliminate an AT in the form of a small UAV. In principle, methods of elimination can be divided into destructive and non-destructive.

4.3.1 C-UAV Effector Technology

Feasible destructive or disruptive methods include:

- Destruction by way of the kinetic energy of firearm projectiles

- • Scatter (shotguns, pellet guns)
- • Single bullet
- Concentrated beams of electromagnetic energy - DEW
  - • High-frequency
  - • Laser
- Partial destruction of a UAV, preventing it from continuing its flight
  - • Intercepting nets (fired at a UAV using a special projectile or delivered by another aircraft)
  - • Water or foam cannons (for short distances only)
  - • Special 'anti-drones'[31]
  - • Trained birds of prey (an 'ornitho-counter-attack'),
- Destructive effects of explosive anti-aircraft missile warheads.

Non-destructive methods can be utilized mainly by affecting the UAV (or other components of the UAS[32]) electronically:

- Jamming
  - • Control signals being transmitted from the operator to the UAV[33,34],
  - • Signals being broadcasted by the UAV to its operator (usually video),
  - • Signals used by the UAV for flight control and stabilisation (GPS, GLONAS, GALILEO)[35],
  - • Sensors located on-board the UAV.
- Infiltrating the UAV control loop (protocols) and taking over the UAV control.

To obtain information about the mission of the enemy UAV, one can also monitor its activity or obtain information from signals directed towards its user. This does not destroy, nor eliminate the UAV, however, in certain situations one may use such information to take adequate countermeasures.

From a defensive perspective, a UAV in flight is a small, low-flying, suddenly appearing, rapidly manoeuvring object for more details in[36]. If we summarise all the typical technical-tactical characteristics of a flying UAV, we are left with a synergic effect in the form of a challenge like none that air defenders have faced for several decades.

4.3.2 C-UAV Effector Research

The portfolio of problems related to the effective elimination of a flying UAV is so extensive that the following list mentions only selected fundamental issues for further research and/or development:

- Guiding the effector to its aerial target (missile guidance methods, anti-drone pathfinding, aiming the cannon).
- Sufficient time necessary to track the threat in order to eliminate it effectively.
- Weapon optimisation: type, calibre, effective range, mobility.
- Terminal ballistics of kinetic weapons.
- Energy ratios needed to destroy a UAV in flight using a DEW beam[37].
- The electromagnetic field intensity necessary to disrupt aircraft electronics.
- Electronic warfare challenges:
  - • Disrupting control signals
  - • Breaching remote control signal protocols to enter the

UAV remote control loop
- • GPS spoofing
- Effector deployment optimisation with regard to the battlefield, environment and possible collateral effects.
- Methods for the military/police special forces training designated to UAVs destruction (disruption).

Therefore, the elimination of a flying UAV[38] is so complex that it cannot be resolved by a single universal effector in the near future[40].

4.4 Related and other Relevant Measures

To defend an area or an object against UAVs, a number of measures must be taken. In general, it is always preferable to avoid an unfavourable situation before dealing with it. From a legislative point of view, legal standards related to UAV acquisition, operation, and control must be created and consistently enforced[41]. The task of security forces is to protect the external borders of the country from the penetration by forces, able to deploy and misuse UAVs.

C-UAV measures are to be implemented through the air defence units mostly for wartime. However, C-UAV measures are very important in conjunction with civilian security organisations and forces also during peace and crisis time in the form of precautionary measures saving civilian and military infrastructure and population.

5. DISCUSSION

SMEs evaluations presented in the paper are based on the experience of the air defence and air forces experts. some experts are skilled in tactics and combat procedures (commanders of air defence units) while the others in aircraft technology (technicians, researchers). That means that from their perspective, the answers are shaped by their own specific experience. That's why the published outcomes and priorities could be slightly altered by each country or defence industry organisation, according to their level of operational and technological maturity.

6. CONCLUSIONS

In the field of military technology, as well as in the application segment of scientific research, several issues are still waiting to be resolved. The author's department is attempting to address some of them (within their capabilities[39]) both analytically and through technical experiments. The subsequent synthesis offers the output for the operational use of the ground based air defence.

Many results from the 'C-UAV' field have already been formulated and presented in some way[38,42]. But the problem to link them up with the Air-defence pillars, according to authors' knowledge, was not published. The conducted study presented in this article can improve directions of the development to meet the C-UAV capabilities.

Also, the intention of this article is to publish the output in a comprehensive professional-themed form here and to present it in the way that includes both components of the defence against UAS- the technical view and operational view.

The outputs of this work are now used as a portfolio of challenges for C-UAV research within the authors' institution.

There is authors' conviction, that other individuals and bodies can use it, develop and elaborate too. This will contribute to the effort to improve the air defence against hostile unmanned aerial vehicles, or systems.

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