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, Countering 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 (e.g. in [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 in: [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.

1. 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 in [5].

In the cited article [5], it is also possible to identify weak, still lagging problems, requiring new technical solutions, and thus directing relevant research and development (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[[1]](#footnote-2) 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 in [5], page 326, Table No 5). A five-degree scale was created for the expert evaluation.

Low “L”

Bellow Moderate “BMod”

Moderate “Mod”

Bellow Mature “BMat”

Mature “Mat”

**Table 1. UAS sophistication quantification**

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | ***Technical view*** | | | | | ***Operational view*** | |  |  |
| **Branch of  Knowledge** | **ICT** | **Geogr.** | **Mech. eng.** | **Mater. eng.** | **Electr. eng.** | **Civil, Social & Politics** | **Military** | **Number of Branches Included** | **Maturity of Aspect** |
| **Aspect** |
| Platform |  |  | BMat | Mod |  |  |  | **2** | **Mod** |
| Propulsion |  |  | Mod | BMat | BMod |  |  | **3** | **Mod** |
| Avionics & 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 & Communication | BMod |  |  |  | Mod |  | BMod | **3** | **BMod** |
| Certification |  |  |  |  |  | Low | BMod | **2** | **BMod** |
| Legal issues |  |  |  |  |  | Low | Low | **2** | **Low** |
| Moral & 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** | |  |  |

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.

1. AIR THREATS AND AIR DEFENCE TECHNOLOGY

Scientific research organizations (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 (see e.g., in [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):

1. **Air Surveillance.** This includes: the detection, recognition, localisation, and identification of an aerial object;
2. **Command and Control**(C2) of all resources included in an AD system;
3. **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 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[[2]](#footnote-3) of distinctive AD-related characteristics of standard ATs versus small UAVs.

**Table 2. Typical standard ATs and small UAVs characteristics comparison**[[3]](#footnote-4)

|  |  |  |
| --- | --- | --- |
| **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 |

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 selectedAT *parameters* with regard to the individual AD *pillars*.

**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 |

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.

1. 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 C‑UAV 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.

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

* + 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 (e.g.[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].

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

* + 1. C-UAV Sensors Research & Development

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 (e.g.[23]).
* Selecting proper radar frequency band.
* Optimising methods of suppressing the radar clutter (e.g.[24]).
* Optimising passive radiolocation methods (e.g.[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.
  1. Command & 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.

* + 1. Command & 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***.

* + 1. C-UAV Information and Communication Technology Research

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 area of responsibility[[4]](#footnote-5),
  + 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.
  1. 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.

* + 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, see e.g. in [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 (see chapter 4.1.1 here, or [36] for more details). 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.

* + 1. 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].

* 1. 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.

1. 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.

1. CONCLUSION

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, examples e.g. in [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 (e.g. [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.

REFERENCES

1. European Aviation Safety Agency [EASA], General Aviation & RPAS Department*.* Study and Recommendations regarding Unmanned Aircraft Geo-Limitations. Executive Directorate Report. Köln (GER). 2016.
2. European Commission. Study Analysing The Current Activities In The Field of UAV. Enterprise and Industry Directorate study No ENTR/2007/065. Brussel (FRA). 2007.
3. Lissone, M. How is Europe preparing for the drone revolution? Expert insight on the main challenges and solutions surrounding drone use in the European sky. *In*: Countering drones live demo conference [on line]. IQPC Ltd, 129 Wilton Road, London [cited 2017-08-11]. Available from: <<https://counteringdroneslivedemo.iqpc.co.uk/how-is-europe-preparing-for-the-drone-revolution>>.
4. Ochsner, F.; Tasman, O. & others. Enhancing Traditional SHORAD Systems For The Counter UAV Role. *In* Counter UAS conference 2017, London, 2017, IQPC Ltd. Outputs available from <https://counteruas.iqpc.co.uk>; / registration required.
5. Demir, K. A.; Cicibas H. & Arica, N. Unmanned Aerial Vehicle Domain: Areas of Research. *Def. Sci. J*., 2015, **65**(4), 319-329. ISSN: 0976-464X. doi: 10.14429/dsj.65.8631
6. Campos, A. C. S. M. & de Almeida, A. T. Using multiple criteria decision analysis for supporting decisions of Business Process Management, *In* IEEE International Conference on Industrial Engineering and Engineering Management, Macao, 2010, pp. 52-56. doi: 10.1109/IEEM.2010.5674424
7. Government Resolution No 107/2017: Methodology of Evaluation of Research Organizations and Evaluation M17+, Prague, Czech Republic, 2017.
8. Office for Science, Research and Innovations: Branch of Knowledge Register. Enclosure to GR No 107/2017, Prague, Czech Republic, 2017.
9. Joint Air Power Competence Centre. Strategic Concept of Employment for Unmanned Aircraft Systems in NATO. JAPCC, UAS CONEMP Report, Kalkar, Germany, 2010.
10. Moses, A.; Rutherford, M. & Valavanis, K. Radar-Based Detection and Identification for Miniature Air Vehicles. *In:* 2011 IEEE International Conference on Control Applications (CCA). Denver (Colorado, USA) 2011, p. 933-940. ISSN 978-1-4577-1063-6. doi: 10.1109/CCA.2011.6044363
11. Logoglu, K. B. & others. Feature-Based Efficient Moving Object Detection for Low-Altitude Aerial Platforms. *In* 2017 IEEE International Conference on Computer Vision Workshops (ICCVW), Venice, 2017, pp. 2119-2128. doi: 10.1109/ICCVW.2017.248
12. Lou, L. & others. A 253mW/channel 4TX/4RX pulsed chirping phased-array radar TRX in 65nm CMOS for X-band synthetic-aperture radar imaging. *In* 2018 IEEE International Solid - State Circuits Conference - (ISSCC), San Francisco, CA, 2018, pp. 160-162. doi: 10.1109/ISSCC.2018.8310233
13. Beale, D. A. R.; Hume, A. L.; Cage, J. & Williams, P. An assessment of multi-static radar remote sensor networks. *In* 2004 IEEE Aerospace Conference Proceedings (IEEE Cat. No.04TH8720), 2004, pp. 2104 Vol.3. doi: 10.1109/AERO.2004.1367992
14. Bok, D.; Galda, D. & Siart, U. A multistatic passive coherent location system with receiver location constraints. *In* 2017 18th International Radar Symposium (IRS), Prague, 2017, pp. 1-10. doi: 10.23919/IRS.2017.8008107
15. Golikov, V. S. & Lebedeva, O. M. Nonadaptive Detection of 3-dimensional Optical Moving Target. *In* 2006 3rd International Conference on Electrical and Electronics Engineering, Veracruz, 2006, pp. 1-4. doi: 10.1109/ICEEE.2006.251912
16. Singh, L.; Srivastava, A. & Sarkate, A. J. Thermal gradient effect on focus shift of laser & infrared optical assembly & thermal lensing by Nd-Yag laser rod in laser assembly of Optical Detection & Ranging System of Fighter Aircraft. *In* 2017 4th IEEE Uttar Pradesh Section International Conference on Electrical, Computer and Electronics (UPCON), Mathura, 2017, pp. 27-32. doi: 10.1109/UPCON.2017.8251017
17. Jones, R.; Ristic, B.; Redding, N. J. & Booth, D. M. Moving Target Indication and Tracking from Moving Sensors. *In* Digital Image Computing: Techniques and Applications (DICTA'05), Queensland, Australia, 2005, pp. 46-46. doi: 10.1109/DICTA.2005.57
18. Ramos, D. B.; Loubach, D. S. & da Cunha, A. M. Developing a distributed real-time monitoring system to track UAVs. *IEEE Aerosp. and Electronic Systems Mag.*, 2010, **25**(9), 18-25. doi: 10.1109/MAES.2010.5592987
19. Wu, Z.; Keatts, W. & Davari, A. Low-cost motion detection and counter attacking test bed for swarm UAVs. *In* Proceedings of the Thirty-Seventh Southeastern Symposium on System Theory, 2005, pp. 362-366. doi: 10.1109/SSST.2005.1460937
20. Nihtilä, T.; Jylhä, J. & Visa, A. High-resolution acoustic imaging in air by synthetic aperture using pixel-wise matched kernels. *In* IEEE SENSORS 2014 Proceedings, Valencia, 2014, pp. 1714-1717. doi: 10.1109/ICSENS.2014.6985353
21. MacDonald, D.; Isenman, J. & Roman, J. Radar detection of hidden targets. *In* Proceedings of the IEEE 1997 National Aerospace and Electronics Conference, NAECON 1997, Dayton, 1997, pp. 846-855 vol.2. doi: 10.1109/NAECON.1997.622739
22. Burita, L. & Vilimek, J. Ways for Copter Drone Acoustic Detection. *In* Proceedings of International Conference on Military Technologies (ICMT), Brno, 2017, pp. 349-353. doi: 10.1109/MILTECHS.2017.7988783
23. Kim, S.; Lee, S. J.; Jung, J. H. & Kim, Y. Radar cross section measurements of quadcopters using long term evolution frequency. *In* 2017 IEEE Asia Pacific Microwave Conference (APMC), Kuala Lumpur, 2017, pp. 1294-1297. doi: 10.1109/APMC.2017.8251699
24. Chen S. & Wang, J. A Study of Suppressing Strong Clutter in Radar Signal Based ICA. *In* 2010 International Conference on Multimedia Technology, Ningbo, 2010, pp. 1-5. doi: 10.1109/ICMULT.2010.5631096
25. Tkachenko, V. N.; Pozdnyakov, Y. K. & Pantyeyev, R. L. New methods for radio sources coordinates determination in the multiposition passive radar system. *In* 2016 4th International Conference on Methods and Systems of Navigation and Motion Control (MSNMC), Kiev, 2016, pp. 259-262. doi: 10.1109/MSNMC.2016.7783156
26. Shin, J.; Kwak, K.; Kim, S. & Kim, H. J. Adaptive range estimation in perspective vision system using neural networks. *IEEE/ASME Transactions on Mechatronics*, 2018, **23**(2), 972-977. doi: 10.1109/TMECH.2018.2798819
27. Kloet, N., Watkins, S. & Clothier, R. Acoustic signature measurement of small multi-rotor unmanned aircraft systems. *International J. of Micro Air Vehicles*, 2017, **9**, 3-14.
28. Bree, H. E. The Microflown. Micro Mechanics group of the University of Twente & mArt, Netherlands, 1997, ISBN 9036509262.
29. *Lockheed Martin* [on line]. Maryland [USA]: F-16 Fighting Falcon. [cited 2017-08-16]. Available from: <http://www.lockheedmartin.com >.
30. *DJI* [on line]. Shenzhen, [China]: Tarot FY680 Pro Hexacopter. [cited 2017-08-16]. Available from: <http://www.dji.com>.
31. Brust, M. R.; Danoy, G.; Bouvry, P.; Gashi, D.; Pathak, H. & Gonçalves, M. P. Defending Against Intrusion of Malicious UAVs with Networked UAV Defense Swarms. *In* 2017 IEEE 42nd Conference on Local Computer Networks Workshops (LCN Workshops), Singapore, 2017, pp. 103-111. doi: 10.1109/LCN.Workshops.2017.71
32. Kratky, M. & Minarik, V. The Non-destructive Methods of Fight Against UAVs. *In* International Conference on Military Technology (ICMT), Brno, 2017, pp. 690-694. doi: 10.1109/MILTECHS.2017.7988845
33. Huy, D. Q.; Zubik, K.; Stekly, V. & Leuchter, J. Optimization of the interfering device for use of interference communication UAV. *In* 2017 IEEE/AIAA 36th Digital Avionics Systems Conference (DASC), St. Petersburg, 2017, pp. 1-5. doi: 10.1109/DASC.2017.8101985
34. Yu, Z. & Feng, L. RMR method for jamming air-ground and mobile wireless communication. *In* 2014 4th IEEE International Conference on Information Science and Technology, Shenzhen, 2014, pp. 476-479. doi: 10.1109/ICIST.2014.6920520
35. Li, C. & Wang, X. Jamming research of the UAV GPS/INS integrated navigation system based on trajectory cheating. *In* 2016 9th International Congress on Image and Signal Processing, BioMedical Engineering and Informatics (CISP-BMEI), Datong, 2016, pp. 1113-1117. doi: 10.1109/CISP-BMEI.2016.7852880
36. Kratky, M. Ground Based Air Defence Technologies for to Fight Unmanned Aerial Vehicles. University of Defence, Brno, Czech Republic, 2015. (Habilitation thesis - in Czech).
37. Palisek, L. Directed Energy Weapons in Modern Battlefield. *Advances in Military Technology (AiMT),* 2009, **4**(2), 55-66.
38. Alexeev, A. *The old and new form of fighting with unmanned aerial vehicles*. (Старые и новые способы борьбы с беспилотными аппаратами). Военное обозрение, Moscow. [cited 2018-04-05] Available from <https://topwar.ru/37629-starye-apparatami.html>. (in Russian).
39. Farlik, J., Kratky, M. & Casar, J. Detectability and jamming of small UAVs by commercially available low-cost means. *In* 2016 IEEE International Conference on Communications. Bucharest, 2016, pp. 327-330. doi: 10.1109/ICComm.2016.7528287
40. Violante, G. The Unmanned Aerial Systems Threat. *In* Counter UAS Conference 2017, London, 2017, Outputs available from https://counteruas.iqpc.co.uk; / registration required.
41. Loh, R.; Bian, Y. & Roe, T. UAVs in civil airspace: Safety requirements. *IEEE Aerosp. and Electronic Systems Mag.*, 2009, **24**(1), 5-17. doi: 10.1109/MAES.2009.4772749
42. Miasnikov, E. Threat of Terrorism Using Unmanned Aerial Vehicles: Technical Aspects. Centre for Arms Control, Energy and Environmental Studies, Moskow, 2005. (in Russian, translated to English).

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1. Applying Czech Government resolution [3] and its enclosure [4]. [↑](#footnote-ref-2)
2. A supersonic fighter is an example of *Standard AT* and middle-class copter as a *Class I, Mini UAV according to NATO classification*. [30] a [29]. [↑](#footnote-ref-3)
3. The symbol “#“ in Table 2 means “several“. [↑](#footnote-ref-4)
4. The so-called “Effector Kill Zone“ [↑](#footnote-ref-5)