UDC 656.7.052(045)

Yuriy Chynchenko[1]
Tatyana Shmelova[2]
Oksana Chynchenko[3]

REMOTELY PILOTED AIRCRAFT SYSTEMS OPERATIONS UNDER UNCERTAINTY CONDITIONS

National Aviation University
Kosmonavta Komarova avenue 1, 03680, Kyiv, Ukraine
E-mails: [1]chynchenko@gmail.com; [2]shmelova@ukr.net; [3]ochynchenko@gmail.com

Abstract. *The article deals with the analysis of the research conducted in the field of influence of uncertainty factors on remotely piloted aircraft systems operations. We reviewed the models suitable for estimation of uncertainty effect on remotely piloted aircraft systems operations. Principles of detailed assessment and further analysis of uncertainty effect on remotely piloted aircraft systems operations are proposed.*

Keywords: aeronautical system; air traffic management; flight operations integration of services; safety assessment; safety of flights; remotely piloted aircraft systems; uncertainty factors.

1. Introduction

Currently civil aviation market is balanced in aspects connected with provision of line personnel, equipment (ground facilities), and also legal aeronautical regulations on international, regional and national levels. One of new markets, which requires same holistic approach is remotely piloted aircraft systems (RPAS), which includes many potentially demanded by customers activities, for example: aerial inspections (relay to remote areas, energy exploration), cargo transport (last mile delivery), exploration (oil rig delivery, etc.), precision farming, security missions, traffic information, etc.

That necessitates elaboration of specific rules for operating RPAS and safety assessment depending type of activity (Fig. 1) taking into consideration uncertainty conditions.

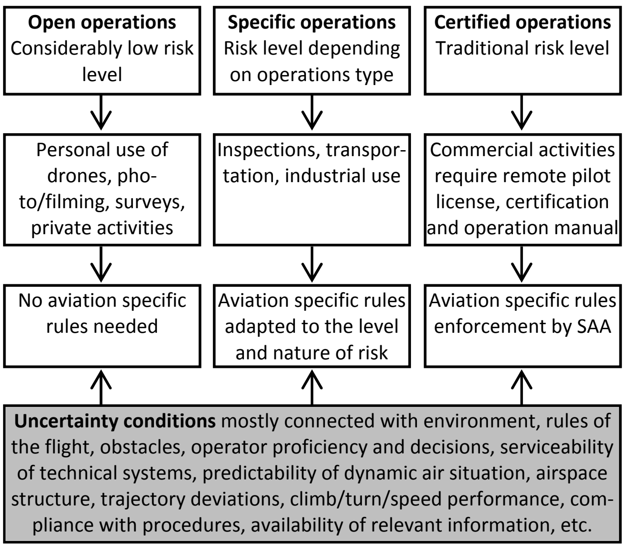

Fig. 1. Rules and safety assessment for RPAS operations

2. Analysis of the latest research and publications

Activities connected with integration of RPAS in national Air Traffic Management (ATM) systems are on-going in most of European countries and described in SESAR JU 2014 annual report [1]. The Single European ATM Research programme is contributing to the integration of the RPAS into the European ATM system, through the launch of the RPAS R&D Definition Phase and on-going demonstrations across Europe [1]. Under consideration are operational improvements, addressing RPAS operations, to be included into the European ATM Master plan and the ICAO Global aeronautical plan [2].

Aspects of unified approach to cooperative and non-cooperative RPAS Detect-and-Avoid are considered in [3]. Avionics sensor fusion for small size unmanned aircraft Sense-and-Avoid are analysed in [4].

But integration of the RPAS into European ATM-system requires solution of set of problems, one of which is taking into consideration the influence of uncertainty factors on drone operations/activities. Some aspects connected with uncertainty factors analysed in [5-9].

3. Principles of integration of the RPAS into the European civil aviation and ATM system

The SESAR demonstrations activities in 2014-2015 regarding integration of the RPAS are bringing us closer to delivering a modernised ATM system and achieving a higher performing aviation sector for Europe [1]. The implementation of the SESAR Solutions on RPAS operations will help aviation industry to become more sustainable and competitive. The SESAR Solutions provide concrete and tangible evidence of the performance benefits that they can bring to the overall performance goals of aviation and air traffic management in Europe.

Currently, nine demonstration activities are performed focusing on the integration of civil RPAS into the European ATM system [1]. These projects aim to demonstrate how to integrate RPAS into non-segregated airspace in a multi-aircraft flight environment, with a focus on identifying operational and technical gaps, uncertainty factors and demonstrating links with SESAR. Both optionally-piloted and fully remotely-piloted systems are participating in these projects, using various types and sizes of RPAS in environments with different uncertainty levels, such as rotary wings, motor gliders, and light observation aircraft, both civil and military.

The European RPAS Roadmap [2], handed over by RPAS stakeholders to the European Commission in 2013, paves the way for the safe integration of RPAS into the non-segregated ATM environments in Europe from 2016. The European RPAS roadmap requires the development of a operational structure, providing further details as to how to fully cover the needs of RPAS ATM integration.

According to the European RPAS Roadmap [2] RPAS should be able to operate in airspace, mixed with a variety of manned aircraft (e.g. from gliders to large airliners) under instrument (IFR) or visual (VFR) flight rules adhering to the uncertainty factors and requirements of the specific airspace in which they are operating.

The RPAS integration should not impact on the current airspace users (no degradation of the safety in the air, no disruption of current operations, no modification of ATC procedures, no additional mandatory equipment caused by RPAS).

In consequence, the European RPAS Roadmap considers that RPAS behaviour in operations must be equivalent to manned aviation, including for the air traffic control. RPAS must comply with the Communication, Navigation and Surveillance requirements applicable to the class of airspace within which they are intended to operate. They must also comply with the trajectory management concept envisaged in SESAR system and with air traffic control rules/procedures.

The European RPAS Roadmap also considers that, as in manned aviation, an RPAS operator will obtain a permission to operate only when essential pre-requisites to safeguard the total aviation safety system are in place. The three following basic prerequisites are expected to apply to RPAS [10]:

1. RPAS must be approved by a competent authority. According to the ICAO, they are systems comprising a remotely piloted aircraft, one or more associated remote pilot station, the required command and control links, including those supported by satellite communications, and any other components as specified in the type design of the RPAS.

2. The RPAS operator must hold a valid RPAS operator certificate.

3. The remote pilot must hold a valid licence.

The European RPAS Roadmap [2] proposes a phased and gradual introduction of RPAS operations, based on three subsequent levels of integration taking into consideration uncertainty factors (Figure 2):

1. Initial operations

At this first level of integration, operations are conducted under restrictions defined by the Civil Aviation Authorities (CAA). In this phase, a significant volume of cross-border operations is not expected. Integration into non-segregated airspace will only be possible under strict conditions. At the same time, the development of the necessary regulation will have started. When national competences exist, rules will be developed by CAAs with the greatest possible degree of voluntary harmonisation.

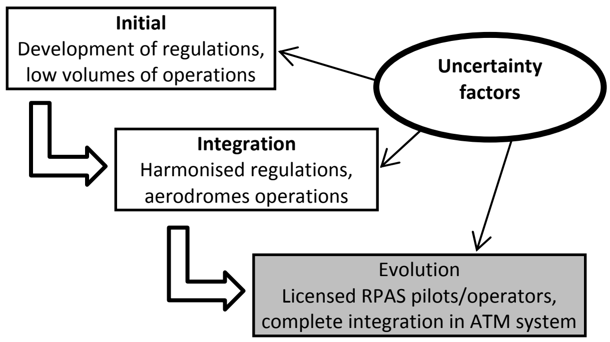

Fig. 2. Three levels of introduction of RPAS operations

2. Integration

In this second integration step, RPAS start conducting their operations according to harmonized regulations, alleviating a number of restrictions/limitations. Operation of RPAS < 150 kgs are progressively based on common rules, which would alleviate some of the restrictions to access non-segregated airspace (controlled and non-controlled) and to operate at aerodromes.

3. Evolution

Further evolution would allow achieving the ultimate goal, where appropriately certified and approved RPAS, flown by licensed remote pilots and under the legal responsibility of certified RPAS operators will be able to operate cross-border, in non-segregated airspace and over any populated territory. In other words, complete integration into the European and global civil aviation system.

One of the principal objectives of the aviation regulatory framework is to achieve and maintain the highest possible and uniform level of safety ***taking into account uncertainty factors of different origin*** [5-9]. RPAS shall be designed, manufactured, operated and maintained in such a manner that the risk to people on the ground and other airspace users is at an acceptable level. This level shall be set through essential requirements adopted by the legislator, following substantial consensus by all involved parties during the rulemaking process. When developing the safety requirements for RPAS, the risk must be considered in relation to the different size of RPAS and the type of operation involved.

4. Research of uncertainty conditions during RPAS operations

In order to safely access all types of airspace the PRAS require cooperative and non-cooperative Detect-and-Avoid (DAA) functions (accounting the influence of uncertainty factors on air traffic flows and safety of flights). Let's consider mathematical models associated with non-cooperative and cooperative DAA functions taking into consideration the overall uncertainty volume in the airspace surrounding RPAS.

The major criteria for DAA systems for RPAS operations under uncertainty conditions are [3]:

– field of view equivalent or superior to that of a pilot in the cockpit;

– accurate and precise intruder detection/recognition and trajectory prediction;

– prior obstacle detection for allowing time for executing the trajectory avoidance manoeuvres.

The DAA candidate-technologies represented in Table 1, both for cooperative and non-cooperative sensors [3,4].

Table 1. The examples of the DAA candidate-technologies for cooperative and non-cooperative sensors

System	Type	Range	Bearing	Trajectory
Visual camera	Non-cooperative, Passive	–	Accurate	Extracted
Light Detection and Ranging	Non-cooperative, Active	Accurate	Narrow	Extracted
ADS-B	Cooperative	Accurate	Calculated	Provided
TCAS	Cooperative	Accurate	Accurate	Extracted

Non-cooperative sensors

The predicted state $\hat{x}(t)$, at time is given by [3]:

$$\hat{x}(t)=\begin{bmatrix}P_x(t)\\P_y(t)\\V_x(t)\\V_y(t)\end{bmatrix}=\begin{bmatrix}1010\\0101\\0010\\0001\end{bmatrix}\begin{bmatrix}P_x(t-1)\\P_y(t-1)\\V_x(t-1)\\V_y(t-1)\end{bmatrix}+\begin{bmatrix}t^2/2 & 0\\0 & t^2/2\\t & 0\\0 & t\end{bmatrix}\begin{bmatrix}a_x\\a_y\end{bmatrix}+\varepsilon(t)$$

where $P_{x,y}(t)$ is the position in the x and y directions respectively as a function of time, t. $V_{x,y}(t)$ is the velocity in the x and y direction respectively, $a_{x,y}(t)$ is the acceleration and $\varepsilon(t)$ is the prediction Gaussian noise.

The track fusion algorithm is defined as the weighted average variance of all the tracks and is given by [3]:

$$\hat{x}_F(k\,|\,k)=\hat{P}_F(k\,|\,k)\times\sum_{i=1}^{n}P_i^{-1}(k\,|\,k)\hat{x}_i(k\,|\,k)$$

$$P_F(k\,|\,k)=\left[\sum_{i=1}^{n}P_i^{-1}(k\,|\,k)\right]^{-1}$$

The errors in predicted trajectory can be derived from the quality of the measurements, reflected in the prediction error, which are expressed as [3]:

$$\sigma^2(k+\tau\,|\,k)=\mathrm{var}[n(k+\tau)-\hat{n}^1(k+\tau\,|\,k)]$$

where $n(k+\tau)$ is the exhibited (modelled) trajectory and $\hat{n}^1(k+\tau\,|\,k)$ is the predicted optimal trajectory at sample time $k+\tau$. For trajectory prediction, the obstacle centre of mass, the target orientation and the geometric shape of the uncertainty volume are determined.

Cooperative systems

The ADS-B measurement model adopted for intruder position and velocity estimates in and cardinal directions is given as [3]:

$$Z(k)=\begin{bmatrix}100000\\010000\\000100\\000010\end{bmatrix}\begin{bmatrix}x\\\dot{x}\\\ddot{x}\\y\\\dot{y}\\\ddot{y}\end{bmatrix}+\begin{bmatrix}V_x(k)\\V_{\dot{x}}(k)\\V_y(k)\\V_{\dot{y}}(k)\end{bmatrix}$$

Assuming that the velocity components, $V_x(k)$, $V_{\dot{x}}(k)$, $V_y(k)$ and $V_{\dot{y}}(k)$ are affected only by Gaussian noise with zero mean, the standard deviation is defined by the covariance matrix given by [3]:

$$R=\begin{bmatrix}E[V_x^2] & 0 & 0 & 0\\0 & E[V_{\dot{x}}^2] & 0 & 0\\0 & 0 & E[V_y^2] & 0\\0 & 0 & 0 & E[V_{\dot{y}}^2]\end{bmatrix}$$

where $E[]$ represents the mean.

The probability of conflict is defined as the volume below the surface of the probability density function, $p(x,y)$ representing the conflict zone. The conflict probability, P_c is expressed as [3]:

$$P_c = \int_{-\Delta y - \Delta yc}^{-\Delta y + \Delta yc} \int_{-\infty}^{+\infty} p(x,y)\,dx\,dy$$

where $\Delta y + \Delta yc$ represents the conflict separation distance.

The overall uncertainty volume is obtained by combining the two error ellipsoids, which must be avoided by the host RPAS. When the errors are correlated tensors analysis is adopted to properly account for covariant or contra-variant components. Six components are associated with a rank-2 symmetrical tensor ϕ_{ij}, which are three diagonal and three off-diagonal components usually occurring in pairs. The equation of an ellipsoid associated with the tensor is given by [3]:

$$r_i \phi_{ij} r_j = 1$$

where r the radius vector having components r_i and r_j. Considering a three-dimensional space, the covariance tensor for the error ellipsoid is given as [3]:

$$T = \begin{bmatrix} \phi_{ii} & \phi_{ij} & 0 \\ \phi_{ji} & \phi_{jj} & 0 \\ 0 & 0 & \phi_{kk} \end{bmatrix}$$

for components (i, j, k) along (X, Y, Z) axes. The partial derivatives of an invariant function provide the components of a covariant vector. A contra-variant vector is the same as a contra-variant tensor of first order. The covariant and contra-variant tensors are used to define the overall uncertainty volume when the errors are correlated.

5. Conclusions

Uncertainty is one of the important factors influencing remotely piloted aircraft systems operations (both applicable for the cooperative and non-cooperative DAA technologies).

The major uncertainty origins, which should be taken into consideration are: detect-and-avoid functions, meteorological conditions, remote pilot licence, procedures and actual hardware/software of RPAS.

The solution of uncertainty originated problems will result in increasing safety level of RPAS flight and contribute the integration of the RPAS into the European civil aviation and ATM system.

References

[1] *SESAR JU 2014 annual report.* Brussels, SESAR JU. 2015. 48 p.

[2] *Roadmap for the integration of civil Remotely-Piloted Aircraft Systems into the European Aviation system.* Brussels, The European PRAS Steering group. 2013. 16 p.

[3] *Ramasamy S., Sabatini R., Gardi A.* Towards a Unified Approach to Cooperative and Non-Cooperative RPAS Detect-and-Avoid. Fourth Australasian Unmanned Systems Conference. 2014. 12 P.

[4] *Ramasamy S, Sabatini R, Gardi A.* Avionics Sensor Fusion for Small Size Unmanned Aircraft Sense-and-Avoid. IEEE Workshop on Metrology for Aerospace. 2014. P. 271-276.

[5] *Kharchenko, V.; Chynchenko, Yu.* Integrated safety management system in air traffic services. Proceedings of the National Aviation University. 2014. N1. P. 6-9.

[6] *Chynchenko, Yu.; Vakhrina, V.; Volianiuk, K.; Kim, I.; Kupaieva, A.; Samartseva, O.* Complex research on improvement of airspace structure and air traffic flows management in terminal control areas. Bulletin of the Engineering Academy of Ukraine. 2014. N2. P. 26-32 (in Ukrainian).

[7] *Kharchenko, V.; Chynchenko, Yu.* Estimation and representation of air traffic flows indices in terminal control areas. Proceedings of the National Aviation University. 2015. N3. P. 15-21.

[8] *Kharchenko, V.; Chynchenko, Yu.* Estimation of effect of uncertainty factors on safety of air traffic flows in terminal control areas. Proceedings of the National Aviation University. 2015. N4.

[9] *Kharchenko, V.; Chynchenko, Yu.* Integrated risk picture methodology for air traffic management in Europe. Proceedings of the National Aviation University. 2013. N1. P. 15-19.

[10] *Annex 2 to the Convention on International Civil Aviation. Rules of the Air.* Montreal, ICAO. 2005. 90 p.

Received 27 October 2015.

Ю.В. Чинченко[1], Т.Ф. Шмельова[2], О.Г. Чинченко[3]. Експлуатація безпілотних авіаційних систем в умовах невизначеності.
Національний авіаційний університет, просп. Космонавта Комарова, 1, Київ, Україна, 03680
E-mails: [1]chynchenko@gmail.com; [2]shmelova@ukr.net; [3]ochynchenko@gmail.com
У статті проаналізовано дослідження щодо впливу комплексних факторів невизначеності на експлуатацію безпілотних авіаційних систем. Розглянуто моделі, придатні для оцінки впливу невизначеності на експлуатацію безпілотних авіаційних систем. Запропоновано принципи детальної оцінки та аналізу впливу невизначеності на експлуатацію безпілотних авіаційних систем.
Ключові слова: аеронавігаційна система; безпека польотів; безпілотні авіаційні системи; інтеграція видів обслуговування; льотна експлуатація; організація повітряного руху; оцінка безпеки польотів; фактори невизначеності.

Ю.В. Чинченко[1], Т.Ф. Шмелева[2], О.Г. Чинченко[3]. Эксплуатация беспилотных авиационных систем в условиях неопределенности.
Национальный авиационный университет, просп. Космонавта Комарова, 1, Киев, Украина, 03680
E-mails: [1]chynchenko@gmail.com; [2]shmelova@ukr.net; [3]ochynchenko@gmail.com
В статье проанализированы исследования в области влияния комплексных факторов неопределенности на эксплуатацию беспилотных авиационных систем. Рассмотрены модели, пригодные для оценки влияния неопределенности на эксплуатацию беспилотных авиационных систем. Предложены принципы детальной оценки и анализа влияния неопределенности на эксплуатацию беспилотных авиационных систем.
Ключевые слова: аэронавигационная система; безопасность полетов; беспилотные авиационные системы; интеграция видов обслуживания; летная эксплуатация; организация воздушного движения; оценка безопасности полетов; факторы неопределенности.

Chynchenko Yuriy (1976). Candidate of Engineering. Associate Professor.
Department of Air Navigation Systems, National Aviation University, Kyiv, Ukraine.
Education: Faculty of Air Traffic Services, State Flight Academy of Ukraine, Kirovograd, Ukraine (1998).
Research area: improvement and automation of a professional selection system and development of professional-major skills of civil air traffic controllers.
Publications: 125.
E-mail: chynchenko@gmail.com

Shmelova Tatyana (1961). Doctor of Engineering. Professor.
Department of Air Navigation Systems, National Aviation University, Kyiv, Ukraine.
Education: Kirovograd Institute of Agricultural Mechanical Engineering, Kirovograd, Ukraine (1983).
Research area: development the evaluation system of decision-making efficiency by a human-operator of sociotechnical air navigation system in the expected and unexpected operating conditions of an aircraft with the influence of the professional and non-professional factors.
Publications: 150.
E-mail: shmelova@ukr.net

Chynchenko Oksana (1984). QA-Engineer.
Centre of Remotely Piloted aircraft systems of Institute of Air Navigation, National Aviation University, Kyiv, Ukraine.
Education: Institute of Computer Information Technologies, National Aviation University, Kyiv, Ukraine (2006).
Research area: improvement and automation of remotely piloted aircraft systems, uncertainty factors, flight operations, integration of aeronautical services.
Publications: 3.
E-mail: ochynchenko@gmail.com