Andrej NOVÁK, Ph.D.[1]
(Corresponding author)
E-mail: Andrej.Novak@fpedas.uniza.sk
Alena NOVÁK SEDLÁČKOVÁ, Ph.D.[1]
E-mail: Alena.Sedlackova@fpedas.uniza.sk
Pavol PECHO, Ph.D.[1]
E-mail: Pavol.Pecho@fpedas.uniza.sk
[1] University of Žilina, Faculty of Operation and Economics of Transport and Communications
Air Transport Department
Univerzitná 8215/1, 010 26 Žilina, Slovakia

Traffic Engineering
Original Scientific Paper
Submitted: 16 Dec. 2021
Accepted: 24 Feb. 2022

DETECTION AND PREDICTION OF A PAIR OF UNMANNED AIRCRAFT CONTACT

ABSTRACT

In the current world of increasing density of unmanned aerial vehicle operations in the airspace, there is an enhanced emphasis on their safety due to the potential for mid-air collision, either with another aircraft or with each other. At the same time, unmanned aerial vehicles are also being used in the context of introducing smart technologies into maintenance processes, where there is also a need to prevent a potentially possible conflict when two drones come close together. The paper introduces a mathematical model for tactical prediction of a conflict between a pair of drones. The tactical prediction of drone conflict is intended to alert the drone operator to an immediate potentially dangerous situation. The mathematical simulation in this paper extrapolates the 3D trajectory in the direction of the relative velocity vector of the convergence over the advance time. If the extrapolated trajectory has at least one point in common with the conflict space of the other drone, the conflict is signalled to the drone operator. This model can then be used in practice to simulate flight operations in shared airspace or to develop the currently required rules in selected situations.

KEYWORDS

conflict; conflict space; algorithm; UAV; prediction.

1. INTRODUCTION

Airspace management and the possibilities of its efficient and safe operation are a very broad issue, which also includes the solution of the problem of fragmented space regarding its penetration. At the same time, it is important to recognise that the provision of air traffic management services is influenced by several factors which are linked to the following problems:

- collision avoidance between aircraft and unmanned aerial vehicles (UAV),
- preventing aircraft and UAVs from colliding with obstacles on the operational area,
- maintaining orderly and expeditious flow of air traffic,
- provision of information suitable for the safe, economical and efficient operation of flights.

Airspace management systems shall be based on automated information and computer systems which, in conjunction with tracking systems, shall be capable of displaying safety warnings and alerts, including collision hazard warnings, minimum safe altitude warnings, obstacle warnings, as well as prohibited and restricted area entry warnings. At the University of Žilina, we have been working for a long time on the use of smart technologies to streamline processes of aircraft maintenance, where we use UAVs for this purpose [1–3]. As the smart technologies and their use will allow us to simplify the processes, an important part and factor is always the time the aircraft spends in maintenance that should be as short as possible. For the above stated reason, after the introduction of the planned procedures and technologies, it is assumed that the inspection of two aircraft will be carried out simultaneously by two drones. This means that it is necessary to ensure that they do not converge and collide with each other [1–3]. For the above stated reason, this paper focuses on the conflict prediction of two drones and builds on previous research that has addressed the conflict prediction of two aircraft. In concordance with continuing research based on the analogy method with the application of Ground Collision Avoidance Systems (GCAS) prediction, these systems can be divided into tactical and strategic systems [4]. Tactical systems (Short Term Conflict Alert - STCA) signal a collision hazard after identification by the tracking system, and strategic systems (Strategic Conflict Avoidance, SCA) signal a collision hazard of the entering aircraft with aircraft in controlled airspace before the aircraft enters controlled airspace. Through substitution, a conflict between a pair of unmanned aircraft or a conflict between an unmanned aircraft and another subject is subsequently resolved. The process of solving the collision hazard of a pair of aircraft is illustrated in the flow chart in *Figure 1*.

This paper presents a theoretical solution and design of a model for tactical conflict prediction of two drones. To achieve the research objectives, it is necessary to develop a custom model and the corresponding algorithm. D'Amato [5] provided a basic perspective on the issue of integrating UAV operations into civilian airspace. Following Hu [6] and Jover [7], it is evident that the problem to be addressed in this research has not yet been identified or comprehensively solved, which allows us to pursue this research further, focusing on exploring the conclusions of Lee [8] and Wan [9], and comparing them with the results of our own research [5–9]. The use of optical identification based conformal tracking sensor detection is addressed in the study by Wang [10]. Based on the aforementioned research of scientific sources described in [11–13], this research focuses on determining the possibilities of defining drone conflict prediction.

2. METHODS AND METHODOLOGY

Tactical drone conflict prediction is intended to alert operators of an immediate potentially dangerous situation. It consists of a program that extrapolates drone trajectories based on positional information for some time ahead, evaluates potential conflicts and signals these to the operator. Current tracking technique implies that continuous evaluation of potential conflict situations is possible, but the conflict must be analysed at certain time intervals and based on data collected at those intervals.

As part of the analysis, it is necessary to process all available information regarding positions, velocities, intended movements, measurement errors, drone navigation equipment, drone performance as

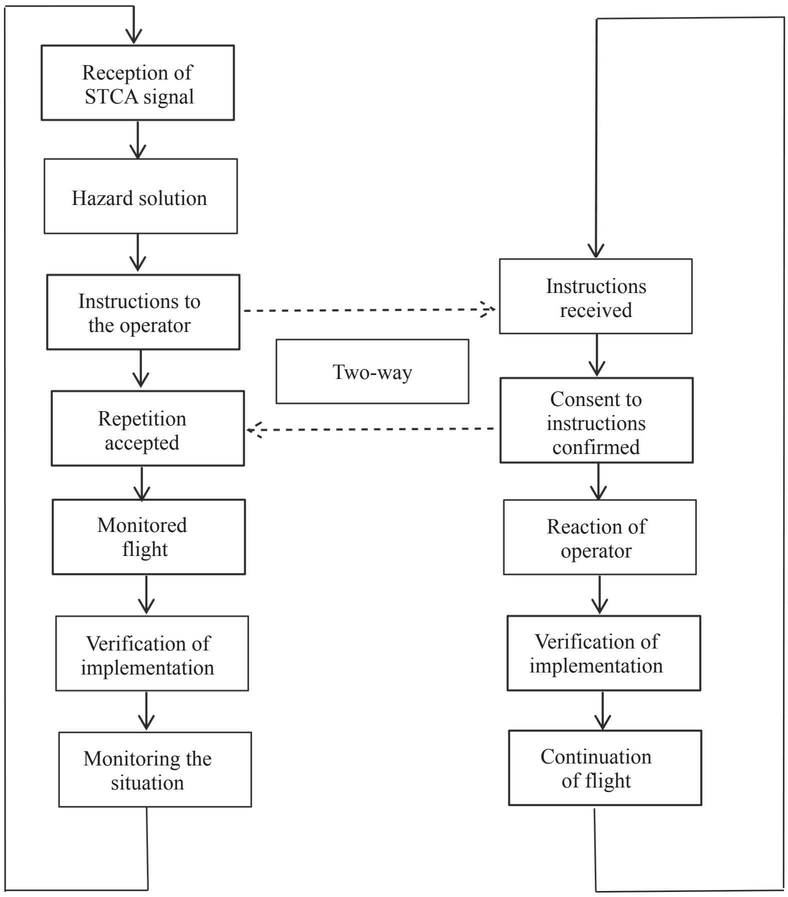

Figure 1 – Flow diagram of the collision hazard signalling and monitoring of a pair of drones

well as other information and calculate worst-case scenarios from it. The basis of the analysis is the mathematical and logical processing of the data to determine future worst-case scenarios. The term worst-case should be understood as describing the most unfavourable combination of factors determining the position of two drones (or N-1 drones).

The paper "A theory of the Tactical Conflict Prediction of a Pair of Aircraft" describes that it is necessary to determine the safe passing distance of two objects, the minimum passing distance and the spacing [4]. Subsequently, to define an area around the drone that must not be disturbed by another drone. For mathematical processing, this space needs to be defined in the vertical and horizontal direction [14].

The horizontal distance shall be greater than minimum horizontal distance (HM) or minimum vertical distance (VM). Based on this, the extrapolated horizontal and extrapolated vertical distances must be increased by the error of the drone's position and velocity measurements, by the operator's ability to change the flight path during the conflict identification period and by random deviations from the flight path [15].

For the purpose of the experiment, we assume linear and unaccelerated motion of drones X and Y over the time interval $\langle 0,p\rangle$, and available information on position including altitude as well as horizontal and vertical velocity. To simplify the solution, we did not consider the error of the position and velocity measurements. The conflict signalling time advance (p) must be a number that is large enough to give the operator enough time to avoid a collision. The minimum of the time advance p depends on:

- the time required to predict a conflict (tracking system performance), it may even be extended as a result of tracking programs and the calculation of the relative speed of one drone to another,
- the operator's response time to conflict signalling, which also depends on the quality of the connection between the operator and the drone,
- operator response time,
- the time required to establish the evasive manoeuvre,
- the time required to execute the evasive manoeuvre.

The minimum time advance is given by the sum of the above mentioned times. It is more problematic to determine the maximum value of the time advance. The greater the period, the more time for evasive manoeuvre and thus the prerequisite for greater safety is created. On the other hand, if the tactical prediction system does not know the drone's intended movements, there must inevitably be false conflict signalling (a very early conflict signalling could be negated by a subsequent intended manoeuvre in a safe direction), which could lead to the drone operator ignoring the actual collision at the end [16].

Also, calculation errors increase with time (short-term changes in velocity vector, equipment errors, etc.). Thus, a trade-off between adequate protection and false signalling has to be established. Furthermore, it is necessary to set a different value for the time advance in the vicinity of the airport (TMA, CTR), where the traffic density is higher and the spacing is smaller than in the controlled area. Hence, there is a requirement for graded conflict signalling time advance values for different altitudes and for different traffic intensities [1, 2].

Let us denote $\mathbf{HM}(t)$ and $\mathbf{HL}(t)$ as the horizontal position vectors of the two drones and $|\mathbf{V}(t)|$ as the difference of their heights. Then $\mathbf{H}(t)=\mathbf{HM}(t)-\mathbf{HL}(t)$ and $\mathbf{V}(t)=\mathbf{VM}(t)-\mathbf{VL}(t)$ is the effective position of drone M with respect to drone L. If VM is the minimum vertical and HM is the minimum horizontal miss distance, then the safe miss condition must meet:

$$|\mathbf{V}(t)| \geq \mathrm{VM} \quad \text{or} \quad |\mathbf{H}(t)| \geq \mathrm{HM} \tag{1}$$

while $t \in \langle 0,p\rangle$ where p is the value of the conflict signalling time advance.

The position vector $\mathbf{H}(t)$ is a function of:

- extrapolated drone position based on the drone's current position and velocity,
- position and velocity measurement errors or velocity calculation errors,
- the ability of the remote pilot or remote operator to change the flight path during the time advance period p,
- random deviation from the flight path.

Therefore, $\mathbf{H}(t)$ can be defined as:

$$\mathbf{H}(t) = \mathbf{H_e}(t) + \mathbf{m}(t) + \mathbf{O}(t) \tag{2}$$

where:

$\mathbf{H_e}(t)$ – extrapolated difference of the position vectors of drones L and M at time t,

$\mathbf{m}(t)$ – measurement error of the drone position and velocity,

$\mathbf{O}(t)$ – deviations from the extrapolated trajectory caused deliberately by the pilot or operator and random deviations due to technical reasons.

Since we cannot assume the direction of the vectors $\mathbf{m}(t)$ and $\mathbf{O}(t)$, the safe misses of the drones are:

$$|\mathbf{H_e}(t)| \geq \text{HM} + |\mathbf{m}(t)| + |\mathbf{O}(t)| \quad \text{with} \quad t \in \langle 0, p \rangle \tag{3}$$

We considered a linearly non-accelerated motion of two drones over the time interval $\langle 0,p \rangle$, where the position and altitude of the drones are available, including their horizontal and vertical velocities. Then:

$$|\mathbf{H_e}(t)| = |\mathbf{H}(0)| + |\mathbf{H`}(0)| \cdot t, \quad t \in \langle 0, p \rangle \tag{4}$$

where:

H(0) – measured relative position (distance of the two drones),

H`(0) – measured relative velocity,

by substituting into *Equation 3*

$$|\mathbf{H_e}(t)| = |\mathbf{H}(0)| + |\mathbf{H`}(0)| \cdot t \geq \text{HM} + |\mathbf{mD}(0)| + |\mathbf{mD`}(0)| \cdot t + |\mathbf{O}(t)| \tag{5}$$

Similarly, $\mathbf{V_e}(t)$ is the extrapolated height difference at time t.

$$|\mathbf{V_e}(t)| \geq \text{VM} + |\mathbf{mV}(t)| + |\mathbf{OV}(t)| \quad \text{where} \quad t \in \langle 0, p \rangle \tag{6}$$

$$|\mathbf{V_e}(t)| = |\mathbf{V}(0)| + |\mathbf{V`}(0)| \cdot t, \quad t \in \langle 0, p \rangle \tag{7}$$

$$|\mathbf{V_e}(t)| = |\mathbf{V}(0)| + |\mathbf{V`}(0)| \cdot t \geq \text{VM} + |\mathbf{mV}(0)| + |\mathbf{mV`}(0)| \cdot t + |\mathbf{O}(t)| \tag{8}$$

where:

V(0) – measured height difference between drones L and M,

V`(0) – measured relative vertical velocity of drones L and M.

3. MATHEMATICAL MODEL

If the conflict distances were the same in the horizontal and vertical directions, then the conflict space would be represented by a sphere. In the case where the conflict distances in the horizontal and vertical planes are not the same, e.g. when a larger safe distance in horizontal forward motion is required, then the conflict space is defined as an ellipsoid. We assume the conflict space of the drone L to be an ellipsoid. The rotational ellipsoid is shown in *Figure 2* and the assumption is made that drone M flies at speed $\mathbf{V_M}$ and drone L flies at speed $\mathbf{V_L}$. We consider drone L as a stationary drone and drone M is moving relative to it with relative velocity $\mathbf{R}=\mathbf{V_M}-\mathbf{V_L}$.

Let $M_p=M+p\cdot\mathbf{R}$ be the position of the drone M at time p assuming a constant relative velocity vector **R** during time p. If the segment M_pM shares at least one point with the conflict space, then the point M lies in the conflict space and a possible conflict should be signalled [3]. The analytical expression of the buffer space defined in this way does not need to be derived, as in the mathematical models of D'Amato [5] and Hu [6] because it is sufficient to know the analytical expression of the conflict space – the rotational ellipsoid whose equation is:

$$1 \geq \frac{x^2}{a^2} + \frac{y^2}{a^2} + \frac{z^2}{c^2} \tag{9}$$

We will call this model the EM model. [4, 5]

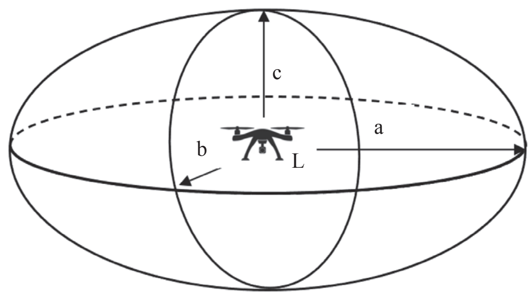

Figure 2 – Conflict space – rotational ellipsoid

4. ALGORITHM FOR SIGNALLING A POSSIBLE CONFLICT

Based on the model, we can then construct an algorithm for signalling a possible conflict using the EM conflict space model of drone L. The division of the time space of the interval $\langle 0,p \rangle$ by the division points $0,p_1,p_2,...,p_{n-1},p_n=p$, where $p_i=i{\cdot}p/n$, $i=1,2,...,n$ $p_0=\frac{p}{n}$ has been created. The number n is a natural number and is chosen so that it is not unnecessarily large. Usually, it is sufficient to choose $n=2$, $n=3$ or $n=4$. Division of the line segment MM_p by the division points $M,M_{p_1},M_{p_2},...,M_{p_{n-1}},M_{p_n}=M_p$ corresponds to this division. Then it is necessary to successively determine whether the point $M_p,M_{p_{n-1}},M_{p_{n-2}},...,$ lies in the conflict space, i.e. whether its coordinates satisfy the Inequality 9. As soon as this inequality is satisfied by any of the points $M_p,M_{p_{n-1}},M_{p_{n-2}},...,$ the possible conflict is signalled and there is no need to continue the detection for the other points. The algorithm generation procedure is illustrated in *Figure 3*.

In order to design a mathematical model for conflict prediction, a Cartesian coordinate system, k.s. $[0;u;v;w]$, needs to be chosen in space, the (u,v)

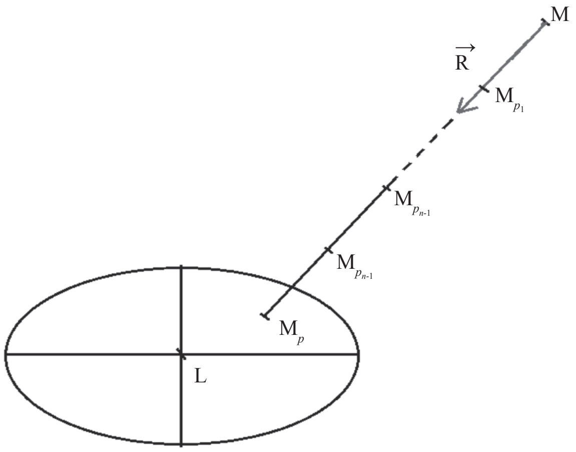

Figure 3 – Visual representation of the algorithm for signalling a possible conflict

plane is horizontal and the tracking system is at the centre of the coordinate system (see *Figure 3*). The input data are the coordinates of the drones L and M in the coordinate system [0;u;v;w] sensed by the tracking system at certain time intervals dt.

In this k.s. system the drone L has coordinates [u_L;v_L;w_L]. Let us shift the k.s. [u;v;w] by the vector **L** (L[u_L;v_L;w_L]) and the result is k.s. [L;x;y;z] centred at L (see *Figure 4*).

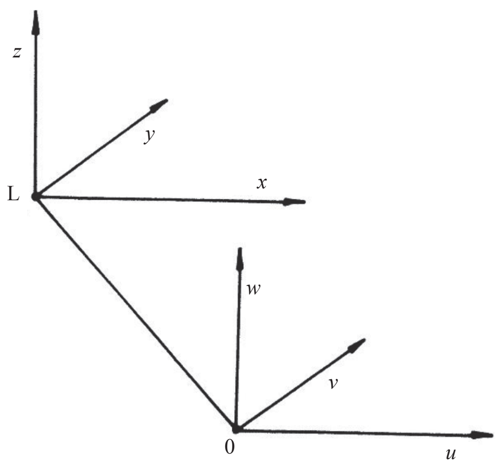

Figure 4 – Transformation of coordinate, k.s. [0;u;v;w] tracking system

The transformation equations of this displacement are:

$$\begin{aligned} X &= U - U_L \\ Y &= V - V_L \\ Z &= W - W_L \end{aligned} \quad (10)$$

Drone coordinates L and M obtained at a given time instant in k.s. [0;u;v;w] will be transformed into k.s. [L;x;y;z] using *Equations 10.* Transformation of the point coordinates of drone L and M obtained in k.s. [0;u;v;w] allows working in k.s. [L;x;y;z], L point coordinates=[0;0;0]. Further work will be done in k.s. [L;x;y;z].

Let **R**=[x_R;y_R;z_R] and the drone M=[x_M,y_M,z_M] be in k.s. [L;x;y;z].

The input are the coordinates of the drones L and M in k.s. [0;u;v;w] periodically updated at interval $t_0=t_{i+1}-t_i$ in the scanning sequences of the tracking system.

The output is an indication of a potential conflict between L and M drones, if it exists.

L_i and M_i are the positions of drones L and M at t_i, i=1,2,3,..., and $L_i=[u_{L_i};v_{L_i};w_{L_i}]$ and $M_i=[u_{M_i};v_{M_i};w_{M_i}]$ in t_i, $L_{i+1}=[u_{L_{i+1}};v_{L_{i+1}};w_{L_{i+1}}]$ and $M_{i+1}[u_{M_{i+1}};v_{M_{i+1}};w_{M_{i+1}}]$ position in t_{i+1}.

Then the speed of the drone L is

$$\mathbf{V_L} = \frac{L_i - L_{i+1}}{t_0} = \frac{1}{t_0}(u_{Li+1} - u_{Li}, v_{Li+1} - v_{Li}, w_{Li+1} - w_{Li}) \quad (11)$$

and drone M

$$\mathbf{V_M} = \frac{M_i M_{i+1}}{t_0} = \frac{1}{t_0}(u_{Mi+1)} - u_{Mi}, v_{Mi+1} - v_{Mi}, w_{Mi+1} - w_{Mi}) \quad (12)$$

We take these velocities to be the instantaneous velocities of drones L and M at time instant t_{i+1}. The relative velocity vector $\mathbf{R}_{i+1}$ of drones L and M at time t_{i+1} is then $\mathbf{R}_{i+1}=\mathbf{V_M}-\mathbf{V_L}$, its components are $(u_{R_{i+1}};v_{R_{i+1}};w_{R_{i+1}})$, where:

$$\begin{aligned} u_{Ri+1} &= \frac{1}{t_0}(u_{Mi+1} - u_{Mi} - u_{Li+1} - u_{Li}) = x_{Ri+1} \\ v_{Ri+1} &= \frac{1}{t_0}(v_{Mi+1} - v_{Mi} - v_{Li+1} - v_{Li}) = y_{Ri+1} \\ w_{Ri+1} &= \frac{1}{t_0}(w_{Mi+1} - w_{Mi} - w_{Li+1} - w_{Li}) = z_{Ri+1} \end{aligned} \quad (13)$$

These components of the vector $\mathbf{R}_{i+1}$ in k.s. [0;u;v;w], if we shift k.s. to k.s. [L_{i+1};x;y;z], and the coordinates of the vector $\mathbf{R}_{i+1}$ do not change and *Equation 13* holds (L_{i+1} because it refers to the time instant t_{i+1}). According to the transformation *Equations 10*:

$$\begin{aligned} x_{Mi+1} &= u_{Mi+1} - u_{Li+1} \\ y_{Mi+1} &= v_{Mi+1} - v_{Li+1} \\ z_{Mi+1} &= w_{Mi+1} - w_{Li+1} \end{aligned} \quad (14)$$

The values from *Equations 13 and 14* are substituted into the equation of the rotational ellipsoid. If these values satisfy *Inequality 9* then drone M is located in conflict space and it is a threat.

5. DISCUSSION

The result of the research is the algorithm for signalling a possible conflict that provides a solution by which a conflicting operation of a pair of drones can be spatially identified. If used to manage conflicts between UAVs, this particular algorithm would be one of the key aspects in the development of future Urban Air Mobility (UAM), aerial work in industrial halls of enterprises, buildings and warehouses [17]. Several scientific papers are devoted to object pair conflict resolution and algorithm design, as mentioned in the introduction. These solutions are usually based on the detection of objects in a spherical conflict zone, and in the case of objects moving in 2D space, a circular conflict space is usually considered. We were able to describe the prediction algorithm of drone trajectory based on the multiple model estimation algorithm from the ADS-B conflict detection technique.

In practice, the dynamic models are used to estimate multiple models that compute estimates of the current state and flight mode of the drone [18]. The motion of the drone can be decoupled into horizontal and vertical motion. The dynamic models correspond to the different flight modes that commonly occur in real flight. The interacting multiple model (IMM) algorithm is used to estimate the position and velocity of an aircraft. The IMM is a computationally efficient suboptimal estimation algorithm for multiple models' estimation. It consists of a bank of Kalman filters matched to each mode and provides final estimates for all Kalman filters by combining the estimates. Our contribution is in expansion of the conflict area and creation of a proposal for an ellipsoidal conflict zone. In the context of tactical conflict management, drones in flight, for example, the author Jover identified the PCAN (Prediction-based Conflict-free Adaptive Navigation) method [19]. This relatively simple navigation technique predicts the occurrence of conflict and avoids it by adjusting the velocity vector of the drone or group of drones in question. Main disadvantage of such technique with respect to our solution is that not in all cases of aerial work the flight speed could be changed.

The basis of the proposed model is the extrapolation of the trajectories of the two drones in 3D space, based on the assumption of a constant vector of relative convergence speed during the time advance, denoted by p. The input data shall be the drone coordinates taken at certain time intervals determined by the refresh rate of the tracking system. The conflict space is defined based on the determined conflict distance in the horizontal direction and in the vertical direction, as shown in *Figure 1*. In this mathematical model, the conflict space of drone L is the rotating ellipsoid. Drone L is located in the centre of the conflict space. In the model, the path of drone M is extrapolated in the direction of the relative convergence velocity vector for the duration of time advance p. If the extrapolated path has at least one point in common with the conflict space of drone L, a conflict is signalled at the output of our algorithm.

This conflict prediction model can be used in automated information processing, usually already in its primary processing. For simplicity, we used a simple calculation of the drone L and M velocities from only two measured positions. In reality, the velocity is computed from multiple position entries or is transmitted in a data message, weighing the measured and computed velocity. Usually, different types of filters are used to compute the drone position and velocity and determine the quality of individual plots, which is referred to as the bias.

In practice, in most cases it is preferable to change the altitude or horizontal direction. Changing the speed should be the last resort. Similar approach has been identified in the study "Integration of a 4D-trajectory follower to improve multi-UAV conflict management within the U-space context" which considered the problem of conflict management for multiple UAVs in the context of U-space in 4D trajectory-based operations (4D-TBO) [20]. The present model provides an advantage in applications that use a more efficient anti-collision system model in unmanned aerial vehicle decision making processes. In the process of future research, it is necessary to think about the vertical distances of airways due to manoeuvrability, or with horizontal zones beyond the designated airspace providing sufficient space for horizontal flight change due to anti-collision trajectory correction. These aspects act as a disadvantage of applying the method in practice, as in enclosed or confined spaces there is a need to include anti-slip routes in the design of airspace. At present, the FLARM system [21] provides anti-collision protection for UAVs as well as civilian sports aircraft. In studies, this system is a benchmark for the application of new anti-collision measures and technical solutions, as it is a standard and a leader in its field. As in the case of the FLARM system, the presented mathematical model provides the operator with signalling of an impending collision, and it is the operator who is obliged to ensure the manoeuvre responsible for avoiding a collision. The task of future research and simulations will therefore be to determine the time of collision signalling in comparison with commercial systems or to determine autonomous decision-making algorithms [22] for performing a passing manoeuvre. Such types of manoeuvres fall within the aforementioned extension of flight paths by evasion zones, which are outside the flight trajectories, but are also the operational area of UAVs.

6. CONCLUSION

The paper is aimed at developing a model for tactical conflict prediction of two drones, the solution which is based on the general considerations defined in the introduction. Conflict prediction model in the research can be used in automated information processing, usually already in its primary processing. The presented mathematical model is based on conflict prediction by detecting common points of conflict space of drones by extrapolation of flight trajectory. In the research, a simple calculation was used from only two measured positions of the drone velocities. Predicting the conflict of a pair or group of drones is the basis of airspace management and one of the fundamental requirements for safety. The application of our proposed model in practice could be, for example in the extension of algorithms for UAM, in warehouse management, industrial production, logistics centres, etc. The model could be used in all drone applications where fixed spaces and sectors for drone movement are not defined, but free movement of drones in space is required. Therefore, the next research direction in this field will be to simulate conflict detection between a group of drones and a group of aircraft in 3D space with temporal interaction.

ACKNOWLEDGEMENTS

This publication was realised with support of Operational Program Integrated Infrastructure 2014 - 2020 of the project: Intelligent operating and processing systems for UAVs, code ITMS 313011V422, co-financed by the European Regional Development Fund.

prof. Ing. **Andrej NOVÁK**, PhD.[1]
E-mail: Andrej.Novak@fpedas.uniza.sk
doc. Ing. JUDr. **Alena NOVÁK SEDLÁČKOVÁ**, PhD.[1]
E-mail: Alena.Sedlackova@fpedas.uniza.sk
Ing. **Pavol PECHO**, PhD.[1]
E-mail: Pavol. Pecho@fpedas.uniza.sk
[1] Žilinská univerzita v Žiline
Fakulta prevádzky a ekonomiky dopravy a spojov
Katedra leteckej dopravy
Univerzitná 8215/1, 010 26 Žilina, Slovakia

DETEKCIA A PREDIKCIA KONTAKTU DVOJICE BEZPILOTNÝCH LIETADIEL

ABSTRAKT

V súčasnom svete zvyšujúcej sa hustoty prevádzky bezpilotných lietajúcich prostriedkov vo vzdušnom priestore je čoraz väčší dôraz kladený na ich bezpečnosť vzhľadom na možný stret vo vzduchu, či už s lietadlom alebo vzájomne. Zároveň sú bezpilotné lietajúce prostriedky využívané aj v rámci zavádzania smart technológií do procesov údržby, kde je tiež potrebné predchádzať potenciálnemu možnému konfliktu pri zblížení dvoch dronov. Článok definuje matematický model taktickej predikcie konfliktu dvojice dronov. Taktická predikcia konfliktu dronov má upozorniť operátora dronu na okamžitú potenciálnu nebezpečnú situáciu. Matematická simulácia v tomto článku extrapoluje 3D dráhu v smere vektora relatívnej rýchlosti zbližovania po dobu predstihu. Ak má extrapolovaná dráha s konfliktným priestorom druhého dronu spoločný aspoň jeden bod, signalizuje sa konflikt pre operátora dronu. Tento model je možné následne využiť v praxi pri simulácii letovej prevádzky v zdieľanom vzdušnom priestore, resp. pri tvorbe aktuálne potrebných pravidiel vo vybraných situáciách.

KĽÚČOVÉ SLOVÁ

konflikt; konfliktný priestor; algoritmus; UAV; predikcia.

REFERENCES

[1] Novák A, et al. Use of unmanned aerial vehicles in aircraft maintenance. *Transportation Research Procedia.* 2020;51: 160-170. doi: 10.1016/j.trpro.2020.11.018.

[2] Bugaj M, Novák A, Stelmach A, Lusiak T. Unmanned aerial vehicles and their use for aircraft inspection. *Proceedings of the 22nd International Conference on New Trends in Civil Aviation*. 2020. p. 45-50. doi: 10.23919/NTCA50409.2020.9290929.

[3] Hruz M, et al. The use of UAV with infrared camera and RFID for airframe condition monitoring. *Appl. Sci.* 2021;11(9): 3737. doi: 10.3390/app11093737.

[4] Havel K, Husarčík J. A theory of the tactical conflict prediction of a pair of aircraft. *The Journal of Navigation.* 1989;42(3): 417-429. doi: 10.1017/S0373463300014715.

[5] D'Amato E, Notaro I, Mattei M. Distributed collision avoidance for unmanned aerial vehicles integration in the civil airspace. *2018 International Conference on Unmanned Aircraft Systems (ICUAS)*. 2018. p. 94-102. doi: 10.1109/ICUAS.2018.8453432.

[6] Hu J, Erzberger H, Goebel K, Liu Y. Conflict probability estimation using a riskbased dynamic anisotropic operational safety bound for UAV traffic management. *AIAA Scitech 2020 Forum.* 2020. doi: 10.2514/6.2020-0738.

[7] Jover J, Bermúdez A, Casado R. A tactical conflict resolution proposal for U-Space Zu airspace volumes. *Sensors.* 2021;21(16). doi:10.3390/s21165649.

[8] Lee J, Lee H, Shim DH. Vision-based state estimation and collision alert generation for detect-and-avoid. *Proceedings of the 2020 AIAA/IEEE 39th Digital Avionics*

Systems Conference (DASC). 2020. p. 1-7. doi: 10.1109/DASC50938.2020.9256797.

[9] Wan Y, Tang J, Lao S. Research on the collision avoidance algorithm for fixed-wing UAVs based on maneuver coordination and planned trajectories prediction. *Applied Sciences*. 2019;9(4). doi: 10.3390/app9040798.

[10] Wang C, Xu C, Dai Y. A crash prediction method based on bivariate extreme value theory and video-based vehicle trajectory data. *Accident Analysis and Prevention*. 2019;123: 365-373. doi: 10.1016/j.aap.2018.12.013.

[11] Wu Z, Li J, Zuo J, Li S. Path planning of UAVs based on collision probability and Kalman filter. *IEEE Access*. 2018;6: 34237-34245. doi: 10.1109/ACCESS.2018.2817648.

[12] Zhang Z, et al. A uniform model for conflict prediction and airspace safety assessment for free flight. In: Liang Q, et al. (eds) *Communications, Signal Processing, and Systems. CSPS 2019. Lecture Notes in Electrical Engineering, vol 571*. Singapore: Springer; 2020. doi: 10.1007/978-981-13-9409-6_131.

[13] Yong J, et al. Traffic conflict prediction model for bottleneck section of expressway construction area based on video recognition. *Proceedings of the 2019 12th International Conference on Intelligent Computation Technology and Automation (ICICTA)*. 2019. p. 259-264. doi: 10.1109/ICICICTA49267.2019.00062.

[14] Lazar T, et al. *Modern Safety Technologies in Transportation (MOSATT): Proceedings of International Scientific Conference, 14-15 Nov. 2017, Herľany, Slovakia*. Vol. 7. Košice: Faculty of Aeronautics of Technical University of Košice; 2017. p. 90-94.

[15] Kraus J. Determining acceptable level of safety of approach to landing. *Transport Means - Proceedings of the International Conference*. 2016. p. 230-235.

[16] Lališ A, Vittek P, Kraus J. Process modelling as the means of establishing semi-automated safety management. *Transport Means - Proceedings of the International Conference*. 2016. p. 254-258.

[17] Novák Sedláčková A, Novák A, Pecho P. Implementation of smart technologies into the civil aviation aircraft maintenance process. *Proceedings of the 2021 International Scientific Conference "The Science and Development of Transport" (ZIRP)*. 2021. p. 123-134.

[18] Baek KY, Bang H. ADS-B based trajectory prediction and conflict detection for air traffic management. *Int'l J. of Aeronautical & Space Sci*. 2012;13(3): 377-385. doi: 10.5139/IJASS.2012.13.3.377.

[19] Jover J, Bermúdez A, Casado R. A tactical conflict resolution proposal for U-Space Zu airspace volumes. *Sensors*. 2021;21(16): 5649. doi: 10.3390/s21165649.

[20] Perez-Leon H, Acevedo JJ, Maza I, Ollero A. Integration of a 4D-trajectory follower to improve multi-UAV conflict management within the U-space context. *Journal of Intelligent and Robotic Systems: Theory and Applications*. 2021;102(3). doi: 10.1007/s10846-021-01415-0.

[21] Duffy B, et al. Onboard autonomous sense and avoid of non-conforming unmanned aerial systems. *2020 AIAA/IEEE 39th Digital Avionics Systems Conference (DASC), 11-15 Oct. 2020, San Antonio, TX, USA*; 2020. p. 1-10. doi: 10.1109/DASC50938.2020.9256776.

[22] Marques M, Brum A, Antunes S, Mota JG. Sense and avoid implementation in a small unmanned aerial vehicle. *13th APCA International Conference on Automatic Control and Soft Computing (CONTROLO)*. 2018. p. 395-400. doi: 10.1109/CONTROLO.2018.8514548.