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AN EVASIVE MANOEUVRE, AUTOMATICALLY CONTROLLED TO AVOID THE ONE OF A GROUP OF MANY OBSTACLES MOVING IN A VICINITY OF FLYING AIRPLANE

ABSTRACT

Detection of a collision threat and an appropriate decision on passing by an obstacle are necessary for solving the problem of collision avoidance in case of aircraft motion within the airspace. In the article a method for detecting a threat of collision with the obstacle is presented for the case of many moving objects appearing within the neighbourhood of the aircraft. The analysis of an algorithm for making a preliminary decision on avoiding a collision with more than one moving obstacle was carried out. The shape of a class of evasive trajectories was proposed, and its reliability was proved. Numerical simulations of flight were completed for the considered type of aircraft in aforementioned conditions. The scope of these simulations covered all phases of obstacle avoiding manoeuvre, including a return to a straight-line part of flight trajectory pre-planned before the start.

Key words:
obstacle avoidance, anti-collision systems, computer simulation, flight dynamics.

INTRODUCTION

A collision with more than one moving obstacle is a threat that appears, among many other hazards, during a flight.

The analysis of moving obstacles avoidance problem should take into account quick changes (very often not completely predictable) of relative geometric configuration of considered objects and its motion. Factors generating this partial predictability are the limit of an effective range of observation, defined by technical features of

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a detector, and quick changes of observed objects [1]. The distance to the objects, especially those located within front half-sphere, decreases during a flight, so the subsequent obstacles that haven't been detected earlier, can be observed. Similar problems may appear as a result of limits of an effective angular sector of a detector's observation zone. In many research works within the area of discussed issue, technical conditions mentioned above have not been taken into considerations. The other question, which should be analysed in detail is the dynamics of an object performing an anti-collision manoeuvre. A shape of manoeuvre trajectories, e.g. in horizontal plane, depends, among others, on the realisable turning radius with its initial and ending phases taken into account [2].

There exist some analogies between tracking of a moving target and guiding a missile to this target [4]. However, many aspects of the task focused on looking for a trajectory to avoid a collision with more than one obstacle are different, when being compared with a missile guidance task. Some important differences are coming, among others, from the necessity for simultaneous tracking of many objects, as well as from the process of airplane's flight corrections, when the subsequent threating obstacles are detected.

There exist many specially hazardous situations, which increase the risk of a collision with moving obstacles. Some of them are listed below:

- a great number of obstacles moving along different directions with different speeds;
- late detection of the moving obstacle; a moment before this obstacle was outside the effective range of a detector (distance and azimuth) or was obscured by another obstacle;
- large size of a moving obstacle;
- close formation of moving obstacles, with relative distances comparable with r_{CMB} radius;
- high speeds of obstacle's motion.

AN ASSUMED TRAJECTORY OF AN EVASIVE MANOEUVRE

The class of trajectories presented in figure 1, which illustrates the complex evasive manoeuvre is has been considered. This manoeuvre consists with four turns and one straight-line phase of flight. All turns are executed with the same turning radius r_{Szi} and with the same time history of yaw angle variation. This is one of many possible shapes of trajectories found to be effective in collision avoidance and then returning to the preliminary pre-planned flight route.

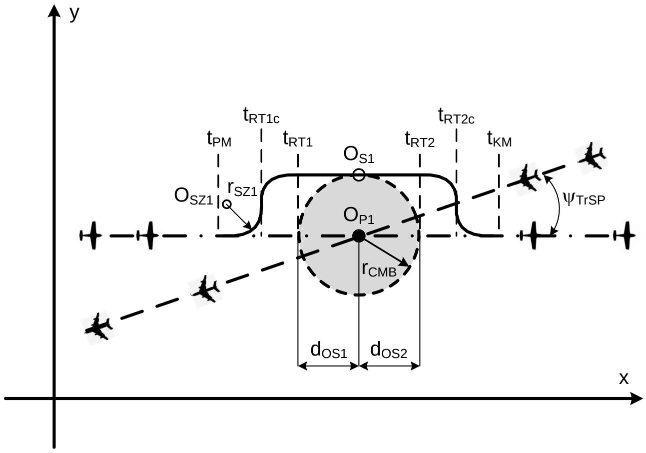

Fig. 1. The proposed trajectory of evasive manoeuvre [own work]

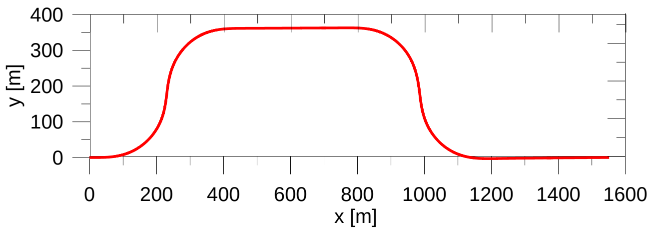

Fig. 2. The trajectory obtained by simulation [own work]

RECOMMENDATIONS FOR THE SELECTION OF AN EVASIVE MANOEUVRE

In a further part of the article, a computational method is presented for checking if there exists a collision threat and an evasive manoeuvre — a possibility to avoid a moving obstacle and then return to the pre-programmed flight trajectory. Due to the great number of possible configurations of obstacles appearing around the airplane as well as, possible types of their motion, the following assumptions are proposed to establish a set of necessary conditions:

– the data of obstacles are obtained only within a close vicinity of aircraft; this data are achieved by a detector of limited area of observation, defined by a limited angular sector and limited range (a maximum distance to observed object);
– information about sizes of obstacles and motion parameters are accessible;
– a deficiency of time necessary for anti-collision manoeuvre is taken into account;

- the process of collision avoidance is realised without negotiations with other moving objects;
- the air traffic regulations are not observed;
- objects within the aircraft's neighbourhood move with constant seeds and directions;
- the evasive manoeuvre is performed in horizontal plane;
- stabilisation and flight control covers 6 degrees of freedom.

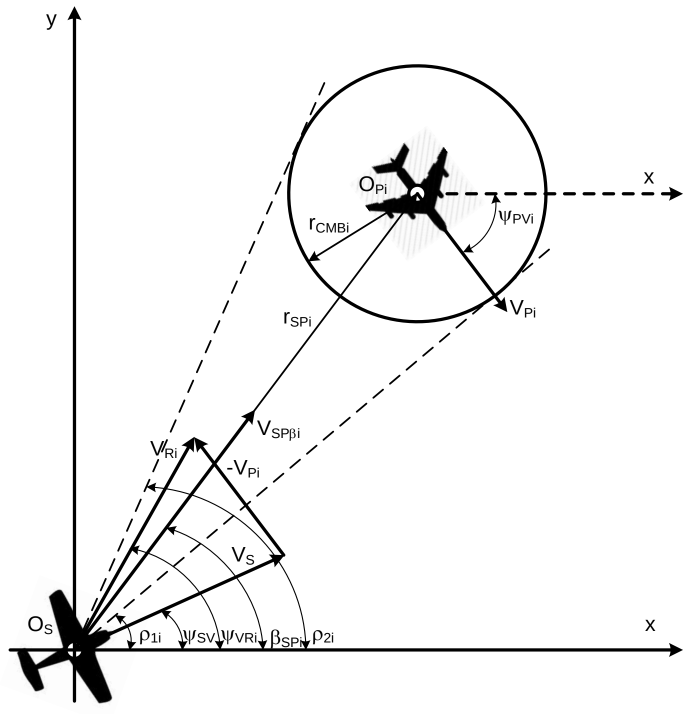

Fig. 3. Variables describing the aircraft — obstacle configuration [own work]

The basic criterion for the assessment of current situation regarding collision threat against moving obstacles and classification of scenarios: exploits the following inequalities:

$$\Psi_{VRi} < \rho_{1i} \quad \vee \quad \Psi_{VRi} > \rho_{2i} \quad \wedge \quad r_{SPi} > r_{CMBi}\,; \tag{1a}$$

$$\left|\Psi_{VS} - \beta_{SPi}\right| < 90^0\,; \tag{1b}$$

$$\left|\Psi_{VS} - \Psi_{VPi}\right| > 90^0 \quad \wedge \quad \left|\Psi_{VS} - \Psi_{VPi}\right| < 270^0\,. \tag{1c}$$

First two parts of condition (1a) relates to the angle of resultant velocity vector Ψ_{VRi} towards the angles of tangents to the circle of radius r_{CMBi} [2]. The third inequality (1a) determines the case when the airplane-to-obstacle distance is below the allowed value or not. If one of two first parts of condition (1a) and the third part of this condition are satisfied, the collision threat does not exist. If the condition (1b) comparing the airplane's angle of speed vector Ψ_{VS} with line of sight angle β_{SPi} [5, 6] is satisfied, the considered obstacle is located within the front half--sphere of the airplane. Further considerations on collision threats detection and collision avoidance are focused only at scenarios satisfying the condition (1b). When the inequality (1c) is not satisfied, the airplane follows the obstacle. In this case the collision threat appears when: $V_S > V_P$. If more than one obstacle generates a threat for the airplane — i.e. at least one obstacle exists, which do not satisfy the condition (1a) (with 1b, 1c taken into account) — the first obstacle to be avoided has to be chosen. Such an obstacle is characterised by the less value of t_k time — the time that the airplane needs to reach the prohibited area. The value of is parameter can be computed according to the relationship (fig. 3):

$$t_{ki\min} = \min\left|\left(r_{SPi} - r_{CMBi}\right)/V_{SP\beta i}\right|, \tag{2}$$

the speed of the process defined as the airplane getting closer to the *i*-th obstacle equals (fig. 3):

$$V_{SP\beta i} = V_S \cos\left|\Psi_{SV} - \beta_{SPi}\right| + V_{Pi}\cos\left|\Psi_{PVi} - \beta_{SPi}\right|. \tag{3}$$

Angles of tangents to the circle with r_{CMBi} radius, which appear in condition (1a) equals (fig. 3):

$$\rho_{1i}, \rho_{2i} = arctg\left((y_{1Pi} - y_{1S})/(x_{1Pi} - x_{1S})\right) \mp \arcsin\left(r_{CMBi}/r_{SPi}\right). \tag{4}$$

The time of execution of the anti-collision manoeuvre, carried out to avoid the collision with the *i*-th obstacle is an essential parameter of a decision-making process. The following relationship describes the length of this period of time (fig. 3):

$$t_{ZKi} = \left|\Psi_{VRi} - \rho_{ji}\right| / \omega_{ZZsr} + t_{MT} \qquad j = 1, 2. \tag{5}$$

The ω_{ZZsr} variable is representing the average angular speed of the turn, performed by the considered airplane operating in current flight conditions [6]. The t_{MT} parameter, with the value established by an experiment, represents a time margin — a length of time period necessary for the appropriate computations and decision-making process before launching the anti-collision manoeuvre. Taking into account the relationships (2) and (5) with conditions (1a, 1b, 1c) satisfied and additionally: $t_{ZKi} > t_{ki}$, it must be guaranteed a suitable early start of anti-collision manoeuvre and, if a need be, the increase of angular velocity component ω_{ZZsr}. The (5) condition is an essential premise for choosing parameters of the anti-collision manoeuvre. The another guideline is the criterion for the choice of the direction of change of angular position of the airplane (around the O_{z1} axis) in order to allow an obstacle avoidance. The airplane is moving to the selected, free-of-obstacle angular sector [2] along the direction, which guarantees a smallest increment of yaw angle, in accordance with the following relationship (fig. 3):

$$\Psi_{SM\min} = \left|\Psi_{SVi} - \rho_{ji}\right|_{\min} . \qquad (6)$$

where ρ_{Fj} is the angle of the closest angular sector free of obstacles [2].

Important recommendations and criteria for an evasive manoeuvre selection need an additional updates and more detailed discussion. This would make possible the synthesis of a compact logic diagram for the decision-making process for the proper selection of the manoeuvre from the wide spectrum of possible scenarios.

SIMULATION RESULTS FOR THE AIRPLANE AND SELECTED OBSTACLES

The mathematical model of the airplane, including control actuators, is represented by the system of ordinary differentia equations [2]. These equations were solved with the help MatLab and forth-order Runge-Kutta method (RK4) with 0.01 s time step. It was decided to use the model of I-23 Manager airplane (the mass 1050 kg). In all of simulation the aircraft is flying with the constant speed of 35 m/s at the constant altitude: 200 m with flaps deflected — in the configuration approach to landing configuration. All of turns were executed with the same roll angle Φ = 40° (in steady-state phase of turn) and resulted in $\Delta\Psi$ = 90° change of yaw angle. Moving obstacles appear at the same altitude with several speeds and directions of motion.

In order to execute the complex evasive manoeuvre to avoid the obstacle No. 1, the ailerons and the rudder had to be necessarily deflected, as it is presented in figure 5a.

During the simulated phase of flight time histories of roll and yaw components of angular velocity (fig. 4a) consisted with similar sequences, typical for urgent turns.

Variations of the angular position of the airplane, presented in figure 4a, proves that the assumed steady-state roll angle 40° and maximum change of yaw angle 90° were reached.

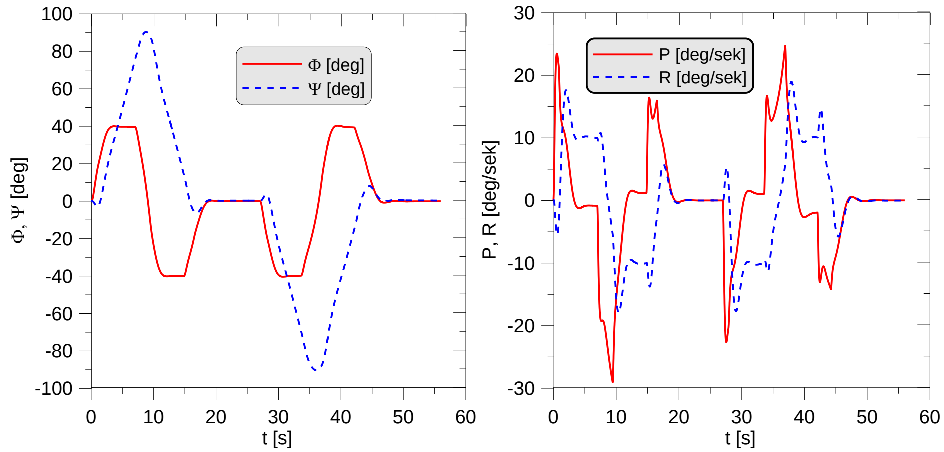

Fig. 4a, 4b. Angles and the appropriate angular velocities for roll and yaw motion (flaps deflected) [own work]

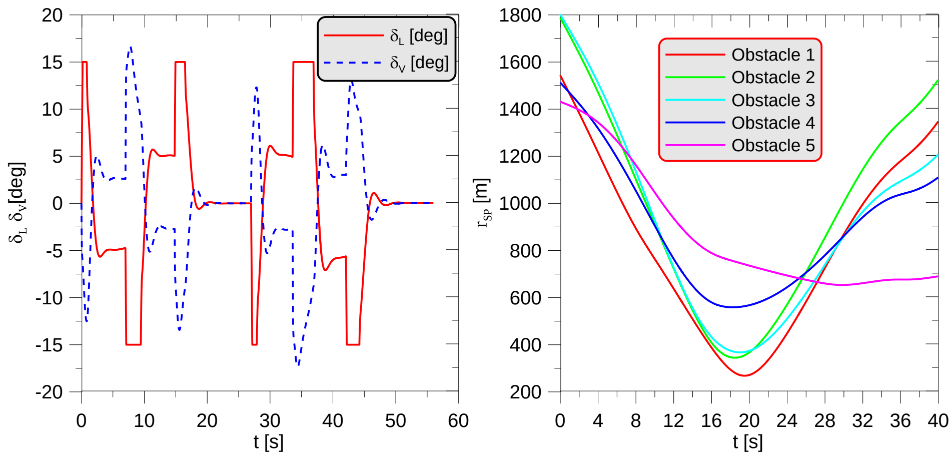

Fig. 5a, 5b. Ailerons and ruder deflections and airplane — to-obstacle distance (flaps deflected) [own work]

Figures 6a, 6b, 7a, 7b are illustrating the behaviour of variables characterising the obstacle No. 1. The condition of no threat of collision with this obstacle was reached after 4 second from the start of manoeuvre and was kept until the end of it. The analogical variables for the obstacle No. 2, are presented in figure 6 and show the short time period of threat (according to condition 1a) within the time period lasted from the 6,5 second until 14 second.

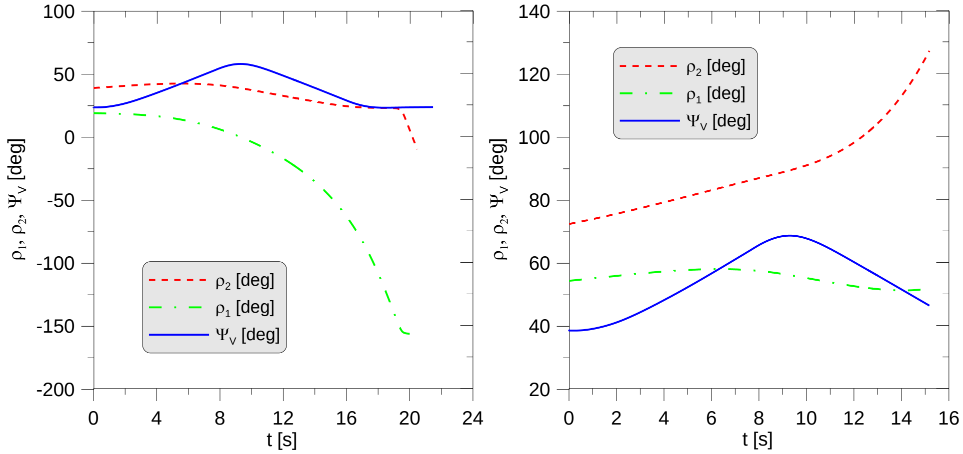

Fig. 6a, 6b. The angles of tangents to the circle of radius r_{CMBi} and the angle of resultant velocity vector of the airplane and obstacles No. 1 and No. 2 [own work]

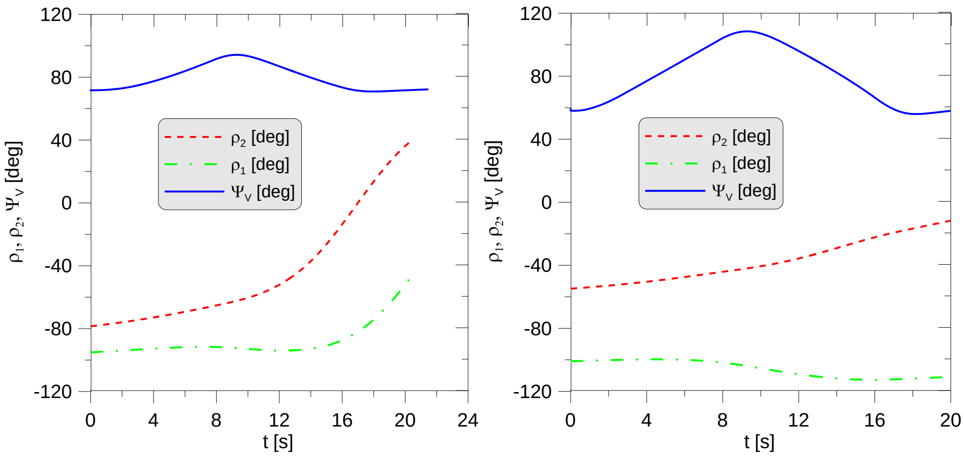

Fig. 7a, 7b. The angles of tangents to the circle of radius r_{CMBi} and the angle of resultant velocity vector of the airplane and obstacles No. 3 and No. 5 [own work]

After the 14th second of the manoeuvre, the obstacle No. 2 did not threatened the airplane. Both of other obstacles did not fulfil either the condition (1a) or the condition (1b), thus did not generate any threat for the airplane within the full time horizon of the simulation. The figure 8 illustrates trajectories of all considered objects, so enables the assessment of the whole situation and collision threats. There are numbered circles on the trajectories — centres of theses circles illustrates positions of discussed objects at the same time moments (for the same manoeuvres).

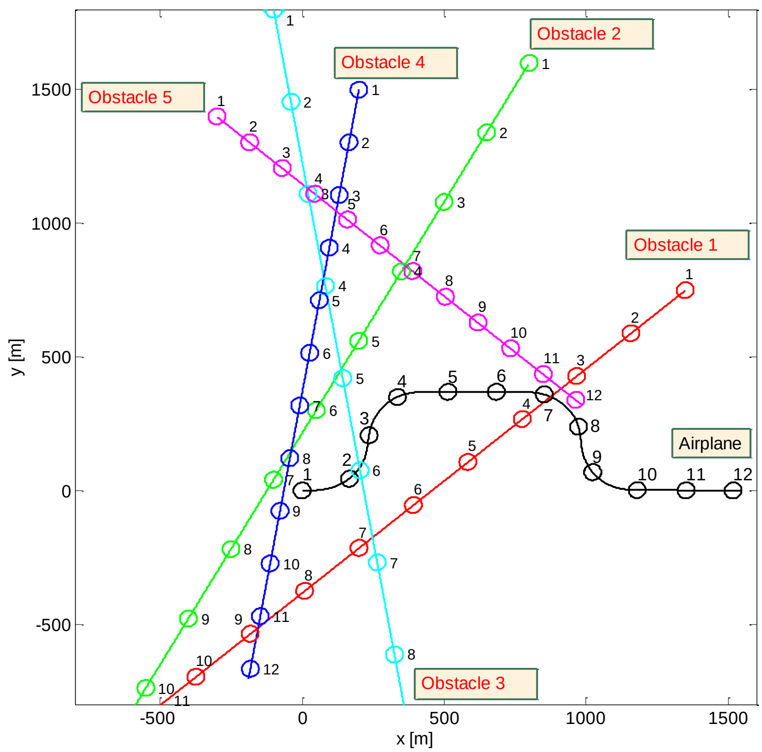

Fig. 8. Trajectories of the airplane and moving obstacles obtained by simulation [own work]

CONCLUSIONS

Presented discussion is leading towards the following conclusions:

1. The mathematical formulas, proposed in the article, classifies effectively a threatening situations resulting from the risk of possible collision by many obstacles moving within the airplane's vicinity.
2. The important conditions and criteria are presented for a decision-making process aimed at the choice of a proper manoeuvre from the wide spectrum of possible scenarios.
3. Simulation results allow a behaviour tracking of important parameters when the anti-collision manoeuvre is executed.

4. The proposed methods can be used to investigate several avoiding manoeuvres performed by an airplane with moving obstacles in its neighbourhood.
5. The presented methods requires an investigations aimed at robustness to external disturbances.

REFERENCES

[1] Graffstein J, *Anti-collision system with radar obstacle detector*, 'Measurement Automation Robotics', 2013, No. 2, pp. 171–175.

[2] Graffstein J., *An influence of selected state variables on accuracy of aircraft trajectory during automatically controlled manoeuvre* [in Polish], 'Transactions of the Institute of Aviation', 2009,No. 202, pp. 51–64.

[3] Graffstein, J., *Simulation of the automatically controlled collision avoidance maneouvre in case of an approach phase of flight and moving obstacle* [in Polish], 'Mechanika w Lotnictwie', 2016, PTMTiS, pp. 113–125.

[4] Koruba Z., Chatys R., *Gyroscope-based control and stabilization of unmanned aerial mini-vehicle (mini-UAV)*, 'Aviation', 2005, No. 9, pp. 10–16.

[5] Paielli R. A., *Modeling maneuver dynamics in air traffic conflict resolution*, 'Journal of Guidance, Control, and Dynamics', 2003, Vol. 26, No. 3, pp. 407–415.

[6] Shim D. H., Sastry S., *An evasive maneuvering algorithm for UAVs in see and avoid situations*, American Control Conference, New York 2007, pp. 3886–3891.

AUTOMATYCZNIE STEROWANY MANEWR OMIJANIA JEDNEJ SPOŚRÓD GRUPY PRZESZKÓD PORUSZAJĄCYCH SIĘ W OTOCZENIU LECĄCEGO SAMOLOTU

STRESZCZENIE

Do rozwiązania problemu unikania przeszkód przez poruszający się samolot w przestrzeni powietrznej niezbędne jest wykrycie zagrożenia kolizji oraz podjęcie właściwej decyzji o odpowiednim sposobie ominięcia przeszkód. W artykule przedstawiono sposób wykrywania niebezpieczeństwa zderzenia z przeszkodą dla przypadku, gdy w otoczeniu samolotu znajduje się wiele ruchomych obiektów. Przeprowadzono analizę algorytmu podejmowania wstępnych decyzji o sposobie unikania kolizji z więcej niż jedną ruchomą przeszkodą. Zaproponowano kształt klasy trajektorii manewru omijania i potwierdzono jej wykonalność na drodze symulacji numerycznej. Wykonano symulację

numeryczną lotu przyjętego typu samolotu we wspomnianych warunkach. Zakres tych symulacji obejmował wszystkie fazy manewru omijania przeszkody, włącznie z powrotem do prostoliniowego odcinka lotu, stanowiącego fragment trasy zaplanowanej przed startem.

Słowa kluczowe:
unikanie przeszkód, systemy antykolizyjne, symulacja komputerowa, dynamika lotu.