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A system for preventing collisions between aircraft and birds

Abstract. *The subject of the article is the design of a system to prevent collisions between aircraft and birds. The theoretical part of the article characterizes the methods of threat minimization used in aviation and the way of using an unmanned aircraft as a device for deterring birds. The article includes the idea of the system, a description of its operation and presents the results of simulations carried out in the MATLAB programming environment.*

Streszczenie. *Przedmiotem artykułu jest projekt systemu zapobiegania kolizjom statków powietrznych z ptakami. W części teoretycznej artykułu scharakteryzowano metody minimalizacji zagrożeń stosowane w lotnictwie oraz sposób wykorzystania bezzałogowego statku powietrznego jako urządzenia do odstraszania ptaków. Artykuł zawiera ideę systemu, opis jego działania oraz przedstawia wyniki badań symulacyjnych przeprowadzone w środowisku programistycznym MATLAB.* (***System zapobiegania kolizjom statków powietrznych z ptakami***).

Keywords: UAV, computer simulation, bird strike, flock, herd control.
Słowa kluczowe: bezzałogowy statek powietrzny, symulacja komputerowa, kolizja z ptakami, kontrola stada.

Introduction

Recently, there has been a significant increase in interest in unmanned aerial vehicles and the search for novel applications for such robots. Thriving research centres are developing advanced systems that take advantage of the latest technological developments [1]. They are equipping small drones with algorithms to adapt the specifics of their work to the required conditions. It has become a popular phenomenon to use drones for work in the most important areas of life, such as medicine and aviation [2].

The article presents the concept of using an autonomous UAV to minimize the hazard of collisions between flocks of birds and aircraft around airports [3-5]. The main idea of the article is to use a UAV that uses bird detection radar data to operate as a robot. This allows it to adapt its mode of operation according to the flock species it detects. The UAV robot is designed to prevent birds from crossing a certain zone, called the safety zone. In Figure 1, this zone is marked by a green canopy around the runway. The parameter h_{min} determines the minimum height (ceiling) of aircraft taking off or landing.

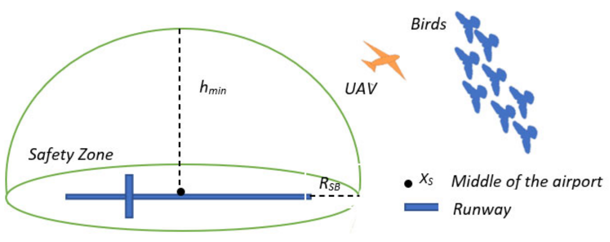

Fig. 1. Concept of UAV use in the airport area

Methods to minimize collisions between aircraft and birds

In aviation, there are two methods of deliberate action to minimize the risk of aircraft collisions with birds. The first is the pro-active method, which involves modifying the location of bird habitats and reducing aviation activity – aircraft traffic. The second method is the re-active method, which consists of active and passive hounds. The first type of crowing includes any human activity in cooperation with trained animals – an example is falconry. The second group includes devices [6] or objects that spontaneously deter birds – such as bang cannons [7]. The division of methods is shown in Figure 2.

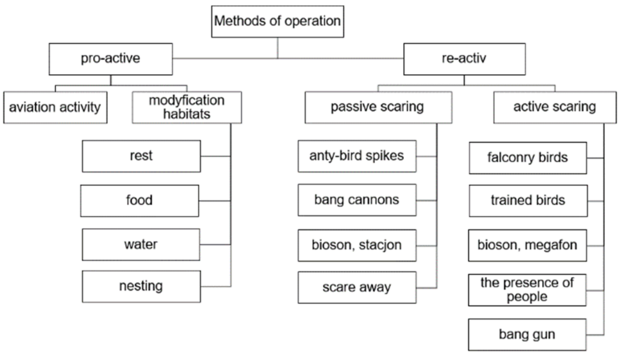

Fig. 2. Division of methods to reduce the risk of aircraft collisions with birds

In addition to the methods shown in Figure 2, the removal of species by authorised bodies should be mentioned. This method involves destroying nests, trapping, shooting or displacing unwanted species. Permits for such activities are issued by the Regional Director of Environmental Protection. Another example of threat minimisation is ecosystem modification. This involves reducing the attractiveness of an area to birds, for example by cutting down trees on which nests are built, or by installing underground water tanks [8]. Threat minimisation methods can also include innovative ways of controlling birds. One example is the use of pesticides in agriculture that cause rotting and death of food for certain species [9]. Another example, used at Amsterdam Airport, is the grazing of pigs on grassy areas near the runways [10].

Project assumptions

During the course of the project it was determined that one of the elements needed to evaluate the effectiveness of the use of UAVs was a combination of three issues relating to animal behaviour in the flock. The first constraint imposed on the project is the flocking model developed by C. W. Reynolds [11]. The author formulated three movement behaviours for creating computer animations of flocks of birds: collision avoidance, speed adaptation and flock centring. Their use allows the reproduction of the natural behaviour of animals in a flock [12-14]. Another limitation is that the model assumes the use of coordination algorithms to maintain flock stability. The final factor used in the development of the programme is the issue of so-called herding, or how the flock moves. This constraint is designed to approximate how birds react to a potential encounter with a predator, i.e. a UAV.

The problem under study was implemented in the Matlab programming environment. In order to evaluate the performance of the UAV, the ability to visualise the situation by means of graphs showing the flight of the birds and the robot and how they interact in their spatio-temporal trajectory was used.

Flock Structure

First, the characteristics of the moving flock were defined. The case studied consists of N birds, moving in a flock. The neighbourhood relationship described by the formula

(1) $$N_i = \{j \in N \mid \|x_i - x_j\| \leq R_0\},$$

where R_0 is the distance between two objects (birds). An example of the relationship between flock elements is shown in Figure 3.

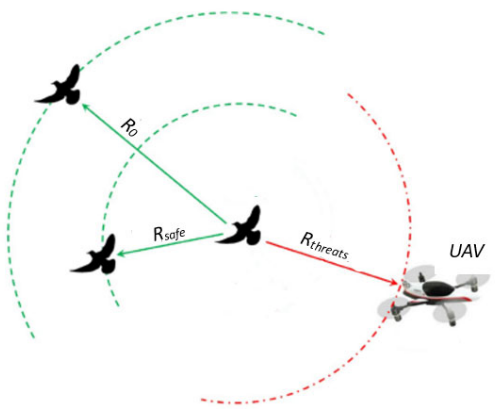

Fig. 3. Relationships between elements in a herd

In order to successfully program a moving herd, it was necessary to take into account the geometric centre of gravity of the object, described by the relation

(2) $$X_c = \frac{1}{N}\sum_{i=1}^{N} x_i.$$

Freeman's [15] centrality formula was used to determine flock cohesion

(3) $$\Theta_D(G) = \frac{\sum_{n_i \in v}[deg(n*) - deg\,(n_i)]}{(N-1)(N-2)},$$

where: v – set of vertices, $deg\ (n_i)$ – degree of the i-th vertex, $n* = \{n_i\colon deg(n_i) = \Delta(G)\}$ – the vertex with the highest degree for $\Delta(G) = max.[deg(n_i)]$.

Taking advantage of the constraints, resulting from the Reynolds flock model [11], it was necessary to introduce an algorithm related to the separation control $u_{i,sep}$ and speed equalisation $u_{i,dop}$:

(4) $$u_{i,sep} = \sum_{j \in N_i}\left(1 - \frac{R_{safe}}{\|r_{ij}\|}\right) r_{ij},$$

(5) $$u_{i,dop} = \begin{cases} \sum_{j \in N_i}(v_j - v_i) & card(N_i) > 0 \\ 0 & \text{for others} \end{cases}.$$

where: card (N_i) is a measure of the number of elements in a herd and the r_{ij} is the distance vector from the i-th to the j-th element.

Another function used to describe herd structure is the tendency of animals to move for a particular purpose, such as foraging or following a leader. This function defines the relationship between

(6) $$u_{i,target} = c_1(x^G - x_i) + c_2(v^G - v_i),$$

while the control function is defined by the equation

(7) $$u_i = K_{sep}u_{i,sep} + K_{dop}u_{i,dop} + K_{target}u_{i,target} + K_{threat}u_{i,threat} + b_i(t),$$

where: b_i – disturbance factor, K – coefficients chosen so that the position of the herd is stable.

Herd control

The paper considers the case where the main objective of the UAV predator is to herd the flock to a safe place. It was also assumed that the robot should maintain a constant flock volume, keep an appropriate distance from the flock and control its flight altitude. The concept of such work is illustrated in Figure 4, where the UAV interacting with specific nodes to achieve the stated objectives is marked in orange.

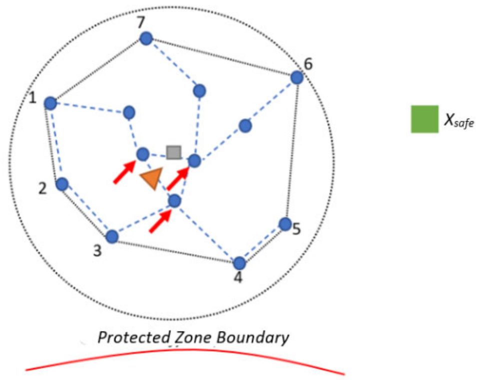

Fig. 4. Relationship between the UAV and selected elements of the herd

The equations of motion for the UAV are as follows [16]:

(8) $$\dot{x_p} = V\cos\gamma\cos\chi,$$

(9) $$\dot{y_p} = V\cos\gamma\sin\chi\,,$$

(10) $$\dot{h_p} = V\sin\gamma,$$

(11) $$\dot{V} = T\cos\alpha - \eta V^2 C_D(\alpha) - g\sin\gamma,$$

(12) $$\dot{\gamma} = \left(\eta V C_L(\alpha) + \frac{T\sin\alpha}{V}\right)\cos\mu - \frac{g\cos\gamma}{V},$$

(13) $$\dot{\chi} = \left(\eta V C_L(\alpha) + \frac{T\sin\alpha}{V}\right)\frac{\sin\mu}{\cos\gamma},$$

where: V – flight speed, γ – flight path angle, χ – global course angle, h – height C_D,C_L – lift and drag coefficients, α – rake angle, η – wind axis pitch angle, T – thrust per unit mass.

The coefficient η is calculated according to the relationship

(14) $$\eta = \frac{pg}{2\bar{W}},$$

where p is the density of the air and $\bar{W}$ is the load on the robot wing.

Programme effectiveness

The research was divided into two parts. First, the behaviour of birds flying towards the airport without the presence of the UAV was studied. The graph (Figure 5) shows the position of a flock of birds in space.

A UAV robot was then introduced to control the birds' behaviour and the flock's behaviour was observed for 40 seconds.

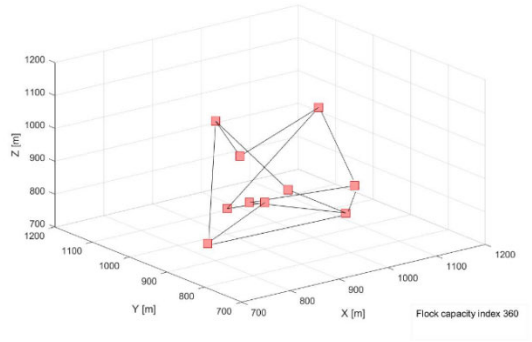

Fig. 5. Visualisation of the position of 10 birds in space during flight without the presence of a UAV

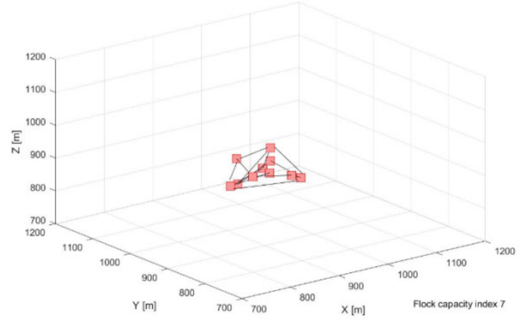

Fig. 6. Visualisation of the position of 10 birds in space 40 seconds after UAV detection

Figure 6 confirms the validity of the earlier assertion that birds form a compact formation in a threatening situation. To facilitate the interpretation of the birds' behaviour, a flocking capacity index was added to determine the relationship between individuals. The lower the value of this parameter, the smaller the flock size and the closer the birds flew to each other.

The flocking behaviour of 100 birds was then studied. The effects of the UAV are shown in Figures 7-8.

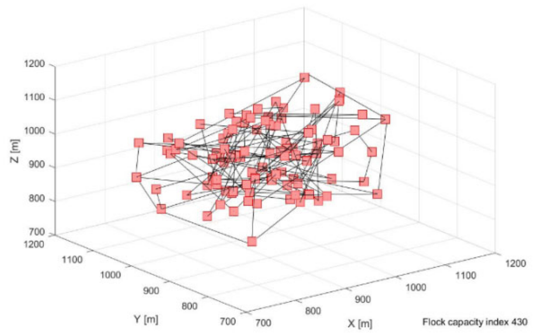

Fig. 7. Visualisation of the position of 100 birds in space during flight without the presence of a UAV

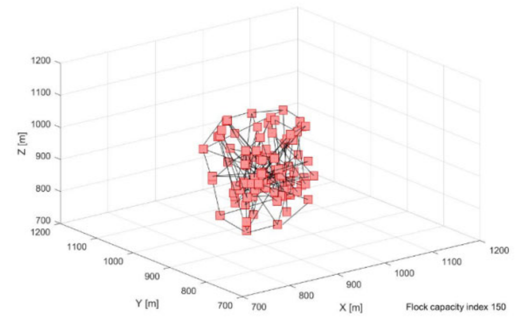

Fig. 8. Visualisation of the position of 100 birds in space 40 seconds after UAV detection

UAV interaction configurations studied

When studying the problem of herd control, it was found that the robot can interact with the herd in different configurations. The final choice depends on the operator's preference. In the study, the following three cases were considered: protecting the safety perimeter (Figure 9), redirecting the flock to a safe place marked as X_{safe} (Figure 10) and redirecting the flock to a safe place marked as X_{safe} and protecting the safety perimeter (Figure 11).

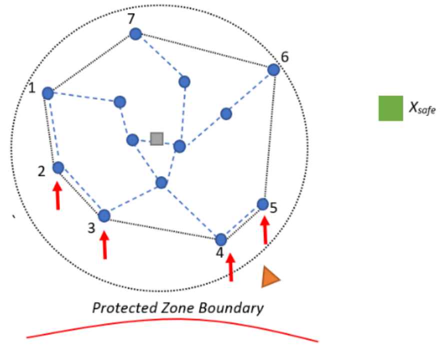

Fig. 9. Impact of drone positioning on perimeter security

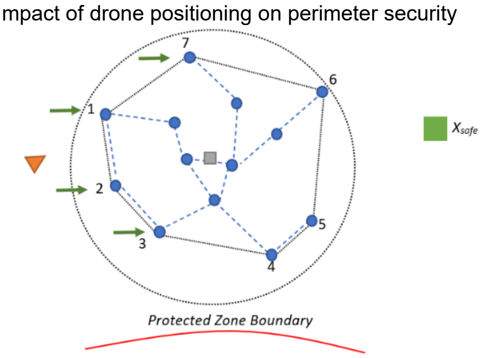

Fig. 10. Impact of drone positioning on herd redirection to a safe location

Depending on the mode of operation, the robot enforces a certain herd behaviour by exerting pressure on individuals located at sensitive points. In the first configuration, the UAV acted on node 4, which was closest to the edge of the safety zone. On the other hand, when redirecting the herd to a safe place, it acted on node 1 - the one furthest away from the X_{safe}. On the final attempt, the UAV acted on node 3, which was the furthest from the X_{safe}, but close to the edge of the safety zone.

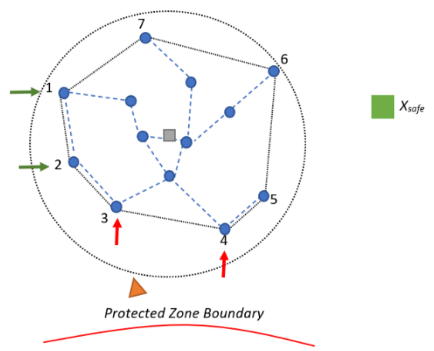

Fig. 11. Impact of UAV to graze in a safe place

To evaluate the effectiveness of the UAV, the position of the centre of the flock and of the robot during the operation and the variation of the distance of the birds from the airport as a function of time were analysed. The results of the impact of the UAV on the flock for border control are shown in Figures 12 and 13.

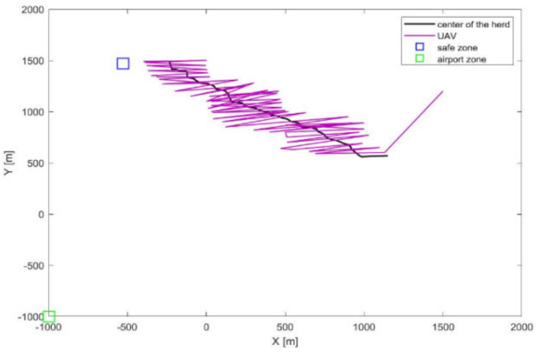

Fig. 12. Location of herd centres and UAV positions during grazing

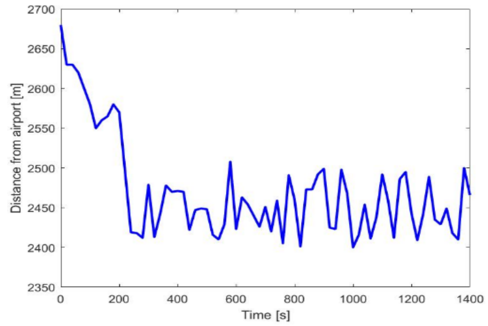

Fig. 13. Herd's observance of the distance to the airport during grazing and during UAV impact

The robot did its job - it followed the centre of the flock and interacted with them. Analysis of Figure 13 also shows that after 200 seconds the birds were flying at a constant distance from the airport (2.4 ÷ 2.5 kilometres). This means that the task set for the UAV was effectively completed as the birds maintained an almost constant distance from the danger zone.

The UAV's next task was to redirect the flock to an X_{safe} safe area. The effects of the programme are shown in Figures 14 and 15, which illustrate the positions of the flock centres and the impact of the UAV.

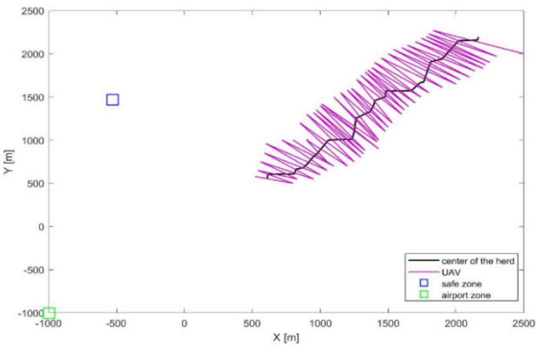

Fig. 14. The positions of the flock centres and the position of the UAV when redirecting the flock to a safe place

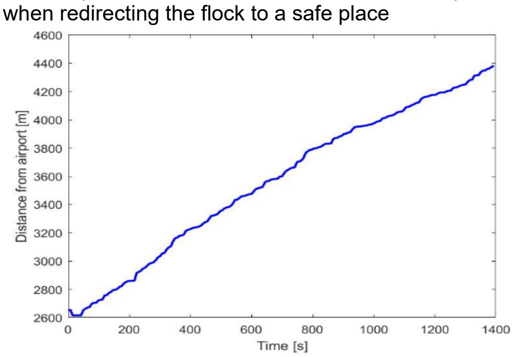

Fig. 15. Change the distance of the herd from the airport while the UAV redirects them to a safe location

Once again, the UAV performed reliably. As a result of its work, the flock increased its distance from the airport and the robot followed the flying birds.

The UAV's final task was to redirect the flock to a safe place and protect the perimeter of the security zone.

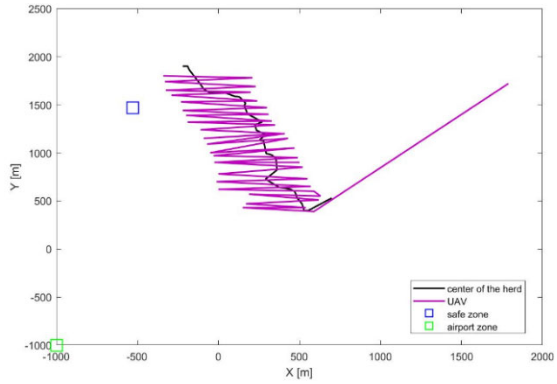

Fig. 16. The positions of the herd centres and the position of the UAV in moving the herd to a safe place and protecting the perimeter of the safety zone

Figures 16 and 17 show the results obtained, confirming the validity of the assumptions made.

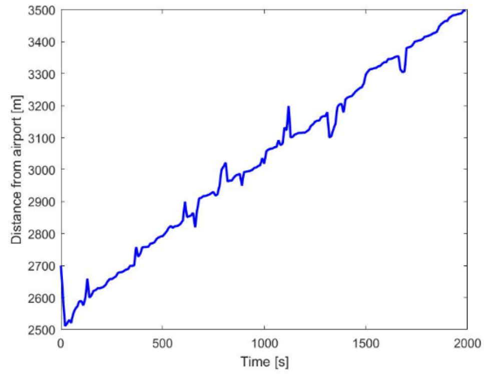

Fig. 17. Changing the distance of the herd from the airport when moving the herd to a safe place and protecting the perimeter of the safety zone

When the results were analysed, it was clear that the robot had done its job. It correctly controlled the flight of the flock, respecting the grazing restrictions and the security and border protection zones. The distance of the flock from the airport increased over time, which is the correct behaviour of birds in the presence of a UAV.

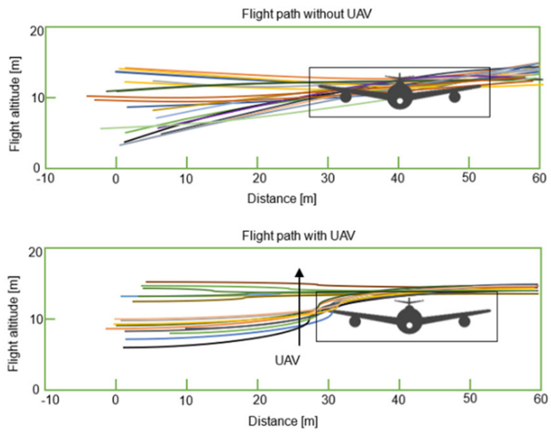

Fig. 18. Flight path of a flock of birds without and with UAV participation for varying flock speed and UAV climb rate

Effect of bird flight speed on UAV effectiveness

When analysing the behaviour of the UAV, the relationship between its rate of climb and the speed of the flock was also checked. Simulation studies were carried out with the flight speed of the flock varying from 10 to 20 [m/s] and the climb rate of the UAV in the range 4÷7 [m/s].In Figure 18, the safety zone - the area where the birds are not allowed - is marked with a rectangle. The study was carried out for a flock of twenty birds and a UAV at a distance of 45 metres from the runway.

Each tested case of varying flock speed and UAV climb rate was tested five times, and the simulation results are shown in Table 1. In the table, the standard deviation of the UAV performance is given in brackets.

Table 1. Percentage effectiveness of UAVs

Speed of birds [m/s]	**UAV climb rate** [m/s]			
	4	5	6	7
10	99.9 (0.06)	99.8 (0.22)	98.8 (0.94)	98.5 (1.17)
15	99.8 (0.18)	99.9 (0.12)	98.3 (1.46)	97.6 (1.26)
20	97.8 (1.34)	97.7 (1.56)	94.9 (2.87)	94.0 (3.47)

Analysis of the cases tested showed that the birds entered the safety zone on each occasion (Figure 18). This was due to the UAV being too close to the runway. The study also showed that using a faster rising robot did not result in better bird deterrence.

Conclusion

The author's task was to design a system for the effective use of UAVs in the process of collision avoidance between aircraft and birds. The project used the experience of ornithologists and mathematical flock models developed by Freeman [15] and Reynolds [11].

For this purpose, a computer program was developed in the MATLAB environment, using the UAV as a robot to interact with the birds and force them to behave in a certain way. The simulation study was carried out for three scenarios of UAV impact on birds: perimeter protection, redirection to a specific location, and a combination of the two. In each case, the behaviour of a flock of birds flying towards the airport without the presence of a UAV and with the presence of a UAV was studied for a flock of 20 or 100 birds. The location of the centre of the flock and of the robot during operation and the distance of the flock from the airport were taken into account when evaluating the performance of the UAV. In the first test scenario, the robot followed and interacted with the centre of the flock so that after 200 seconds the birds were flying at a constant distance of 2.5 kilometres from the airport. Looking at the UAV's operation to redirect the flock to a safe place, it can be seen that the flock increased its distance from the danger zone as a result of the UAV's operation. The final scenario carried out during the simulation study was to redirect the flock to a safe place and protect the perimeter of the safety zone. The robot correctly controlled the movement of the flock, respecting the grazing restrictions and safe places and protecting the perimeter. As a result, the distance of the flock from the airport increased. In general, in each case of the study, the UAV performed its task and the birds formed a compact formation in an emergency situation.

The effect of the UAV's climb speed on the effectiveness of stopping the flock from entering the safety zone was also investigated. The simulation showed that this factor is irrelevant if the minimum distance of the UAV position from the runway is not maintained.

The results of the simulation studies of the designed system for preventing aircraft collisions with birds confirmed that the use of a robotic UAV is justified, as it is able to effectively interact with birds and force them to behave in a certain way.

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