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ANALYSIS OF METHODS AND CONTROL SYSTEMS OF UNMANNED PLATFORMS

ANALIZA METOD I SYSTEMÓW STEROWANIA PLATFORM BEZZAŁOGOWYCH

Abstract: *The key aspect affecting the safety of routing and the unmanned platform mission execution is the autonomy of control systems. To achieve the mission goal, control algorithms supported by advanced sensors have to estimate the obstacle location. Moreover, it is needed to identify potential obstacles, as well as algorithms for trajectory planning in two or three dimensions space. The use of these algorithms allows to create an intelligent object that performs tasks in difficult conditions in which communication between the platform and the operator is constricted. The article mainly focuses on unmanned aerial vehicle (UAV) control systems.*
Keywords: aviation, unmanned aerial vehicles, control systems, obstacle avoidance

Streszczenie: *Kluczowym aspektem mającym wpływ na bezpieczeństwo trasowania oraz realizacji misji platformy bezzałogowej jest autonomia systemów sterowania. Z tego względu algorytmy sterowania wspierane przez zaawansowane czujniki muszą oszacować lokalizację przeszkody. Poza tym, należy identyfikować potencjalne przeszkody oraz algorytmy dotyczące planowania trajektorii w dwóch lub trzech wymiarach przestrzennych. Zastosowanie wyżej wspomnianych algorytmów umożliwia stworzenie inteligentnego obiektu wykonującego zadania w trudnych warunkach, podczas których komunikacja pomiędzy platformą a operatorem jest ograniczona. Artykuł opisuje głównie systemy sterujące bezzałogowych statków powietrznych (BSP).*
Słowa kluczowe: lotnictwo, bezzałogowe statki powietrzne, systemy sterowania, unikanie przeszkód

1. Introduction

Most UAS (Unmanned Aerial Systems) consist of: flying platforms, ground control station (GCS), avionics, navigation and wireless communication subsystems. The GCS is interface between human (UAV pilot) and UAS. Wireless communication is based on radio modules, GSM modules or Satellite Communication. All of these types of wireless communication can be disturbed. Therefore, autonomous flight is so important. UAV is controlled by the Flight Control Computer (FCC). FCC is connected to Attitude and Heading Reference System (AHRS), Air Data Computer and GPS navigation system. These sensors provide input data to State Observer which estimates state vector of UAV. Moreover, State Observer can be completed with other sensors such as range finders, encoders, vision processing data, etc.

Navigation of any UAV is based on Inertial Navigation System (INS) and Global Navigation Satellite Systems (GNSS).

Another source of position information can be achieved from on board radio navigation subsystem. Radio navigation is a method of navigating unmanned aircraft based on navigational elements determined by radio technology, whose operation is based on the properties of electromagnetic waves. Based on the information received from radio stations emitting electromagnetic waves to the aircraft, the location of UAV as well as its speed and course is determined.

Radar navigation uses information from radar station. The digital terrain map was compared with the terrain map obtained by the UAV radar station. The whole process is automated, and patterns of terrain images previously obtained in reconnaissance flights or from satellite images are stored in the on-board computer memory.

Nowadays, simultaneous localization and mapping (SLAM) navigation is dynamically developed, and it provides high-accuracy positioning data.

2. Control algorithms

Control algorithms have to be fitted to the type of UAV. Most of the currently used control systems are based on PID regulators, which provides control signals from errors given by desired values and estimated states. Basic control algorithms such as stabilization, navigation are supported by obstacle avoidance subsystems, mission computers, etc. which generates a desired flight path.

2.1. GPS/INS integrated navigation system

In the GNSS/INS integrated navigation system, information about that is provided by an inertial system. The GNSS/INS integrated navigation systems calculates state vector in

North-East-Down coordinate system (NED): location of an UAV, its horizontal and vertical speed and Euler angles.

$$X = [x_g, y_g, z_g, U, V, W, \phi, \theta, \Psi]^T$$

where:
x_g, y_g, z_g – location coordinates in inertial frame,
U,V,W – three speed vectors in inertial frame,
ϕ, θ, Ψ – Euler angles: roll, pitch, yaw in inertial frame.

2.2. Control algorithms using vision systems

Vision systems used in autonomous control algorithms are based on digital image processing. Vision sensors such as cameras and digital signal processors (DSP) are the most important elements here. One or two cameras can be used in the control process. This is conditioned by the algorithm used. Thanks to them and the stereovision technique, it is possible to obtain image depth and location. The control algorithm using one camera is more complicated. In the two camera system, the pinhole camera model is used to determine the position:

$$u_{imeas} = u_i + e_{pix} = \frac{X_i f}{Z_i} + e_{pix} \quad (1)$$

where:
f – focal length,
X_i – the position of the object perpendicular to the optical axis of the camera,
Z_i – distance from camera to object,
u_i – location of the object on the image,
e_{pix} – pixel error.

Based on the difference in the location of the same object on images from two cameras, the vision system determines the distance Z:

$$Z = \frac{Bf}{u_{1meas} - u_{2meas}} = \frac{Bf}{p_{meas}} \quad (2)$$

where:
Z – distance from camera to object,
B – camera spacing,
F – focal length,
u_{1meas} – location of the object based on the first camera,
u_{2meas} – location of the object based on the second camera.

Thanks to information about the distance Z and location of X registered obstacles, the system plans a flight trajectory that will allow to avoid obstacles. The dynamic model of the aircraft is determined by the following equations:

$$\dot{x}(t) = V \cdot cos(\psi(t)) \quad (3)$$

$$\dot{y}(t) = V \cdot sos(\psi(t)) \quad (4)$$

$$\dot{\psi}(t) = \omega(t), \quad (5)$$

$$\omega(t) = u(t - T_d) \quad (6)$$

$$u \in [-\omega_{max}, \omega_{max}] \quad (7)$$

where:
x, y – aircraft position,
V – speed,
Ψ – course,
ω – angular velocity,
T_d – iteration time constant,
u(t) – given turn rate.

There are two methods for generating flight trajectories based on:

- model predictive control,
- set theory.

2.2.1. Methods based on set theory

Due to the limitations of the aircraft's dynamics and due to its location relative to the aircraft, the first set of space points has predetermined properties. The defined point sets are as follows:

- set of dangerous points,
- set of prohibited points,
- set of achievable points.

Due to vision system errors that may not notice the smaller obstacle in front of the larger one, a set of dangerous points is used. The set of dangerous points is an increase of the set of prohibited points, taking into account that the set of prohibited points contains smaller obstacles. The set of points of space surrounding an obstacle is called a set of prohibited points.

The set of achievable points is derived from the imposition of aircraft maneuvering restrictions on the surrounding space. It is such a set of points to which the aircraft can move from its current position.

The disadvantages of control algorithms based on set theory are:

1. single task at a time limit,
2. large number of calculations is required,
3. some of the calculations are unnecessary,
4. errors resulting from obstacle location using stereovision.

2.2.2. Predictive Control

It is based on predicting the future states of the object and determining optimal controls. It is an extension of the set theory method, thanks to which it is possible to use predictive control. The generalized control algorithm is as follows:

1. Calculation of the optimal control $u[k+i]_{i=0}^{T}$,
2. The use of optimal control at a specified time $k \leq t \leq \tau$, where $0 \leq \tau \leq T$,
3. Repetitions of items 1 and 2 for the new point $x_{observer}[k+\tau]$ at the moment $k+\tau$.

Single camera system

A single camera can be used to locate obstacles and thereby determine the trajectory of the flight. By analyzing two successive video frames, the so-called field of motion vectors of structured and unstructured blocks specified on the analyzed frames is created. Determining the location of the considered objects is possible thanks to the knowledge of the motion vectors of individual blocks and the flight parameters of the aircraft. From the data used, it is possible to determine the distance between the aircraft and the obstacle.

Due to the common feature of concentrating the greater part of total energy in the low and medium frequency range, image blocks can be divided into structured and unstructured. The algorithm is as follows:

- Application of DCT (Discrete Cosine Transform) to isolated image blocks;
- Sorting of the coefficients obtained by DTC in ascending order by frequency;
- Calculating the indicator determining the proportion of total energy r;

$$r = \frac{\sum_{i=1}^{0,2S} x_i^2}{\sum_{i=1}^{S} x_i^2} \tag{8}$$

where:
S – the number of all coefficients,
x_i – individual coefficients.

- Determination of the structured blocks with the highest value of the proportion of total energy. The remaining blocks are marked as unstructured.

Structural blocks are then associated with two adjacent image frames for full image analysis. This is done by setting a comparative criterion. The measure of similarity is the sum of the absolute differences determined by the equation:

$$d_0(A,B) = \sum_{ij} |a_{ij} - b_{ij}| \tag{9}$$

where:
A, B – adjacent frames,
a, b – pixel value,
i, j – pixel coordinates.

The angular velocity vector is determined by the equation:

$$\Omega = [(\Gamma \cdot A)^t \cdot (\Gamma \cdot A)]^{-1} \cdot (\Gamma \cdot A)^t \cdot (\Gamma \cdot A) \tag{10}$$

and the distance value Z:

$$Z^j = \arg\min_z \left[x_j^m - f(x, y, Z)\right]^2 + \left[y_j^m - f(x, y, Z)\right]^2 \tag{11}$$

$$E^j = \left[x_j^m - f(x, y, Z^j)\right]^2 + \left[y_j^m - f(x, y, Z^j)\right]^2 \tag{12}$$

$$j^* = \arg min_j E^j \tag{13}$$

where:
Z^j – distance to the object,
E^j – estimation error,
j^* – vector index.

By determining the distance, we are able to create a spatial map of the aircraft's surroundings. This allows us to design in advance a flight trajectory avoiding stationary objects.

2.2.3. Autonomous control using a laser rangefinder

The autonomous control algorithm is based on the use of a laser distance sensor. Thanks to the built-in device controlling the direction of the laser beam and the appropriate algorithm, the system is able to scan the entire UAV's environment. Such an algorithm consists in:

- locating dynamic obstacles using a laser distance sensor and avoiding them,
- avoiding static obstacles based on the map of the environment.

Avoiding dynamic obstacles, which are all the obstacles that suddenly appear on the flight trajectory of the aircraft, and which were not previously included in the UAV's environment map used to generate the flight trajectory, involves dynamic change of the flight path. For this purpose, the RPP (Reactive Path Planner) control algorithm is used, whose task is to localize the obstacle and provide the optimal flight trajectory so as to complete the previously planned task avoiding the obstacles encountered. The algorithm for scanning the surroundings of the aircraft utilizing a laser sensor used to determine the position of the obstacle is as follows:

1. scanning space in the vicinity of the current flight path,
2. scanning the surrounding space to acquire information about the size of the obstacle.

In the first stage of scanning, it is necessary to know the future location in which UAV will be at a later moment, which can be determined by the equation as follows:

$$\dot{x} = V \cdot \cos\psi \tag{14}$$

$$\dot{y} = V \cdot \sin\psi \tag{15}$$

$$\dot{\psi} = V \cdot \tan\phi \tag{16}$$

$$\dot{V} = \alpha_V \cdot (V^C - V) \tag{17}$$

$$\dot{\phi} = \alpha_\phi \cdot (\phi^C - \phi) \tag{18}$$

$$\hat{r}(\sigma, t) = \binom{N}{E} + \frac{V^2}{g\tan\phi} \cdot \begin{pmatrix} -\cos\left(\psi + \frac{\sigma \cdot g \cdot \tan\phi}{V}\right) + \cos\psi \\ \sin\left(\psi + \frac{\sigma \cdot g \cdot \tan\phi}{V}\right) - \sin\psi \end{pmatrix} \tag{19}$$

where:
x, y – current aircraft position,
t;$x_{r,}y_r$ – future aircraft position,
t+ σ, V – flight speed,
g – gravitational constant,
ϕ – bank angle,
t – time,
ψ – flight course,
σ – anticipation of future position estimation $x_{r,}y_r$,
V^C – given flight speed,
ϕ^C – given bank angle,
$\alpha_\phi \alpha_V$ – dynamic model inertia constants.

The system performing the control algorithm at the moment of detecting the object proceeds to determine the size of the obstacle.

1. Scanning the environment with a laser sensor.

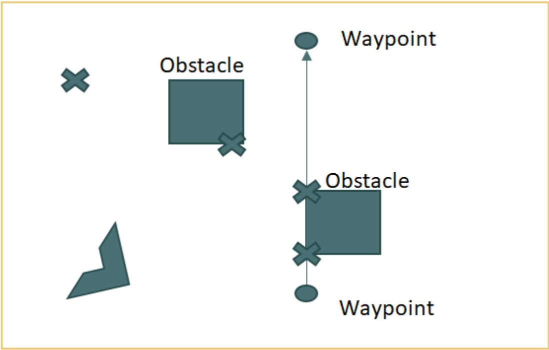

Fig. 1. Diagram of obstacle size determination

2. Elimination of detected objects behind the aircraft.

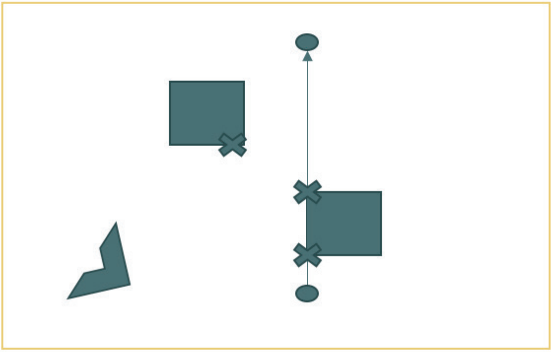

Fig. 2. Diagram of obstacle size determination

3. Generating triangles in areas showing obstacles.

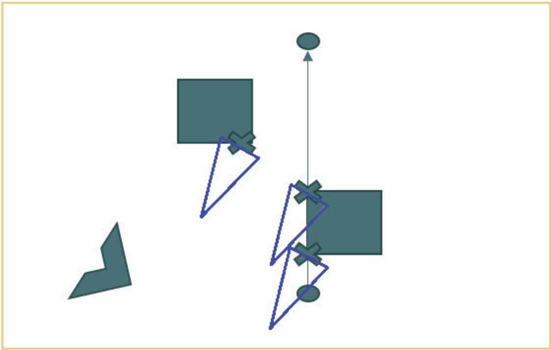

Fig. 3. Diagram of obstacle size determination

4. Elimination of base lines of triangles.

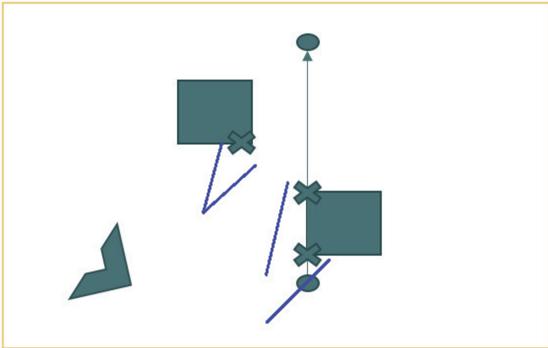

Fig. 4. Diagram of obstacle size determination

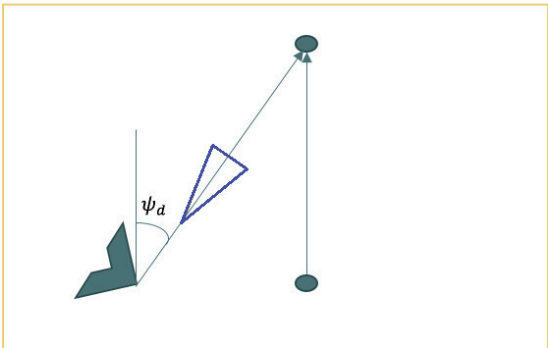

Fig. 5. Diagram of obstacle size determination

Static obstacles are avoided by generating a flight path based on a map of the environment that was known in advance. For this purpose, the RRT (Rapidly exploring Random Tree) random search algorithm is used, which looks as follows:

1. Start searching the RRT tree at x_{init}.
2. Determination of a random node x_{rand} in space R^3 and assuming the low probability that $x_{rand} = x_{goal}$ to move the tree towards the target.
3. Determining of the x_{near} node nearest to x_{rand}.
4. Making a transition from the x_{near} node by a unit distance in the x_{rand} direction thereby creating another x_{new} node.
5. Checking for no obstacle between x_near and x_new with the known environment.
6. If no obstacle exists adding the node x_{new} and the branch $x_{near} - x_{new}$, otherwise return to step 2 to designate a new node x_{rand}.
7. Checking if x_{new} can be directly connected to x_{goal}. If not, we add the segment $x_{new} - x_{goal}$ to the tree. If so, then we return to step 2 and perform another iteration.

2.3. State observer

2.3.1. AHRS

AHRS (Attitude and Heading Reference System) is based subsystem which can provide Euler angles: roll, pitch, and yaw. Mostly, it is based on three axis sensors: gyroscopes, accelerometers and magnetometers. In aircraft, it is need to add GPS velocity vector or airspeed to compensate centripetal acceleration.

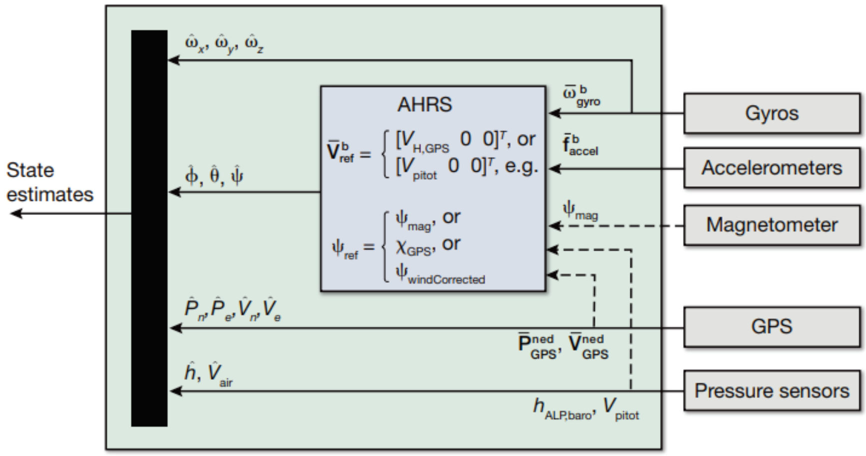

Fig. 6. AHRS spatial orientation system [www.jhuapl.edu/Content/techdigest/pdf/V31-N02/31-02-Barton.pdf]

Euler angles describe the orientation of the aircraft body axis to the north, east and down, which means longitudinal, lateral and normal coordinates. Here, θ is the pitch angle, φ is the roll angle, and ψ is the yaw angle according to the scheme.

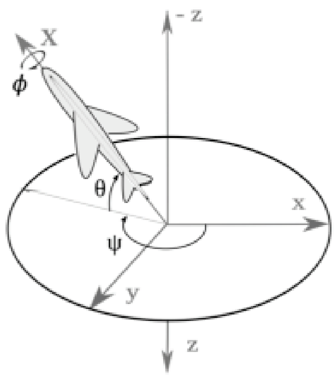

Fig. 7. Axes and coordinates definitions

The angular velocity vector expressed in the body frame is P for the roll rate, Q for the pitch rate, and R for yaw rate. It is related to the Earth's frame by the transformation given by the kinematic equation:

$$\begin{bmatrix}\dot{\phi}\\ \dot{\theta}\\ \dot{\psi}\end{bmatrix} = \begin{bmatrix}1 & \tan\theta\sin\phi & \tan\theta\cos\phi\\ 0 & \cos\phi & -\sin\phi\\ 0 & \frac{\sin\phi}{\cos\theta} & \frac{\cos\phi}{\cos\theta}\end{bmatrix}\begin{bmatrix}P\\ Q\\ R\end{bmatrix} \quad (20)$$

An integrating equation gives numerical instability and can be blocked – gimbal lock. For this reason, quaternion representation can be used:

$$\mathrm{q} = \mathrm{q}0 + \mathrm{q}1\mathrm{i} + \mathrm{q}2\mathrm{j} + \mathrm{q}3\mathrm{k} \quad (21)$$

$$\textstyle\sum_{i=0}^{3} q_i = 1 \quad (22)$$

In the case where the quaternary norm is 1, and their elements derived from Euler angles are equal:

$$q_0 = \cos\phi'\cos\theta'\cos\psi' + \sin\phi'\sin\theta'\sin\psi' \quad (23)$$

$$q_1 = \sin\phi'\cos\theta'\cos\psi' + \sin\phi'\sin\theta'\sin\psi' \quad (24)$$

$$q_2 = \cos\phi'\sin\theta'\cos\psi' + \sin\phi'\sin\theta'\sin\psi' \quad (25)$$

$$q_3 = \cos\phi'\cos\theta'\sin\psi' + \sin\phi'\sin\theta'\sin\psi' \quad (26)$$

where: $\varphi' = \varphi/2$, $\theta' = \theta/2$, and $\psi' = \psi/2$.

The kinematic equation can be rewritten in a linear form using quaternion elements.

$$\begin{bmatrix}\dot{q_0}\\ \dot{q_1}\\ \dot{q_2}\\ \dot{q_3}\end{bmatrix} = \frac{1}{2}\begin{bmatrix}0 & -P & -Q & -R\\ P & 0 & R & -Q\\ Q & -R & 0 & P\\ R & Q & -P & 0\end{bmatrix}\begin{bmatrix}q_0\\ q_1\\ q_2\\ q_3\end{bmatrix} \quad (27)$$

Rotation matrix based on quaternion representation is equal:

$$\boldsymbol{L}_{gq} = \begin{bmatrix}q_0^2 + q_1^2 - q_2^2 - q_3^2 & 2q_1q_2 - 2q_0q_3 & 2q_0q_2 + 2q_1q_3\\ 2q_0q_3 + 2q_1q_2 & q_0^2 - q_1^2 + q_2^2 - q_3^2 & 2q_2q_3 - 2q_0q_1\\ 2q_1q_3 - 2q_0q_2 & 2q_0q_1 + 2q_2q_3 & q_0^2 - q_1^2 - q_2^2 + q_3^2\end{bmatrix} \quad (28)$$

2.3.2. Extended Kalman filter

Kalman filter is an algorithm for prediction of object states and data fusion from many sensors. Kalman filter in its base form can be used only for linear systems. Therefore, the Extended Kalman Filter (EKF) is mainly used in UAS.

$$\boldsymbol{x}_k = f(\boldsymbol{x}_{k-1}, \boldsymbol{u}_{k-1,} \boldsymbol{w}_{k-1}) \tag{29}$$

$$z_k = h(\boldsymbol{x}_k, v_{k-1}) \tag{30}$$

where:
xk – predicted state estimate,
u_{k-1} – input vector,
w_{k-1} – process noise,
zk – predicted measurement,
vk – measurement noise.

Covariance matrix:

$$\boldsymbol{P}_k = \boldsymbol{F}_{k-1}\boldsymbol{P}_{k-1}\boldsymbol{F}_{k-1}^T + \boldsymbol{G}_{k-1}\boldsymbol{Q}_{k-1}\boldsymbol{G}_{k-1}^T \tag{31}$$

where:

$$\boldsymbol{F}_k = \left(\frac{\partial f}{\partial \boldsymbol{x}}\right)_k$$

$$\boldsymbol{G}_k = \left(\frac{\partial f}{\partial \boldsymbol{u}}\right)_k$$

Kalman gain:

$$\boldsymbol{K} = \boldsymbol{P}_{k|k-1}\boldsymbol{H}_k^T(\boldsymbol{H}_k\boldsymbol{P}_{k|k-1}\boldsymbol{H}_k^T + \boldsymbol{R}_k)^{-1} \tag{32}$$

where:

$$H_k = \left(\frac{\partial h}{\partial \boldsymbol{x}}\right)_k$$

Innovation:

$$\varepsilon = h\left(\boldsymbol{x}_{k|k-1}\right) - z \tag{33}$$

Update states:

$$\boldsymbol{x}_{k|k} = \boldsymbol{x}_{k|k-1} + \boldsymbol{K}\varepsilon \tag{34}$$

Update Covariance matrix:

$$\boldsymbol{P}_{k|k} = (\boldsymbol{I} - \boldsymbol{K}\boldsymbol{H}_k)\boldsymbol{P}_{k|k-1} \tag{35}$$

3. Conclusion

The navigational and traffic situation in the air is constantly changing, at least due to the increase in air traffic. Technological progress enables more precise control of aircraft. This is one way to increase the capacity of airways and airports. Reducing separation requires a reduction in tolerance for deviations from the prescribed flight parameters (course, altitude, speed, time). Meeting such high requirements is only possible thanks to the use of very precise Air Data Computers and navigation devices. The currently introduced systems are able to provide the required accuracy, even without the use of ground-based radio navigation aids.

One of the most difficult challenges in ensuring UAV's autonomy will be the synchronization of all airspace users. That unmanned aerial vehicles could move everywhere, not only in designated areas and closed sectors, an adequate level of safety should be ensured for such flights. There is a tendency to create a sort of anti-collision zone around each aircraft. After contact of these two spheres, systems preventing collisions of aircraft will be automatically activated.

The basic requirement for UAVs is the ability to observe the movement of other aircraft, maneuver between them and avoid them. The unmanned aerial vehicles will have to be equipped with appropriate sensors and provided information algorithms for building situational and spatial awareness. Relying on image transmission to operators does not provide sufficient time to react, the system should inform the operator in advance about the impending threat. In addition, a fully automatic system is required in the event of a communication failure or transmission delay. Moreover, this system should be able to identify the type of aircraft, its color or markings.

The challenges facing collision detection and avoidance systems are as follows:

- motion detection,
- determining convergent or collision courses,
- route evaluation, flight speed and altitude assessment,
- determining the right of priority flight,
- determining the response to the situation occurring.

One of the methods to deal with this problem may be the use of transponders. However, they cannot be applied in military aircraft.

Controlling UAV as well as manned aircraft requires continuous two-way communication. It must be ensured that all messages and commands are sent, received and interpreted correctly. In the case of the cooperation of the UAV group, or joint flights of manned aircraft with unmanned vehicles, all aircraft must interpret messages uniformly, and formations should have the same mission plans and objectives.

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