10. Safety Issues Addressing Unmanned Aerial Vehicle Operation

Nataliia Kuzmenko

National Aviation University Kiev, Ukraine

Safe integration of Unmanned Aerial Vehicles (UAVs) into the European aviation system is currently a top priority for supporting the aviation industry in Europe for the entire aviation community. EASA, Eurocontrol, SESAR JU, JARUS and the European Commission are promoting the integration of UAVs into the European aviation system. According to the last stage of the integration plan for the 2024-2028 period, UAV flights are expected [1] to operate in most nonsegregated airspace, mixed with manned aviation, following the same air traffic management procedures and ensuring the same level of safety and security. As a result, based on the general rules, UAV operators will be able to operate UAV flights across borders, avoiding administrative burdens in obtaining special permits for the flight plan.

An aircraft without a pilot on board generates a wide range of sources of danger to civil aviation. These sources of danger need to be identified and threats to flight safety should be reduced. According to recent international studies, one of the priority issues in the development of UAV is the flight data recovery in case of unpredicted factors and automatic monitoring of UAV flight state [1, 2].

The purpose of the article_ is consideration of aviation safety issues presenting UAV flight data processing and collision avoidance techniques.

10.1 UNMANNED AERIAL VEHICLE FLIGHT DATA PROCESSING BY SPLINE APPROACH

Nowadays, UAVs operate in real missions with various levels of autonomy. They are used for searching, rescuing, monitoring, collaborative indoor and outdoor surveillance and protection. Moreover, UAV applications include firefighting, some level of policing, support in case of natural disasters, remote sensing, scientific research, and geographical surveying. It is commonly acknowledged that the development of UAVs gives the possibility to perform missions that are too dull, dirty or dangerous for humans.

During the flight, a variety of events may affect the operation of UAVs. These include faults, or malfunctions, and failures, or complete breakdowns, in flight-critical components, platform damage, faults and failures in intervehicle information flow, anomalous behaviours or extreme weather. Removing a human being from some of the flight control tasks and replacing them by software systems is a challenge that addresses safety implications.

When UAVs fly, their onboard systems exchange the necessary information via the communication network. Suppose one of the actuators of a UAV develops a fault. If the control system of the faulty UAV is not equipped with some form of robustness to fault, or if the control system is not capable of providing sufficient recovery to the fault, the vehicle may lose stability and exhibit an unpredictable behaviour.

Faulty aerial vehicles fail to fulfil mission objectives, and represent danger to humans.

Thus, continuous UAV data flow monitoring has an extreme importance and is a key challenge for predictive control.

There are different approaches for data recovering in case of UAV information faults [3-5]. Existing methods of data recovery allow choosing the most appropriate one considering input data, technical possibilities and aims of research.

The majority of researches divide the recovery methods into the following groups: method of incomplete objects exclusion; methods of data completing; methods of weighing and methods based on modeling [3].

Very often researches have to deal with the problem of missing data processing in data arrays. The reasons that lead to the missing data, is the inability of data obtaining or processing, its distortion or concealment.

Most of the known methods of data analysis can not process such information, therefore it is necessary to complete and recover missing data. In case of UAV that is a dynamic system and has a variety of flight data the most of existing methods con not meet the requirements of data recovering in real time.

Therefore the main purpose of the chapter is choosing the most appropriate approach for UAV data processing and recovering.

Analysis of data recovering methods

In the common way data recovering is a flexible method of solving the tasks with missing data during arrays processing.

There are four groups of data recovering methods:
1. Methods of incomplete objects exclusion. In case of absence of some object values a simple solution is to remove such incomplete object of analysis and to process data without missing data. This approach is easily implemented and can be satisfied with a small number of missing data. However, sometimes it causes serious shifts and usually is not very effective.
2. Methods of data completing. Missing data are filled and received "completed" data is processed by conventional methods. To receive correct conclusions it is necessary to introduce modifications into standard methods that distinguish filled and real data.
3. Methods of weighing. Conclusions by sample survey with missing data are usually built on the weight of the plan, which is inversely proportional to the probability of selection, but these methods change the weight to take into account missing data.
4. Methods based on modeling. A wide class of methods based on constructing a model of missing data formation. Conclusions are received by likelihood function, which is based on fairness conditions of the model with parameter estimation by methods with maximum likelihood type. The advantages of this approach are that it is flexible and allows reject the methods developed for specific cases.

The methods of missing data recovering in sample surveys are the following:

1. Filling by the average values of the existing in the sample. Average values can be formed within the groups is similar groups formed for weighing procedures. By this approach, filling the average leads to estimates similar to the estimates by the weighing method at a constant sample weights in the weighting classes.
2. The procedure of missing data filling with the selection can be generally described as a method in which the substitution is selected for each missing value estimating the distribution, in contrast of filling the missing data by average when average distribution is substituted.
3. Filling without selection. Missing data is filled by constant value from an external source, such as the value of the previous observations of the same survey.
4. Replacement – method of missing data processing during the data collection phase in the survey. It is based on the replacing of the object with the absence of response to another object that is not included in the sample.
5. Filling by regression based on the replacement of missing data by value we substitute in filling the regression with the remainder in the sum reflecting the uncertainty of the predicted value. Filling by the average can be considered as a special case of filling by regression [4].
6. The method of spline interpolation is a mathematical interpolation method, showing good results.
7. At the methods of multiple filling a missing data is filled by multiple values. The main advantage is that they overcome the disadvantages of single filling methods in the sense of the greater spread of estimation variance.
8. Composite methods are based on the ideas of several methods.
9. ML-assessment – refers to the category of modeling methods. The peculiarity of these methods is the construction of a model of missing data generation, followed by the conclusions obtained on the basis of the likelihood function.
10. The use of factor analysis methods. There is no requirement of a priori fill the missing data, there is a need for pre-normalization of data and existing of requirements of factor analysis.
11. The use of cluster analysis methods. Its application is not based on any probabilistic model, but to estimate the properties in statistical terms is not possible.
12. Neural network methods as one of the approaches to the data recovery are used. The main conditions of this method application are probabilistic relationship between data, the number of existing observations, which recover missing data shall not to be small.

Spline Approach for Data Processing

Spline approach is a universal mean of parameters processing and recovering by computer-based techniques. Spline is continuous and defined on fragments function S, which consists of fragments that are functions of the same species and docked in a special way. Points of docked fragments are called spline nodes.

The basic condition for joining the fragments is continuity of values and derivatives at the docked points.

Spline approach has a row of advantages:
First, good differential, approximation and algorithmic properties.

Second, experimental information has a discrete nature (for example, the values of a process at different times) using splines can be converted to a continuous form recorded as a function of approximately reflecting the real process.

Third, the experimental data, no matter how they are obtained, always have some errors. Using such data as input for the various calculations can lead to significant distortion of the result. Smoothing in many cases allows transforming the initial information to a form suitable for the further use.

The advantages of spline interpolation include high processing speed of computational algorithm as spline is a piecewise polynomial interpolation function and at the same time data is processed by a small number of measurement points belonging to the fragment under consideration at the moment.

Investigation model can be represented as a regression model at the interval [0, T] with k parameters of observation:

$$\vec{y}_i = \vec{S}_0(t_i) + \vec{E}_i, \quad i = \overline{1,n}$$

where $\vec{S}_0(t) = (S_0^{(1)}(t), \ldots, S_0^{(k)}(t))^T$.

The components $S_0^{(j)}(t)$ are cubic C^2–smooth splines with known nodes

$$\tau_0 = 0 < \tau_1 < \cdots < \tau_N = T.$$

The moments of observations are ordered:

$$0 = t_1 < t_2 < \cdots < t_n < T, \text{ and } t_n > \tau_{N-1}.$$

Random errors $\vec{E}_i$ are unbiased:

$$E\vec{E}_i = \vec{0}, \quad i \geq 1$$

where E-mathematical expectation.

One of the most suitable spline curves is B-spline. It possesses a good interpolation and approximation properties for UAV data processing and recovering. Also it guides through basic points which provides the possibility of precise fitting.

B-spline interpolation is grounded on data separation into several intervals (N) with the corresponding interpolation at each interval. Resultant curve is a sum of splines at each interval. In a common way B-spline curve can be represented by the following formula:

$$S(t) = \sum_{j=1}^{N} B_j(t) x_j, \quad 0 \leq t \leq T,$$

where $B_j(t)$ – B-spline for specific time t; x_j – control points coordinates.

B-spline functions can be of different order and can be calculated using the Cox-De Boor relations [6]. There are a lot of challenges when it is necessary to estimate multi-parametrical data simultaneously. B-spline interpolation in such case can applied in a simple way by adding new control points and inserting B-splines into main formula.

One of the most important problems in spline interpolation is intervals selection. Typically interpolation intervals are uniformly distributed and the task is to estimate the optimal grid step. But for more precise fitting is suitable to use non-uniformly distributed intervals. In that case the most appropriate methods of interval calculation are chord length and centripetal methods [6].

During the flight UAV transmits a set of flight data. In the common way it includes all sensors data. One of the most valuable is UAV position information in specific coordinate system. An UAV position information fault is one of the major hazards during the flight.

During the modeling real data of UAV flight was used. The flight was performed in automatic mode with neglible wind component by pre-planned trajectory of "eight" form.

Data is represented in local NED coordinate system. Coordinates are represented as a distance from the starting point in meters on fig.1-3 indicated by stars. Z axe has downside direction.

During fault simulation data for some short time has been absent. Fault period was chosen for the moment from 128 s till 148 s of flight. Data of the fault period was recovered using spline interpolation. The results of recovering are represented on fig 1-3 by circles.

Spline interpolation errors of position data are represented in fig. 4. The maximum error value is less than 23 m.

During the flight, a UAV is a subject of information flow fault due to a lot of reasons.

To guarantee flight safety the continuous UAV data flow monitoring has a primary importance for predictive control. Spline approach is a universal mean for continuous UAV flight data processing and recovering. The results of fault recovering simulation for real UAV position data indicate quite accurate results (fig.4) and prove the usage of spline approach for UAV flight data processing [7].

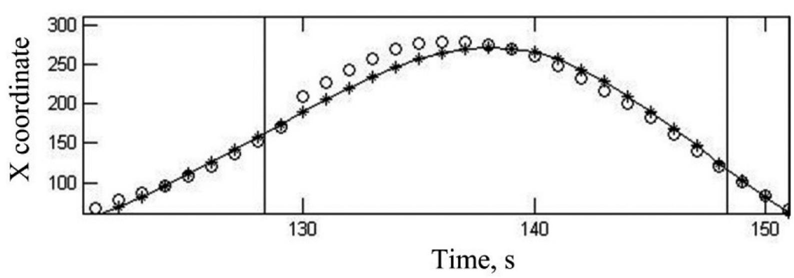

Fig. 1 [7]. X coordinate representation

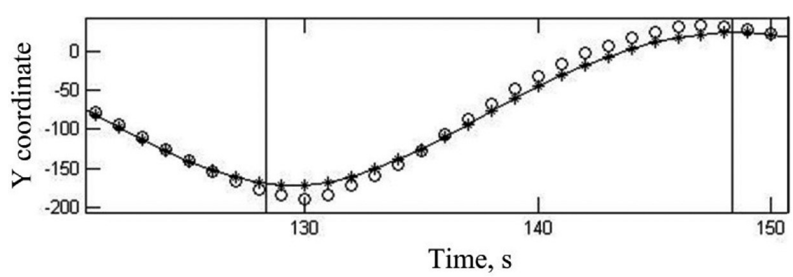

Fig. 2 [7]. Y coordinate representation

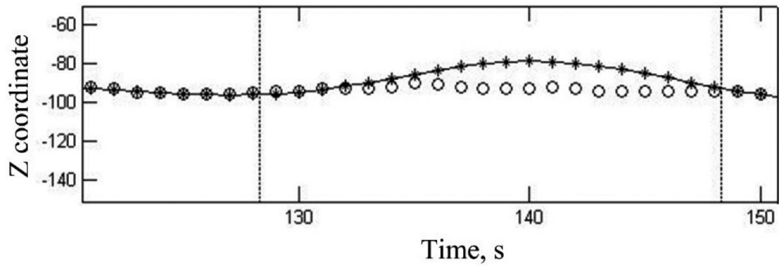

Fig. 3 [7]. Z coordinate representation

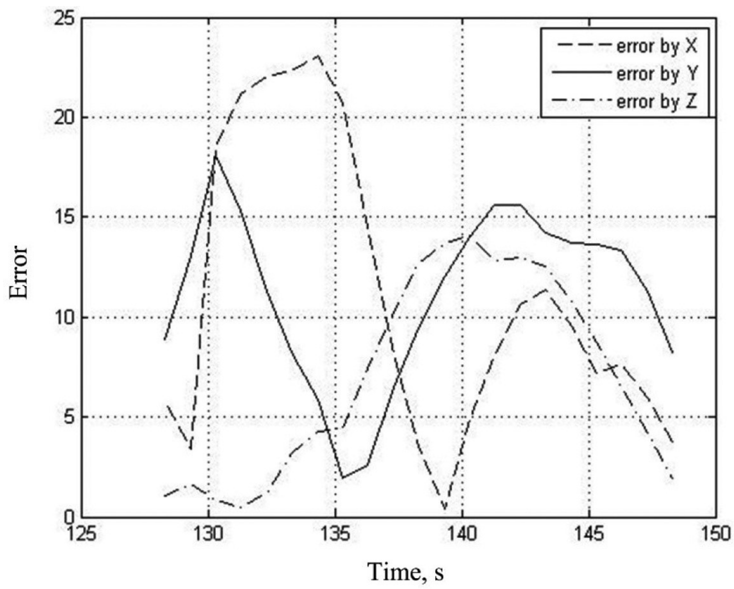

Fig. 4 [7]. Spline interpolation errors of position data

10.2 MINIMIZATION OF UNMANNED AERIAL VEHICLE TRAJECTORY DEVIATION DURING THE COMPLICATED OBSTACLES OVERFLY

The usage of UAVs has been increasing rapidly. Such aircrafts are capable of planning their own trajectory in the transition between desired locations, and they can also avoid any obstacles on their path.

But if it is necessary to move UAVs outside of the restricted areas into the areas of general use, it is necessary to take into account that UAVs must be able not only to avoid fixed obstacles, but they can effectively deal with moving obstacles as well.

The change of the planning problem from the fixed obstacles to the moving ones changes the problem from a geometric (prohibition to enter the restricted area) to a dynamic one (prohibition to enter the restricted area at certain period of time taking into account the ability of UAVs to change their location at time).

As far as conflict detection is concerned, a solution thet can be reliable is to have the ability of the model to predict the future, the most concrete difference between modeling approaches involves the method by which the current states are projected into the future. There are three fundamental extrapolation methods such as Nominal, Worst-Case and Probabilistic.

For the UAVs collision avoidance the following methods are used as well:
– Methods using dimensions of state information (vertical, horizontal, or three-dimensional);
– Conflict detection threshold;
– Conflict resolution method (prescribed, optimized, force field, or manual);
– Maneuvering dimensions (speed change, lateral, vertical, or combined maneuvers);
– Management of multiple aircraft conflicts (pairwise or global).

Besides, regarding UAVs collision avoidance it is necessary to take into account the specific character which current states and metrics are used to make conflict detection and resolution decisions, how uncertainty is managed in the model, and the degree to which the model which assumes coordination between aircrafts is involved in a conflict.

But all these methods do not take into account the exact shape of the obstacle specifying it by some geometrical Fig.s i.e. circle or ellipse.

The purpose of the chapter is methodic development of trajectory choice of minimal deviation from the complicated forms of the objects.

One of the possible UAV collision avoidance methods with obstacles is probabilistic method based on the UAV heading and turn rate changes. These methods give a set of UAVs trajectories for the change of its location in case of a possible conflict situation.

The Model of UAV Movement

There are a lot of different models of UAV movements. Each of them is used for particular tasks connected with the UAV trajectory simulation. Besides, the choice of the model depends on the UAV type and its dynamic peculiarities. But all the models are characterized by maximal and minimal allowable parameters. To solve the navigation task of minimized deviation from flight plan trajectory the simplified model can be used. It is described by the following formula:

$$X_i = X_{i-1} + \begin{pmatrix} V\sin(\psi) \\ V\cos(\psi) \end{pmatrix},$$

where X_i are coordinates of the location at the ith moment of time;

V is UAV velocity;

Ψ is UAV heading.

It is necessary to take into account that

$$V_{\min} \leq V \leq V_{\max},$$

$$\psi_{\min} \leq \psi \leq \psi_{\max}.$$

At every moment of time it is possible to guide the UAV position by the change of its velocity and heading [8]. The possible ways of UAV trajectories with random change of velocity and heading in every time moment have the image of a tree. The example of the initial position (0, 0) modeling is shown in fig. 5.

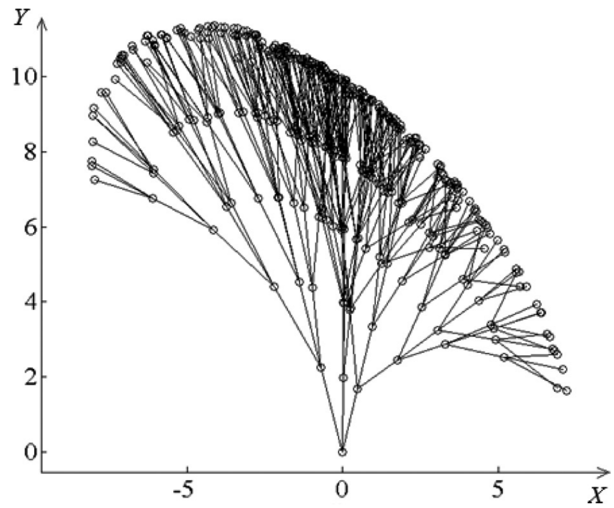

Fig.5 [9]. The possible ways of UAV trajectories for automatic conflict avoidanc

Collision Avoidance Guidance

The task of UAV missions is based on the input of initial position and coordinates of the destination. Coordinates of the initial position can be determined by the use of a satellite navigation system or indoor navigation systems (Inertial Navigation System, whether they can be set by user in the local coordinate system). The coordinates of the destination point are set according to the mission task. The coordinates of the initial and destination positions are represented in matrix form:

$$\mathrm{XL} = \begin{pmatrix} x_{01} \\ x_{02} \end{pmatrix},$$

$$\mathrm{YL} = \begin{pmatrix} y_{01} \\ y_{02} \end{pmatrix},$$

where x_{01}, y_{01} are coordinates of the initial position;

x_{02}, y_{02} are coordinates of the destination.

Due to obtaining this data it is possible to determine the UAV trajectory that will be described with the help of line equation:

$$\mathrm{Ax} + \mathrm{By} + C = 0,$$

where *A*, *B*, *C* are line coefficients which are determined like:

$$A = \frac{1}{x_{02} - x_{01}},$$

$$B = \frac{-1}{y_{02} - y_{01}},$$

$$C = -\mathrm{A}x_{01} - \mathrm{B}y_{01}.$$

But the aviation safety requires the detection of obstacles at the planned flight trajectory.

The obstacle is determined by the vector-row of top coordinates

$$\mathrm{XO} = (x_1, x_2, \dots, x_n),$$

$$\mathrm{YO} = (y_1, y_2, \dots, y_n).$$

If there is a crossing of planned flight trajectory with any point of an obstacle it is necessary to overfly the obstacle with minimum deviation from the planned trajectory regarding the aerodynamic possibilities of a UAV.

For a new trajectory creation one should find the maximum coordinates of the obstacle tops from the both sides of the crossing.

To perform this operation it is necessary to find the distances matrix from the tops to the line of the trajectory (fig.6):

$$d = \frac{A \cdot \mathrm{XO} + B \cdot \mathrm{YO} + C}{\sqrt{A^2 + B^2}}.$$

The sign *d* informs about the location of the tops relatively to the line.

In such a way the tops are separated by the sides according to the line.

For a new trajectory creation it is necessary to choose the obstacle overfly direction. The choice will be prior to the side where the deviation will be minimal.

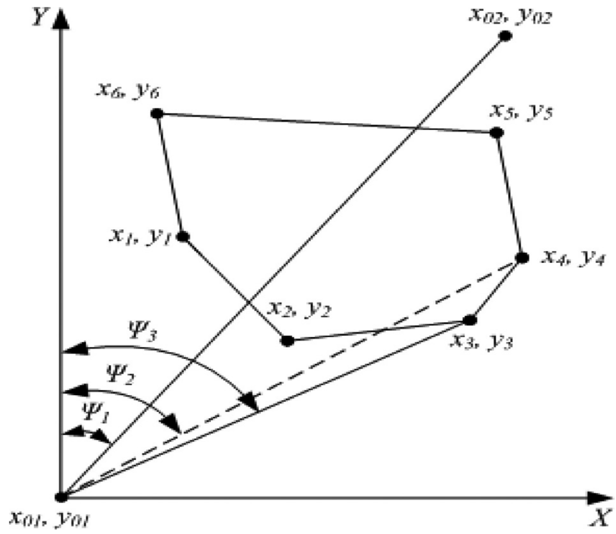

Fig. 6 [9]. Principle of obstacle overfly trajectory creation

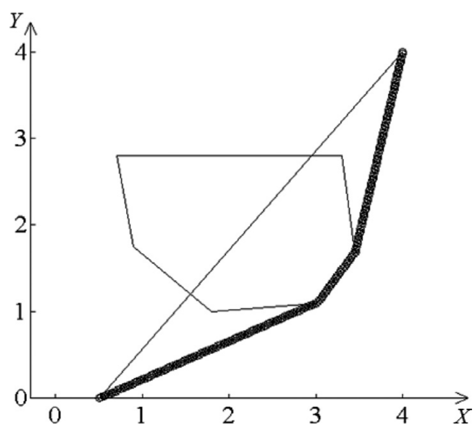

Fig. 7 [9]. The resultant overfly of complicated form obstacle

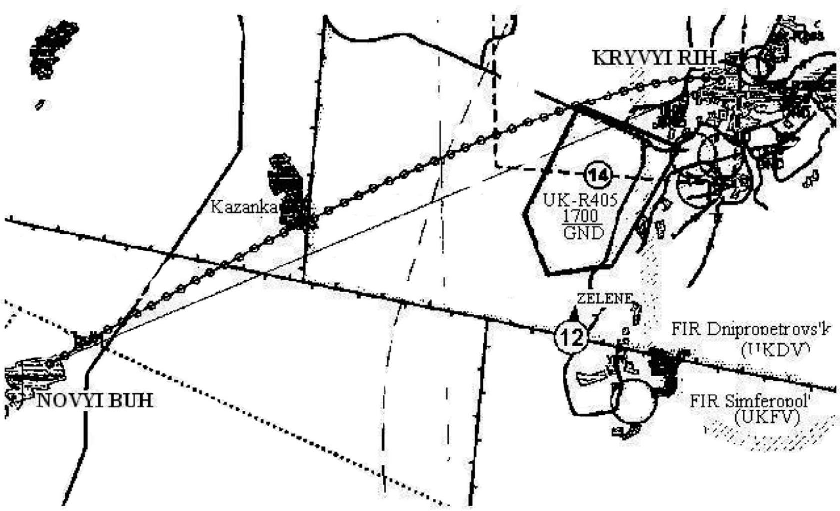

Fig.8 [9]. An overfly of the restricted area at the aeronautical chart

Thus, one should find the maximum deviation from the both sides of line and choose their minimum:

$$d_{\min} = \min\left(\left|\begin{pmatrix}\max(d)\\ \min(d)\end{pmatrix}\right|\right).$$

Using $d_{\min}$, the coordinates of the intermediate overfly point are defined.

The next step will be the heading change of the planned trajectory including the top at the next step of iteration.

But the obstacle has complicated form and the changed trajectory can also cross the shape of the obstacle.

Hence, the previous procedure should be done once more regarding the new trajectory with current position and the obstacle overfly point (fig. 6).

If any positive point is found, the destination will be changed prior to it.

As a result the first obstacle overfly point will be determined that will provide the heading change according to this point:

$$\psi_i = \operatorname{arctg}\left(\frac{-A_i}{B_i}\right),$$

where A_i and B_i are the line coefficients that link UAV and obstacle overfly point.

The procedure of heading choice is shown in the fig. 6.

Performing this check for each point of the flight the resultant obstacle overfly is shown in the fig. 7 The modeling can be applied to the aeronautical charts that are characterized by prohibited (P), dangerous (D) and restricted (R) areas.

Modeling of an overfly of the restricted area at the aeronautical chart of Ukraine is shown in the fig. 8. An initial position is Novyi Buh, destination is Kryvyi Rih. The obstacle at the planned trajectory is the restricted area under the number UK-R405.

UAVs can be used not only in civil aviation, but also provide other effective applications. Therefore UAV flights should be safe (omitting all the prohibited, dangerous and restricted areas), fast and with minimum consumption of the resources.

Therefore, nowadays the trajectory choice of minimal deviation from the complicated form objects is an important challenge [9].

10.3 UNMANNED AERIAL VEHICLE COLLISION AVOIDANCE USING DIGITAL ELEVATION

The usage of Unmanned Aerial Vehicles (UAVs) has been increasing rapidly. Their usage has been characterized as the next great step forward in the evolution of civil aviation. Compared with their manned counterparts, UAVs have the advantages of small weight and space-occupancy, low cost, good concealment, excellent robustness and flexibility, thus are excellent in executing the dull, dirty or dangerous tasks.

Such aircrafts are capable of planning their own trajectory in the transition between desired locations and they can also avoid any obstacles on their path.

A lot of scientific researches were devoted to the development of the reliable UAVs collision avoidance methods (Gardiner, Waseem 2011 [10]; Loe 2007 [11]; Han, Bang 2004 [12]; Liao 2012 [13]; Kharchenko, Kuzmenko 2012 [14]). But all of these methods have the lack of information about obstacle and represent it as a geometrical shape. None of these methods can provide the precise form and position of an obstacle that is not convenient for use in real life.

Thus, from the literature overview it is obvious that it is necessary to develop more reliable UAV collision avoidance method that will include exact data of the surrounding environment.

The usage of Digital Elevation Models (DEM), Digital Terrain Models (DTM) and Digital Surface Models (DSM) is one of the possible ways to provide information, being aware that it is a key element in the safety of aviation.

The purpose of the chapter is the analysis of existing DEM web sources and the development of the UAV geometrical collision avoidance method in the vertical plane, using DEM.

A Digital Elevation Model is a digital model or 3D representation of a terrain's surface commonly used for Earth, moon, or asteroid created from terrain elevation data.

The term Digital Surface Model represents the earth's surface and includes all objects on it.

In contrast to a DSM, the Digital Terrain Model represents the bare ground surface without any objects like plants or buildings.

The term DEM is often used as a generic term for DSMs and DTMs, only representing height information without any further definition about the surface.

The DEM could be acquired through techniques such as:
- LIDAR;
- Stereo photogrammetry from aerial surveys;
- Block adjustment from optical satellite imagery;
- Interferometry from radar data;
- Real Time Kinematic Global Positioning Systems;
- Topographic maps;
- Doppler radar;
- Focus variation;
- Inertial surveys;

– Surveying and mapping drones.

The uses of DEMs include:
– Extracting terrain parameters;
– Creation of relief maps;
– Rendering of 3D visualizations;
– 3D flight planning;
– Creation of physical models;
– Geographic Information Systems (GIS);
– Engineering and infrastructure design;
– Global Positioning Systems;
– Line-of-sight analysis;
– Base mapping;
– Flight simulation;
– Surface analysis.

Digital Elevation Model Data Sources

The web sources of DEM data are the following:

NASA Reverb (http://reverb.echo.nasa.gov/ reverb/). Search the entire ASTER data archive. The following products are available to all users at no cost: ASTER L1B data over the U.S. and territories, the ASTER Global Digital Elevation Model (GDEM), and the North American ASTER Land Surface Emissivity Database (NAALSED).

GDS IMS (http://ims.aster.ersdac.jspace systems.or.jp/ims/html/). Search the entire ASTER data archive. All billable orders for ASTER data must be placed using the GDS IMS system.

Earth Explorer (http://earthexplorer.usgs.gov/). Free ASTER data for all users: ASTER L1B data over the U.S. and territories, the ASTER GDEM, and NAALSED products.

GloVis (http://glovis.usgs.gov/). Search the entire ASTER data archive using a browse-based map interface. The following products are available to all users at no cost: ASTER L1B data (day and night) over the U.S. and territories.

GDEx (http://gdex.cr.usgs.gov/gdex/) Free ASTER GDEM data for all users. User-friendly geographic interface.

Data Pool (https://lpdaac.usgs.gov/get_data/ data_pool). Free ASTER L1B data over the U.S. and territories for all users.

Shuttle Radar Topography Mission (SRTM) (http://dds.cr.usgs.gov/srtm/version2_1/SRTM3). Free SRTM data.

Bluesky (http://www.bluesky-world.com/). LiDAR 1m DSM.

The data bases are generally in one of the following different resolutions:
– 30-meter data: point elevation values on a 30-meter grid;
– 1-second: point elevation values on a 1-second (approximately 30-33 m) grid;

– 3-second: point elevation values on a 3-second (approximately 90-100 m) grid;
– 30-second point elevations:- point elevation values on a 30-second (approximately 1 km) grid;
– 30-second averaged elevations: averaged elevation values on a 30-second (approximately 1 km) grid.

Digital Elevation Model File Extension

Data can be obtained with file extension .xyz, .las, .hgt. These types of file extension can be converted to the .txt file with the help of different converting programs such as LASUtility and VTBuilder.

Obtained data involve 3 columns and denote x, y and z data in meters in the local coordinate system that can be easily used for the further processing.

Collision Avoidance Guidance

The task of UAV missions is based on the input of initial position, coordinates of the destination and obligatory flight points as a set of latitude, longitude and elevation data.

Furthermore, the appropriate DEM for the desired flight region should be obtained. The initial flight plan data should be also converted into a local coordinate system of DEM format.

Collision avoidance method is based on the conflict detection that is shown in Fig. 9.

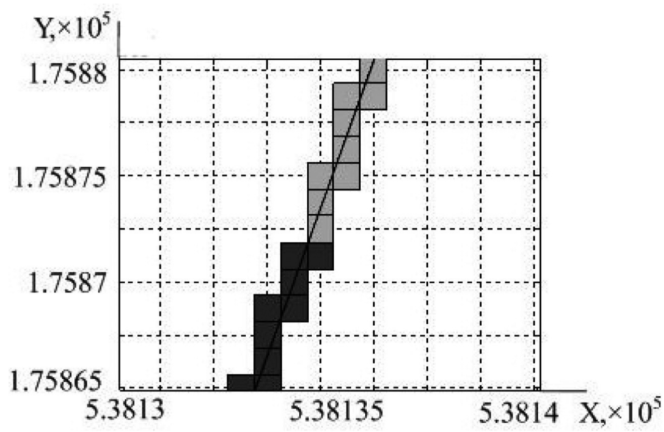

Fig. 9 [15]. Cell conflict detection with initial flight plan trajectory

Using cell coordinates of a DEM it is possible to determine the intersection of a trajectory line with each cell side.

Then, to determine the point of flight plan and surrounding obstacle intersection, the algorithm of the method determines the intersection of rectangular which tops are located at the cell coordinates and a trajectory line. This step is applied to all the cells that are involved in the flight plan.

If the point of intersection exists and the conflict is determined, the points of obstacle overfly are added to the initial flight plan as it is shown in Fig. 10.

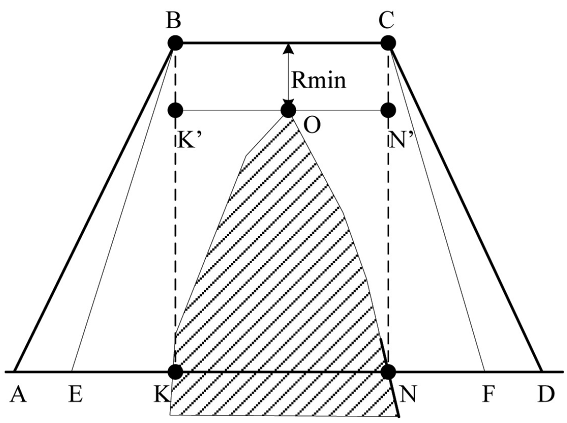

Fig. 10 [15]. Obstacle overfly using extended flight plan:

AD – the initial flight trajectory;

KON – obstacle;

K, N – starting and ending points of trajectory and obstacle intersection;

O – maximum obstacle height;

K', N' – starting and ending points of trajectory and obstacle intersection elevated to the maximum obstacle height;

B, C – starting and ending points of trajectory and obstacle intersection elevated to the maximum obstacle height with minimum safe altitude Rmin;

E, F – critical points for overfly performance that take into account UAV velocity and heading

The possible values of UAV velocity and heading are in the boundaries:

$$V_{\min} \le V \le V_{\max},$$

$$\psi_{\min} \le \psi \le \psi_{\max}.$$

where *V*, Ψ are UAV velocity and heading.

In order to increase flight safety, it is necessary to choose points A (initial point of the flight plan final part) and D for beginning and finishing an overfly performance.

In such a way overfly points B and C are added to the extended flight plan that can be easily calculated using UAV technical characteristic.

Extended flight plan data can be used for UAV's flight performance.

There are a lot of different models of UAV movements. Each of them is used for the particular tasks connected with UAV trajectory simulation. Besides, the choice of the model depends on the UAV type and its dynamic peculiarities.

For the simulation of UAV movement a simplified model that takes into account wind influence can be used. It is described by the following navigation formulae (Chawla, Padhi 2011) [16].

$$\dot{x}_i = U\cos\theta\cos\psi + V(\sin\varphi\sin\theta\cos\psi - \cos\varphi\sin\psi) + +W(\cos\varphi\sin\theta\cos\psi + \sin\varphi\sin\psi);$$

$$\dot{y}_i = U\cos\theta\sin\psi + V(\sin\varphi\sin\theta\sin\psi + \cos\varphi\cos\psi) + +W(\cos\varphi\sin\theta\sin\psi - \sin\varphi\cos\psi);$$

$$\dot{h}_i = U\sin\theta - V\sin\varphi\cos\theta - W\cos\varphi\cos\theta,$$

where U, V, W – velocity components.

Speed parameters can be defined by total UAV speed as:

$$U = V_T\cos\alpha\cos\beta;$$

$$V = V_T\sin\beta;$$

$$W = V_T\sin\alpha\cos\beta,$$

where V_T – UAV speed;
α – angle of attack;
β – side slip angle.

Influence of forces on UAV is described by following differential equations (Singh, Padhi 2009) [17]:

$$\dot{U} = \mathrm{RV} - \mathrm{QW} - g\sin\theta + X_a + X_t;$$

$$\dot{V} = \mathrm{RW} - \mathrm{RU} + g\sin\varphi\cos\theta + Y_a;$$

$$\dot{W} = \mathrm{QU} - \mathrm{PV} + g\cos\varphi\cos\theta + Z_a,$$

where P, Q, R – roll, pitch and yaw rates respectively about the body axis;
X_a, Y_a, Z_a – the aerodynamic forces per unit mass;
X_t – the force per unit mass in direction X due to thrust.

Equations of rotation moments are represented by the formulae:

$$\dot{P} = c_1\mathrm{RQ} + c_2\mathrm{PQ} + c_3L_a + c_4N_a;$$

$$\dot{Q} = c_5\mathrm{PR} + c_6(P^2 - R^2) + c_7(M_a + M_t);$$

$$\dot{R} = c_8\mathrm{PQ} - c_2\mathrm{RQ} + c_4L_a + c_9N_a,$$

where L_a, M_a, N_a – the aerodynamic moments about the body axis;
M_t – the moment around the Y axis caused by thrust offset from the center of gravity of the UAV;
c_1-c_9 – inertia coefficients.

Kinematic equations of UAV movement are the following:

$$\dot{\varphi} = P + Q\sin\varphi\tan\theta + R\cos\varphi\tan\theta,$$

$$\dot{\theta} = Q\cos\varphi - R\sin\varphi;$$

$$\dot{\psi} = Q\sin\varphi\sec\theta + R\cos\varphi\sec\theta;$$

$$\dot{h} = U\sin\theta - V\sin\varphi\cos\theta - W\cos\varphi\cos\theta,$$

where φ, θ, ψ – euler angles;
h – the height above ground.

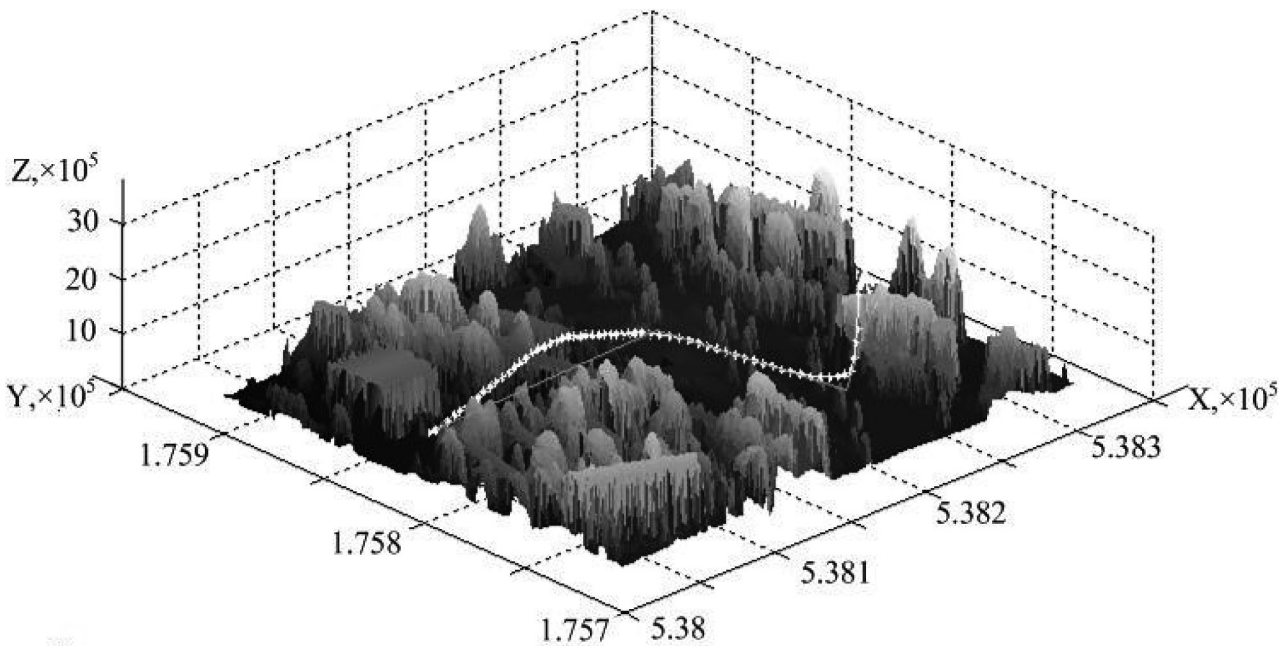

Fig. 11 [15]. Representation of collision avoidance method using DEM

The modeling of developed geometrical UAV collision avoidance method in the vertical plane, using DEM is represented in Fig. 11. Modeling was performed in Matlab software for the British region.

Collision avoidance methods have a lot of drawbacks connected with the precise 3D obstacle determination. The developed geometrical UAV collision avoidance method allows obtaining an accurate data of surrounding environment and avoiding collision due to obstacle overfly in the vertical plane [15].

Nataliia Kuzmenko
National Aviation University Kiev, Ukraine
nataliakuzmenko3107@yandex.ru
ORCID 0000-0002-1482-601X