Nguyen Dinh Dung, Utku Kale, Jozsef Rohacs

Developing the Fuzzy Control Based Orbits – Straight Lines Trajectory for Increasing the UAV Landing Accuracy

The revolution in technology catalyses to develop advance controls for increasing the landing accuracy of the small unmanned aerial vehicles. *There are several* international projects developing such new control systems for Unmanned Aerial Vehicles *(UAVs)* as (i) 'STOCK' *using a communications relay pod on the UAV to extend the range of control of Unmanned Ground Vehicles (UGVs), (ii) 'GABRIEL' demonstrating the possible implementation of MagLev technology to support the aircraft take-off and landing by use ground measurements in controlling the UAV landing on the moving platforms or (iii) 'IRKUT-70V' developing a small UAV for socio-economic and security-defence purposes.*

The authors had a deeper research on logistics, algorithms to calculate and determine a real motive orbit of an unmanned aerial vehicle in the process of landing approach. This paper studies and shows the time depending changes in UAVs' parameters. The dynamic and physical parameters of UAV IRKUT-70V are analysed by MATLAB simulation developed by authors for simulation of the landing processes.

The most important novelties of this paper are the followings: (i) introducing a method for determining the he optimized orbit trajectory as part of the landing approaches, (ii) developing the fuzzy logic controllers for maintaining the desired landing orbits, (iii) demonstrating the advantages of the created method by use of simulation of UAV IRKUT-70V landings in MATLAB environment, and (iv) evaluating the errors in realising orbit of the controlled UAVs compering to desired orbit clearly.

Key words: *orbit, unmanned aerial vehicle, landing, survey, control UAV, fuzzy controller*

INTRODUCTION

Aerial unmanned vehicles have proved usefulness in military and civil areas of various applications about for over a hundred years, while enhancing their capabilities over time, and fulfilling ever-changing mission requirements. UAVs offer a unique set of advantages compared to piloted aircrafts with smaller, safer and lighter platforms. Future UAVs are expected to perform extended missions with higher manoeuvrability and higher degrees of autonomy in more complex weather situations.

The revolution in technology catalyses to develop advance control system in unmanned aerial vehicles. There are several international projects on developing new control systems for Unmanned Aerial Vehicles (UAVs). The project 'STORK' [1] introduces a communications relay pod on the UAV to extend the range of control of Unmanned Ground Vehicles (UGVs). The EU supported 'GABRIEL' project designing a ground support system for aircrafts and UAVs during take-off and landing [2, 3]. The Vietnamese 'IRKUT-70V' [4] project supported in framework of cooperation with Russia studies and develops a small UAV for socio-economic and security-defence purposes.

The development of UAVs' take-off and landings is always a difficult problem. There are so many studies on UAVs autonomous landing developing by universities and research organizations. These works use different methods for improving the landing accuracy. For example, the Andrew Miller [5] and colleague introduced an autonomous landing of UAV that is based only vision system. This study described a method for estimating the relative location of the runway by performing image registration against a stack of images in which location of the runway is known. Dinh Meng [6] practical template matching in order to recognize and track runway in image sequences, (i) the runway is separated from background using segmentation by threshold (ii) template design is initialized according to the characteristics of runway. Mayank Garg [7] used terrain information from digital elevation maps to find a list of potential landing sites for a fixed-wing UAV, especially in emergency conditions.

The international team of GABRIEL project [8] developing the radically new solution supporting the aircraft take-off and landing by implementing the magnetic levitation technologies had tested the concept of landing the undercarriage-less aircraft on the moving platform by use of UAVs [2, 3]. There was developed a special rendezvouses control system, with prediction model, reducing the effects of air turbulences, using the ground measurements and synchronisation of motions of aircraft and moving platform by optical sensors. Later, the analogical principle was developed and applied by DLR to land a UAV on the top of a moving car [9]. Pillar Eng [10] presented a path planning algorithm that extended Dubins curves to 3D space which combined with a nonlinear guidance and control logic. The Simulated results of the planning, guidance and control module demonstrate the ability of the glider aircraft to follow the prescribed path in winds, with average path deviation errors that are comparable to or even better manned, and powered aircraft. For controlling UAVs' automatic landing, Shashiprakash Singh [11] designed a nonlinear control by using dynamic inversion approach. The trajectory parameters of UAVs also were calculated [11] as a sink rate at touchdown remains within specified bounds.

There are several other methods and special solutions like using the vision based control to autonomous landing [12], or investigation the parachute flight dynamics [13, 14] as well as combining the mathematical modelling an simulations methods [15] were studied before developing a special method using an optimal orbit trajectory [16] before the landing. The orbits originally were applied to the UAV landing on the oscillating platform.

This paper introduces an orbit trajectory for increasing the landing accuracy of UAVs, especially in case of side wind and air turbulences.

There was a Vietnamese project in 2015, called IRKUT-70V [4], which designed a small UAV for remote monitoring. This UAV can be widely used for socio-economic and security-defence needs. Remote monitoring can be applied both day and night in two modes: real-time live video observation and offline viewing (image transmission or video playback). The IRKUT-70V (Fig. 1.) does not need yard because it is launched from the launcher and recovered with parachute.

In this paper, the desired landing orbit of the IRKUT-70V will be calculated based on mathematic methods and dynamic parameters of UAV. The control system of the UAV will be designed by using fuzzy logic controller for automatic landing. It will be analysed in MATLAB simulation as well.

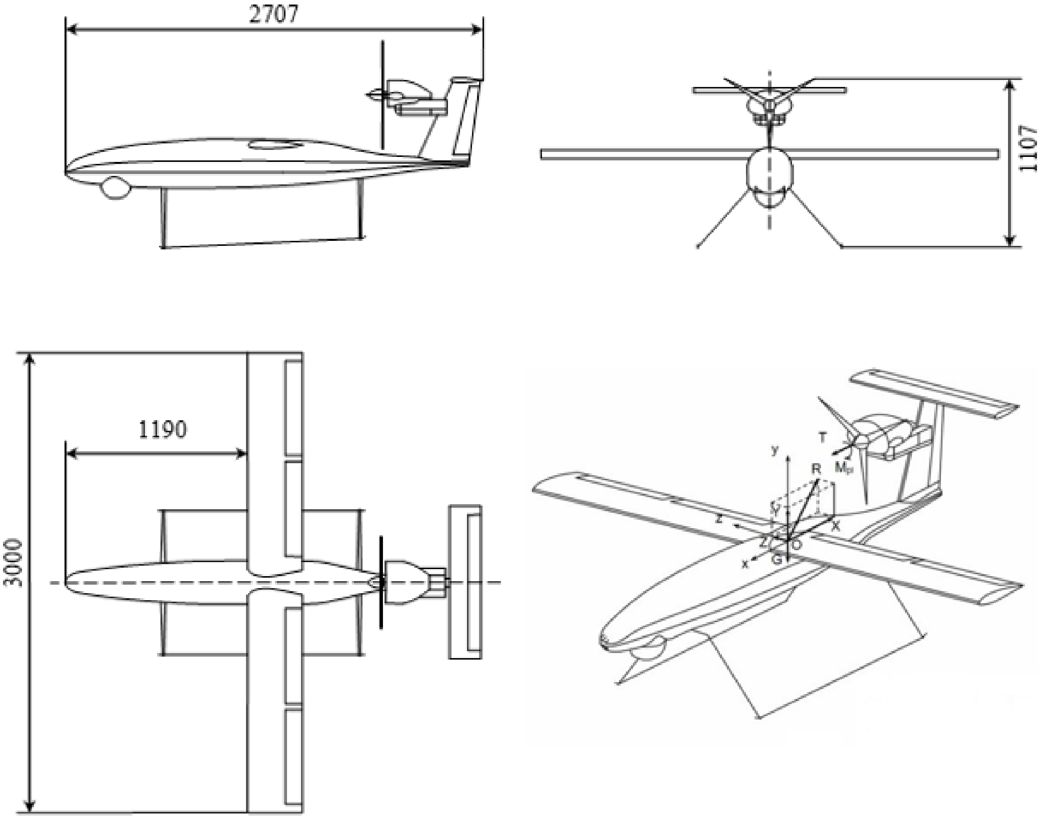

Figure 1. Three faces of UAV IRKUT-70V and 3D view of the UAV (on the left below)
(The dimensions: length: 2707 mm; height: 1107 mm; wingspan: 3000 mm.)

The most important novelties of this paper are the followings: (i) introducing a method for determining the he optimized orbit trajectory as part of the landing approaches, (ii) developing the fuzzy logic controllers for maintaining the desired landing orbits, (iii) demonstrating the advantages of the created method by use of simulation of UAV IRKUT-70V landings in MATLAB environment, and (iv) evaluating the errors in realising orbit of the controlled UAVs compering to desired orbit clearly.

1. METHODOLOGIES

1.1. Determining the desired orbit trajectory

This paper recommends to use an orbit trajectories for increasing the landing accuracy, especially in case of side wings. Let design the approach - landing trajectory of an UAV that should land to opposite the wind (w) direction. The UAV receiving the landing command at current point M (Figure 2.) must land at predefined point 0. The approach and landing process might be constructed from the strait lines and orbit curves. The distance from the point M to the point of reaching the landing coordinates, E, just before opening parachute, may contain two arcs of radius R_{min} (MA and BE) connected by an AB line. From point E, the UAV lowers the altitude (line EF) and reduces the speed (line F0).

The UAV can make left or right turn to reach one of the R_{min} circle on the left or right side of wind direction.

Turning left or right to reach one of the R_{min} circle on the left or right side will be selected by comparing travel distance. In this study, the possible four cases will be shown and the shortest route will be selected as a desired landing orbit.

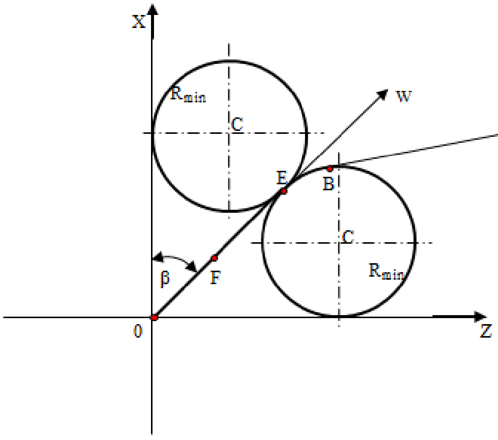

Figure 2. Landing process of UAV

Turning left or right to reach the left circle can be seen realized as it shown in Figure. 3. The distance from the point M to "0" can be calculated by use of the following simple functions:

$$\boldsymbol{L_1 = R_{min}.(\psi_1 + \psi_2 + \psi_4 - \psi_3) + \sqrt{(Z_A - Z_B)^2 + (X_A - X_B)^2}} \quad (1)$$

$$\boldsymbol{L_2 = R_{min}.(\psi_1 + \psi_2 + \psi_3 - \psi_4) + \sqrt{(Z_{A'} - Z_{B'})^2 + (X_{A'} - X_{B'})^2}} \quad (2)$$

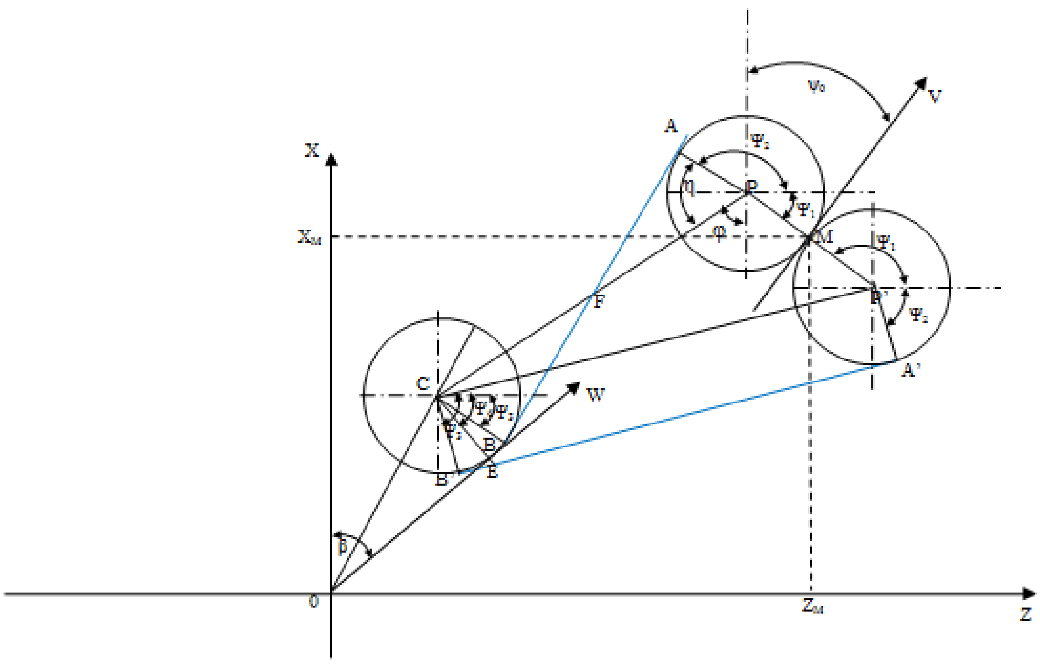

Figure 3. UAV turns left or right to reach the left circle

Turning left or right to reach the right circle are demonstrated in Figure. 4. The distance from the point M to "0" can be calculated as following:

$$L_3 = R_{min}.(\psi_1 + \psi_2 + \psi_4 - \psi_3) + \sqrt{(Z_A - Z_B)^2 + (X_A - X_B)^2} \quad (3)$$

$$L_4 = R_{min}.(\psi_1 + \psi_2 + \psi_4 - \psi_3) + \sqrt{(Z_{A'} - Z_{B'})^2 + (X_{A'} - X_{B'})^2} \quad (4)$$

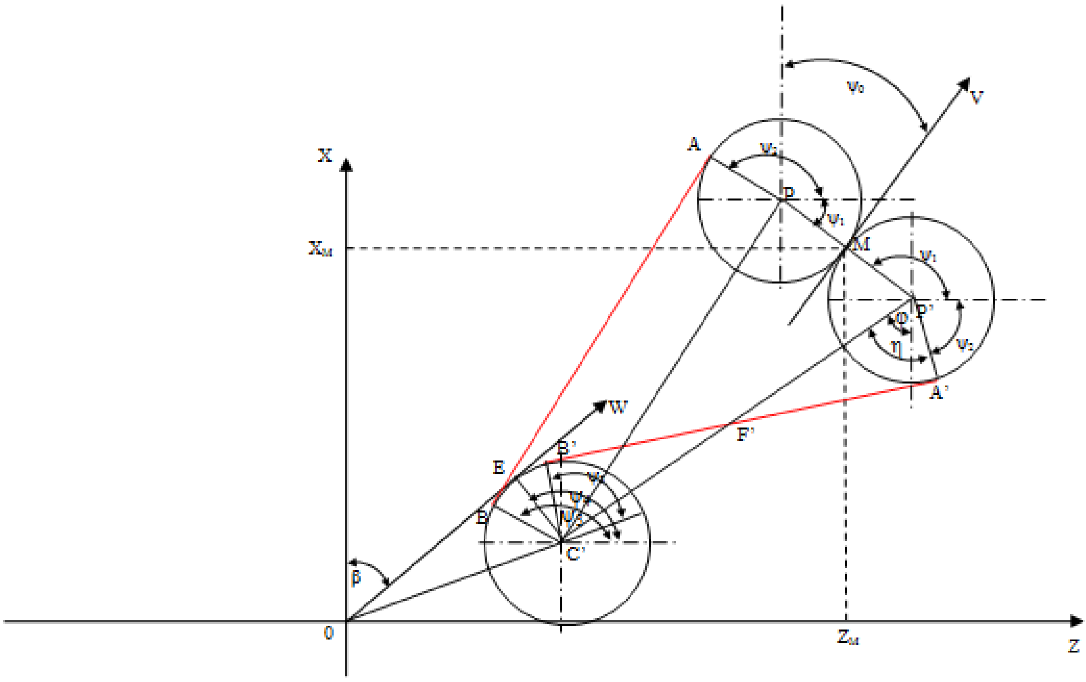

Figure 4. UAV turns left or right to reach the left circle, Applying the fuzzy – based controls

1.2. Applying the fuzzy controls

This paper proposes fuzzy logic control for UAV approach. This is the main difference of the reported study with the other works seen in the literature.

Basically, a fuzzy logic system consists of three main parts: (i) fuzifier, (ii) fuzzy inference engine, (iii) defuzzifier. The fuzzifier maps a crisp input into some fuzzy sets. The fuzzy inference engine uses fuzzy IF-THEN rules from a rule base to reason for the fuzzy output. The output in fuzzy terms is converted back to a crisp value by the defuzzifier.

In this paper, the fuzzy logic controllers adopt the following fuzzy IF-THEN rules:

$$R^l: If\ (x_1\ is\ X_1^l)\ AND\ \dots AND\ (x_n\ is\ X_n^l)\ THEN\ y_1\ is\ Y_1^l, \dots, y_k\ is\ Y_k^l \quad (5)$$

where R^l is the lth rule $x = (x_1, ..., x_n)^T \in U$ and $y = (y_1, ..., y_k)^T \in V$ are the input and output state linguistic variables of the controller respectively, $U, V \subset \Re^n$ are the universe of discourse of the input and output variables respectively, $(X_1, ..., X_n)^T \subset U$ and $(Y_1, ..., Y_n)^T \subset V$ are the labels in linguistic terms of input and output fuzzy sets, and n and k are the numbers of input and output states respectively.

In addition, a multi-input and single-output (MISO) fuzzy logic controller ($k = 1$) was considered, which has singleton fuzzifier. Using triangular membership function, algebraic product for logical

AND operation, product-sum inference and Centroid defuzzification method, the output of the fuzzy controller has the following form:

$$\boldsymbol{y_j} = \frac{\sum_{l=1}^{M}(\prod_{i=1}^{N}\boldsymbol{\mu x_i^l(x_i)})\boldsymbol{y_j}}{\sum_{l=1}^{M}\prod_{i=1}^{N}\boldsymbol{\mu x_i^l(x_i)}} \tag{6}$$

where *N* and *M* represent the number of input and output variables and total number of rules respectively. $\boldsymbol{\mu x_i^l}$ denote the membership function of the *l*th input fuzzy set for the *i*th input variable.

In order to control landing UAV, three fuzzy logic controller are designed to control roll angle, the altitude and the speed.

1.2.1. Altitude controlling channel

Using fuzzy controller of which desired value of the angle δ_c^* is a nonlinear function of altitude error Δy and vertical velocity component ΔV_y and two additional components to the control law. The first additional component is the balance value (approximately) of the elevation angle δ_{cbb} received by solving the linear algebraic equations of force and torque balance when flying at a certain altitude and velocity. It is necessary because when there is no error, the fuzzy controller would normally state the altitude elevation angle at "0" this will be caused the imbalance between power and torque. Due to the continuous adjustment of the altitude elevation angle, UAV will be fluctuated according to Pitch angle. The second additional component is attenuating, $k_{cd}.\omega_z$.

Thus, the algorithm of the fuzzy controller changes the altitude controller.

$$\boldsymbol{\delta_c^* = fuzzy1(\Delta y, \Delta V_y) + \delta_{cbb} + k_{cd}.\omega_z} \tag{7}$$

where: *fuzzy1*: nonlinear function of altitude errors and vertical velocity received by fuzzy logic;

δ_{cbb} - the balance value of the elevation angle;

k_{cd} - the attenuating coefficient of vertical channel.

Apparently, $|\delta_c^*|$ is limited by a certain maximum value $\delta_{c\,\max}$ through a limited angle which is caused by an overload sensory channel n_y and by changing the desired value of the vertical velocity component V_y^* followed by time law.

$$\boldsymbol{V_y^* = f(t, n_y)} \tag{8}$$

The desired altitude value H^* is measured by the differentiation equation:

$$\boldsymbol{H^* = H_0 + \int_0^t V_y^* dt} \tag{9}$$

1.2.2. Speed controlling channel

The control of UAVs' velocity is also implemented by the fuzzy controller's traction (*T*) with neutral traction value. The traction can be adjusted depend on (i) constant flight, (ii) increasing altitude, (iii) decreasing altitude. The control of UAVs' velocity also depends on V_y^*.

Here, it can be used the algorithm adapting for traction T by the fuzzy controller as follows:

$$T = fuzzy2(\Delta V) + mg\theta^*; \qquad \theta^* = \boldsymbol{V_y^*/V} \tag{10}$$

where: *fuzzy2* – nonlinear function of velocity error received by fuzzy logic;

mg – weight of UAV;

θ^* - desired elevation angle orbit;

V – flight velocity.

Apparently, traction T is limited by the maximum (T_{max}) and minimum (T_{min}) values. These values depend on current altitude and velocity. Controlling traction *T*, through the throttle position, is considered immediately without time delay.

1.2.3. Roll controlling channel

Using fuzzy controller in which the desired aileron deflection angle (δ_l^*) is a nonlinear function of roll angle error ($\Delta\gamma$) and its derivative ($\Delta\omega_x$) combined with attenuating the rate of roll angle to the control rules.

$$\delta_l^* = fuzzy3(\Delta\gamma, \Delta\omega_x) + k_{cl}.\omega_x; \quad |\delta_l^*| \leq \delta_{l\,max} \tag{11}$$

where: *fuzzy3*: Nonlinear function of roll angle error and its derivative received by fuzzy logic.

k_{cl} –proportional coefficient of the rate of roll angle.

1.2.4. Yaw controlling channel

In this channel, It has been used the control algorithm rate as following:

$$\delta_h^* = k.n_z \tag{12}$$

where: δ_h^* - the desired value of the angle given by the computer on board;

k - rate coefficient, determined by experiment;
n_z – load factor (measured in the linking coordinate system).

This control channel is necessary to reduce the sliding angle by the overload in z-axis.

2. RESULTS OF SIMULLATION

The calculations and surveying of landing phase were done by utilizing MATLAB software for the small UAV. All the parameters of the UAV were taken from the IRKUT-70V [4].

Figure 5 illustrates the program to survey UAV landed by following desired landing orbit.

The simulation results of the UAVduring the landing operation is shown in three cases as follows:

2.1. Case 1:

Input data:

- Northern wind with speed 3m/s, landing in the opposite of the wind direction
- Current position of the UAV in space:
  - Coordinate (X Y Z) = (2200, 500, 1200) [m]

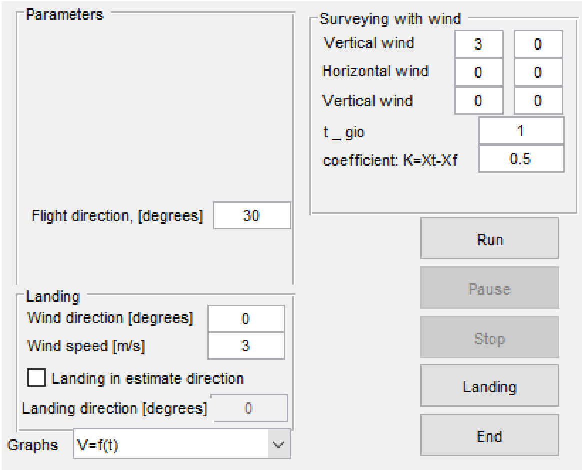

Figure 5. The program to survey controlling UAV

- Flight direction (angle) = 30 [^{0}]
- Initial velocity V_0 = 40 [m/s]

Simulation results can be seen in Fig. 6 :

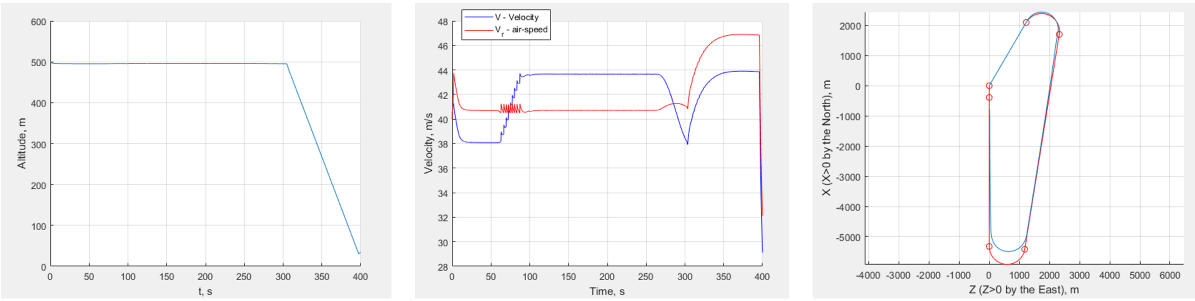

Figure 6. The process of landing approach of UAV (on the left side), the altitude (middle) and velocity (on the right side) of the landing process in the opposite of the wind direction

The simulation result indicates that the error in orbit deviation starts from "0". The controlling channels start working during the first turning which cause control errors. However, due to tiny error parameters the orbital deviation also will be small.

During the flight, all the orbital parameters are hardly changed because both yaw and speed channels work together.

In the second turning, automation has worked in sync, when the orbit deviation and input speed is low, velocity controlling channel combines with orbital roll-angle controlling channel to work together with small errors. Hence, the error in orbital deviation is small, real and desired orbit are quite the same. In the process of lowering altitude, yaw and altitude channels (fuzzy V_y) work together, orbital deviation is small.

2.2. Case 2:

Input data:

- ➢ No wind (*w* <= 1m/s), land in the shortest distance.
- ➢ Current position of the UAV in space:
  - Coordinate (X Y Z) = (2500, 500, 1400), [m]
  - Flight direction (angle) = -30 [^{0}]

- Initial velocity V_0 = 40 [m/s]

In this case, the wind direction was suggested that the direction from the coordinate „0" to the current position of UAV in space when the UAV is ordered to land.

Simulation results can be seen in Fig. 7:

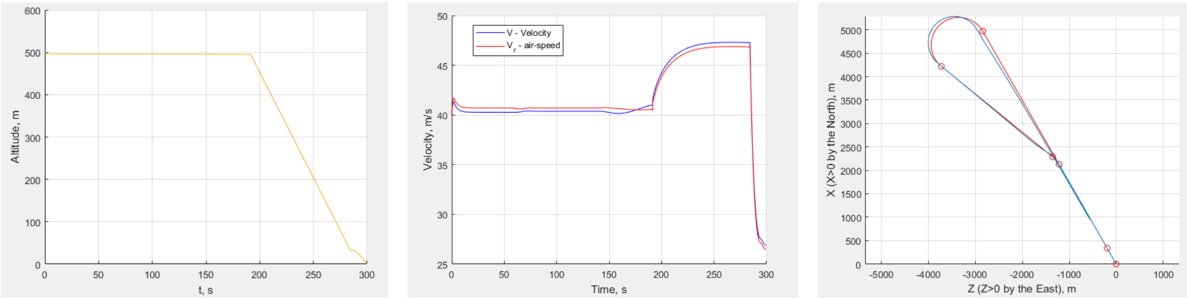

Figure 7. The process of landing approach of UAV (on the left side), the altitude (middle) and velocity (on the right side) of the landing process in the shortest distance

It is clear to see in the first period of turning the error of the orbit deviation starts at "0", meanwhile the UAV is barely affected by the wind. However, due to the short time of turning (short desired distance), and area of adjusting the roll-angle is large ($\pm 20^0$). So the fuzzy gamma controlling channel works and causes more errors than in the case 1 (Fig.6), that will lead the whole real orbit errors in comparison with the desired orbit in the case 1.

2.3. Case 3:

Input data:

- Northern wind, speed 3m/s, land in the estimated direction.
- Current position of the UAV in space:
  - Coordinate (X Y Z) = (2200, 500, 1200), [m]
  - Flight direction (angle) = 30 [^{0}]
  - Initial velocity V_0 = 40 [m/s]

In this case, the input data is the same in the case 1 and the estimated direction for landing is considered.

It can be seen the simulation results in Fig. 8:

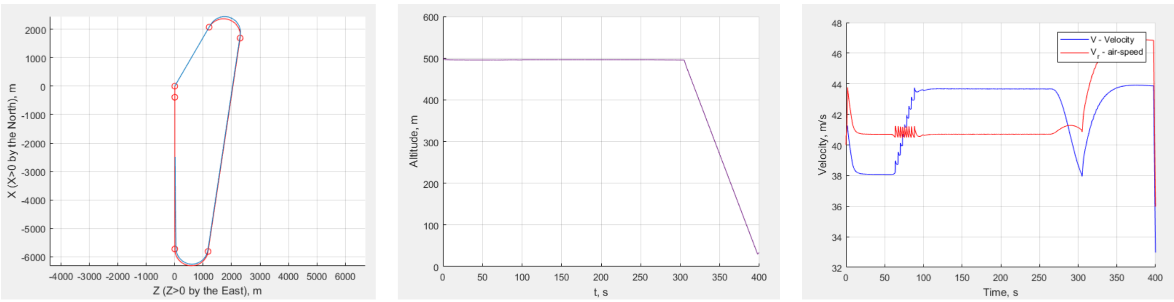

Figure 8. The process of landing approach (on the left side), the altitude (middle) and velocity (on the right side) of the landing process in the estimated direction

Apparently, with input parameters chosen as the same with those in the case 1 and the estimate landing direction is the wind direction as the same in the case 1. According to the comparation between the results in the case 1 and the case 3 can be found as follows;

- The desired landing orbits are the same;
- Actual landing orbits are the same.

Throughout the survey results of controlling process of UAV and desired landing approach, it can be assumed that the program has run smoothly and appropriately. The errors of orbital deviation highly depend on controlling errors. They are mainly caused by the desired orbit, the wind speed, and the number of control channels operating at the same time. However, all the errors remain within the limits allowed by the automation. This ensures that the UAV would approach landing at desired location.

CONCLUSION

Today, UAVs play an increasing role in many public tasks such as weather monitoring, wildlife surveys, military training, and local law enforcement. Therefore, it is needed to do extensive investigation of various theoretical and practical options to improve UAVs' control system and design.

In this paper, the dynamic parameters of UAV IRKUT-70V was used to calculate the desired landing orbit which is illustrated by the shape of orbit, the change of altitude and the velocity. A special method was developed for determining the optimal approach and landing process for increasing the landing accuracy. The approach trajectory was completed from orbits and straight lines.

The control of the UAV, follows the calculated landing trajectories is implemented with the fuzzy logic controllers. The MATLAB application was used to simulate the landing approach process. The simulation results of three introduced cases have demonstrated the increases in landing accuracy applying the fuzzy controlled orbits – straight lines approach – landing. Based on this study the control system will be designed and taken in order to practical studies in real environment. To do so, an overall training is required to improve basing decisions and system effectiveness.

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Fuzzy kontrol alapú kör és egyenes vonalakból álló trajektória meghatározása UAV leszállási pontosságának a növelésére

A technológiai forradalom katalizálja az ember nélküli légjárművek (UAV - Unmanned Aerial Vehicles) leszállási pontosságát növelő kontrol megoldások fejlesztését. Több nemzetközi project fejleszt ilyen fejlett kontrol megoldásokat úgymint (i) a UAV-ket kommunikációs átjátszóként alkalmazó STOCK T projekt a földi robotok irányítási távo9lságának a növelésére, (ii) a GABRIEL projekt a mágneses levitációval segített repülőgép fel- és leszállásának a megvalósíthatóságát földi méréseket is felhasználva bizonyította, midőn a UAV modell leszállt a mozgó platformra, vagy (iii) az 'IRKUT-70V', melyete alapvetően szociális, gazdasági és védelmi (security) feladatok ellátására fejlesztenek.

A szerzők behatóan vizsgálták a UAV-k leszállása során alkalmazható körív trajektóriák logisztikai, kutatás-fejlesztési, kérdéseit, matematikai leírását és optimalizálását. Ez a cikk elemzi és megmutatja a a UAV paramétereinek az időinvariáns változásait. Az IRKUT-70V UAV dinamikai és fizikai jellemzőit az erre a célra kidolgozott szimulációs programmal vizsgálják.

A tanulmány legfontosabb újdonságai: (i) bemutatja a leszállás bevezetése során alkalmazható körív trajektóriák meghatározására kidolgozott módszert, (ii) az tervezett körív trajektóriák tartását biztosító Fuzzy logikára épülő *kontrol kifejlesztése, (iii) a kifejlesztett leszállási eljárás előnyeinek a bizonyítása az IRKUT-70V UAV leszállásának szimulációs vizsgálatával és (iv) a tervezett és valós trajektóriák közötti eltérések értékelése, különösen oldalszél eseteire.*

Kulcsszavak: ember nélküli légijármű, körív trajektória, leszállás, Fuzzy kontrol,

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