Roll Control of Unmanned Aerial Vehicles using Fuzzy Logic

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Abstract: - This paper presents an effective methodology for the simplified representation of the kinematics and the horizontal flight control of Unmanned Aerial Vehicles (UAVs). A real UAV has been used as a model in this project. The flight behavior of the UAV has been modeled in terms of simple analytic relationships, which proved very helpful in representing UAV's actual horizontal motion. A fuzzy controller for the autonomous navigation of UAVs on the horizontal plane, has been developed. The controller inputs are the heading error of the aircraft and its current roll angle, whereas the output is the change command of the roll angle. Despite its simple design, the controller achieved the desired performance as evidenced from various simulated test flights.

Key-Words: - Unmanned Aerial Vehicles, Roll Control, Kinematics Model, Fuzzy Logic.

1 Introduction

Intelligent control implementations in the field of autonomous navigation of Unmanned Aerial Vehicles (UAVs), have been developed astonishingly in the last decade. More and more research groups are occupied with the development of intelligent navigation controllers and autopilots in order to face this attractive problem. Some of the methodological frameworks employed are, neural networks [1], non-linear adaptive control [2], fuzzy logic [3] as well as combinations of these methods, such as, neuro–fuzzy control, or fuzzy logic and evolutionary or genetic algorithms [4].

Apart from the intelligent control approach, the conventional control theory has played an important role in the growth of civil and military aviation. Many feedback control systems have been developed for the design of simple autopilots systems that can be used by the flight crew to lessen their work load during cruise and to help them land their aircraft during adverse weather conditions [5]. In any case, the challenge of the fully autonomous navigation and the consecutive evolution of the computer science have led to the development of the intelligent control theory and its application to the aircrafts. Many universities, institutes and industries are developing intelligent control systems. CIRCA-II [6] and WITAS [7] are two examples in this field. The first is a control system, which has been developed by the University of Michigan and using techniques, such as real-time artificial intelligence and control theory, constitutes an intergraded control system. WITAS UAV project is a long-term basic research project, which is developed by the Linkoping University (LiU), Sweden. The purpose of this project is the development of the technologies and functionalities, which will lead to a fully autonomous UAV. In addition, the department of Aerospace Engineering at Georgia Institute of Technology has developed powerful controller architectures, using techniques of feedback linearization and adaptive neural networks [8].

A number of problems could be appeared during the development of the autonomous navigation system. The differences, which present the UAVs, in terms of a typical aircraft, regarding their flying behavior are one of the most significant obstacles in the design of control systems.

In this paper, we present an intelligent approach to the roll control problem of an UAV by utilizing fuzzy logic techniques. The paper is structured in the following manner. In Section 2 the UAV NEARCHOS is briefly presented. This vehicle is used as a model for the development of the roll controller. Data preprocessing is presented in Section 3 whereas in Section 4, a kinematics model based on simple mathematical formulas is derived. The kinematics model is developed to aid the simulation of NEARCHOS's flight behavior and it is validated trough comparisons with the actual flight data. In Section 6, the fuzzy logic control system, which has been designed for the roll control of a UAV, is described. Section 7 presents several tests of the fuzzy roll controller and finally, in Section 8 we present conclusions and future extensions of this work.

2 NEARCHOS UAV System

The UAV NEARCHOS is a high payload, medium range and endurance, multi-role inhabitant aerial vehicle. It can be used for military and civilian operations, such as surveillance, aerial reconnaissance, target acquisition, communication data relay, geological and oceanic applications, traffic surveillance, environmental data acquisition etc. The main technical characteristics of NEARCHOS are exhibited in Table I.

The flight of NEARCHOS is controlled by two independent control loops. The first has as input the roll command, which is the desirable roll of the aircraft. The gyroscope, which is installed at the NEARCHOS, offers the factual roll of the vehicle. Thus, the control system compares the two angles and outputs an appropriate command to the ailerons of the aircraft. The second loop controls the pitch angle. It has two inputs, which are the desirable and the factual pitch angle and an output, which is the command to the elevators of the aircraft.

TABLE I
MAIN TECHNICAL CHARACTERISTIC
OF NEARCHOS

Length:	3.95 m
Wingspan:	5.10 m
Height:	1.15 m
Empty Weight:	60 kgr
Operation Altitude:	7000 m
Operational Speed:	75 – 220 km/h
Flight Endurance:	8 – 10 h

Fig. 1. The UAV NEARCHOS.

In this paper, it is assumed that the aircraft moves only in the two dimensional horizontal plane, with no altitude variations.

3 Data preprocessing

The design of the roll controller is based on data from actual test flights. These data include the roll, pitch, rudder and altitude commands, as well as the following telemetry data: roll and pitch angles, rpm, airspeed, heading, coordinates (latitude and longitude), and the time of flight (UTC). All the data are transmitted to the ground with a frequency of about 38 samples per second, except the GPS data, which are transmitted with a frequency of one sample per second.

Since flight data are transmitted to the ground very rapidly, data samples were averaged during each second. Thus, the design of the kinematics model, which links the roll angle with the position of the NEARCHOS, was actualized with the averaged data.

4 Kinematics Model

In the general case, the motion of the aircraft center of mass is defined by seven variables, namely the position coordinates x, y, z, the speed V, the flight path angle γ, the heading angle ψ and the mass m (Fig. 2). Considering a relatively short segment of the flight path, the weight $W = mg$ can be assumed as constant (negligible change in m due to the fuel consumption). Then, the equations of flight are listed below [9]:

$$\frac{dx}{dt} = V \cdot \cos\gamma \cdot \cos\psi \tag{1}$$

$$\frac{dy}{dt} = V \cdot \cos\gamma \cdot \sin\psi \tag{2}$$

$$\frac{dz}{dt} = V \cdot \sin\gamma \tag{3}$$

$$\frac{dV}{dt} = g\left[\frac{T}{W}\cos\varepsilon - \frac{D}{W} - \sin\gamma\right] \tag{4}$$

$$\frac{d\gamma}{dt} = \frac{g}{V}\left[\left(\frac{L}{W} + \frac{T}{W}\sin\varepsilon\right)\cos\varphi - \cos\gamma\right] \tag{5}$$

$$\frac{d\psi}{dt} = \frac{g}{V}\left(\frac{L}{W} + \frac{T}{W}\sin\varepsilon\right)\frac{\sin\varphi}{\cos\gamma}, \tag{6}$$

where φ is the roll angle (the angle between the vertical plane and the plane of symmetry of the airplane), ε is the angle between the trust and the velocity vectors (thrust angle-of-attack), L is the lift force, and D is the drag force. If we consider that thrust T is nearly collinear with the velocity vector, angle ε is practically zero. Assuming a flight in a constant altitude, angle γ becomes zero, as well as $d\gamma/dt$. Then, for a zero angle ε, eq. (5) results in:

$$L\cos\varphi = W \tag{7}$$

If we assume a constant speed V, then the derivative dV/dt becomes zero and eq. (4) results in:

$$T = D \tag{8}$$

Similarly, equations (1), (2), (3), and (6) are simplified in the form:

$$\frac{dx}{dt} = V \cdot \cos\psi \tag{9}$$

$$\frac{dy}{dt} = V \cdot \sin\psi \tag{10}$$

$$\frac{dz}{dt} = 0 \Rightarrow z = const. \tag{11}$$

$$\frac{d\psi}{dt} = \frac{g}{V}\frac{L}{W}\sin\varphi\,. \tag{12}$$

Replacing eq. (7) in (12) we get

$$\frac{d\psi}{dt} = \frac{g}{V}\tan\varphi\,. \tag{13}$$

In a turn at constant speed and constant altitude, as eq. 8 states, the thrust balances the drag and their common line of action is along the direction of velocity (for $\varepsilon = 0$), which is perpendicular to the plane formed by lift L and gravity force W.

Because of the nonzero roll angle φ, the lift has a horizontal component equal to $L\sin\varphi$ (Fig. 3), which is balanced by the centrifugal force, with magnitude $F = mV^2/R$, where R is the radius of curvature of the flight path (i.e. the turning radius). Then the radial acceleration is given as

$$\alpha_{rad} = \frac{V^2}{R}, \tag{14}$$

directed towards the center of the turn and perpendicular to the velocity vector.

In our case, we assume that the flight takes place in a nearly constant altitude. Additionally, the actual flight with a varying speed V and varying roll angle φ is modeled as a sequence of small flight turns, each one with constant speed V and constant roll angle φ, but with different values between the successive flight path segments. This approach is based on the small speed variations of the actual flight paths considered in this work. It is attempted to approximate the airplane motion as a sequence of lines and circular arcs, for short time intervals. Thus, there are three different types of motions, which the airplane may execute:

1. A motion with zero roll angle.
2. A right turn (non zero roll angle).
3. A left turn (non zero roll angle).

In the case where roll angle is zero, lift L and gravity force W are collinear (Fig. 4), and eq. (13) becomes:

$$\frac{d\psi}{dt} = 0 \Rightarrow \psi = const. \tag{15}$$

This means than the flight path is a straight line with constant heading angle ψ. The integration of eq. (9) and (10) provides the new position of the airplane after the specified time interval:

$$\begin{aligned} x_{i+1} &= x_i + V_i\cos(\psi_i)\cdot(t_{i+1} - t_i) \\ y_{i+1} &= y_i + V_i\sin(\psi_i)\cdot(t_{i+1} - t_i) \end{aligned} \tag{16}$$

If at time t_i the airplane is located at point A (x_i, y_i), by executing a motion with constant velocity and zero roll angle, after time (t_{i+1}-t_i) moves to point B (x_{i+1}, y_{i+1}), with constant heading angle ψ, equal to heading ψ_i at point A (Fig. 5).

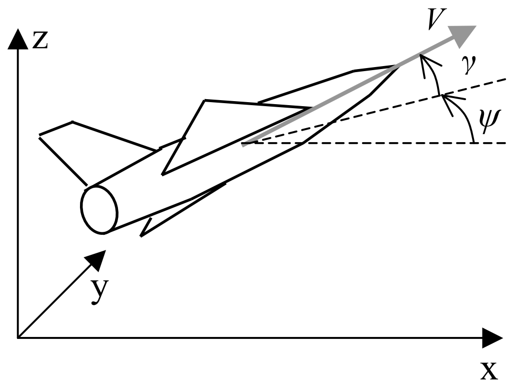

Fig. 2. A three-dimensional motion of an airplane.

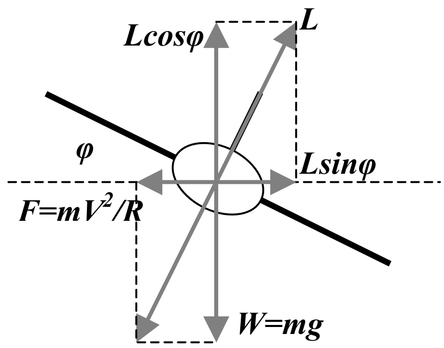

Fig. 3. Forces acting on the aircraft during a turn in a horizontal plane with constant speed.

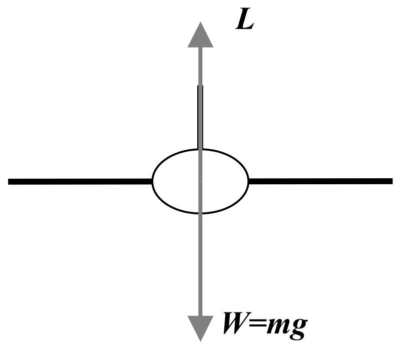

Fig. 4. Forces acting on the aircraft during a flight at zero roll angle at constant altitude and speed.

In the case of a non zero roll angle, from Fig. 3

the centrifugal force F is calculated as:

$$F = ma_{rad} = W\tan(\varphi) = mg\tan(\varphi) \tag{17}$$

while using eq. 14 and 17 the turn radius results as:

$$R = \frac{V^2}{g\tan(\varphi)}. \tag{18}$$

The radius of the circular trajectory depends on speed V and roll angle φ. In other words, sharp maneuvers lead to circular path segments with small radius of curvature, whereas regular maneuvers lead to circular path segments with large radius of curvature.

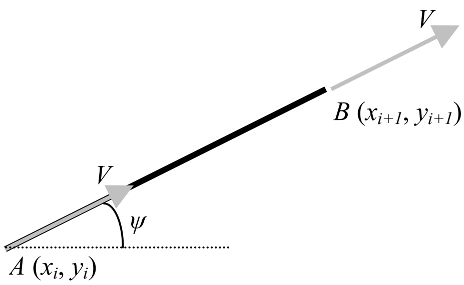

Fig. 5. Uniform straight – line motion of the aircraft.

Let us assume that the airplane is performing a right turn with roll angle φ, starting from point A, at a given time instant t_i. At time t_{i+1} the airplane has been moved to the point B as shown in Fig. 6.

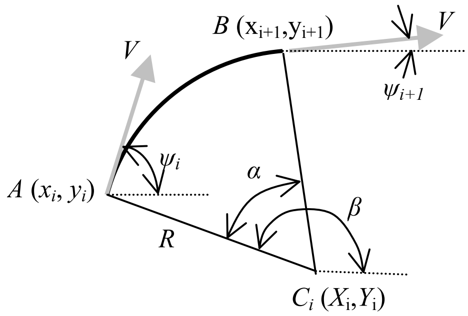

Fig. 6. Uniform right turn of the aircraft.

During the right turn the heading angle ψ varies from ψ_i το ψ_{i+1}. The coordinates of temporal center C_i of the turn in Fig. 6 can be calculated as:

$$\begin{aligned} X_i &= x_i + R_i \cos\left(\frac{\pi}{2} - \psi_i\right) \\ Y_i &= x_i - R_i \sin\left(\frac{\pi}{2} - \psi_i\right) \end{aligned}. \tag{19}$$

while the coordinates of the final position are calculated as:

$$\begin{aligned} x_{i+1} &= X_i + R_i \cos(\beta - \alpha) \\ y_{i+1} &= Y_i + R_i \sin(\beta - \alpha) \end{aligned} \tag{20}$$

where

$$\beta = \psi_i + \frac{\pi}{2} \quad , \qquad \alpha = \frac{V_i}{R_i}(t_{i+1} - t_i). \tag{21}$$

The final heading angle ψ_{i+1} results as:

$$\psi_{i+1} = \psi_i - \alpha \tag{22}$$

In order to model the left turn, let assume that the vehicle starts at time t_i from point A with heading angle ψ_i as in Fig. 7. At time t_{i+1} the aircraft is located at point B, with heading angle ψ_{i+1}.

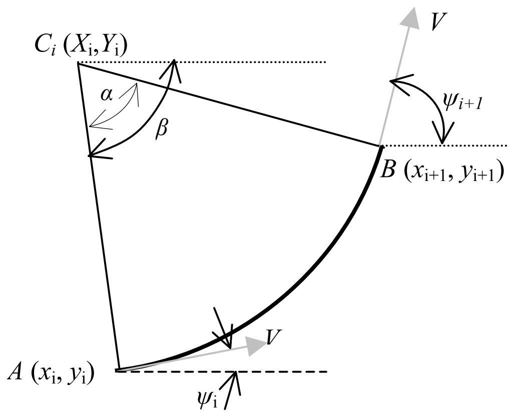

Fig 7. Uniform left turn of the aircraft.

The coordinates of temporal center C_i of the turn in Fig. 7 can be calculated as:

$$\begin{aligned} X_i &= x_i - R_i \cos\left(\frac{\pi}{2} - \psi_i\right) \\ Y_i &= x_i + R_i \sin\left(\frac{\pi}{2} - \psi_i\right) \end{aligned}, \tag{23}$$

while the coordinates of the final position are calculated as:

$$\begin{aligned} x_{i+1} &= X_i + R_i \cos(\beta + \alpha) \\ y_{i+1} &= Y_i + R_i \sin(\beta + \alpha) \end{aligned} \tag{24}$$

where:

$$\begin{aligned} \beta &= \psi_i - \frac{\pi}{2} \\ \alpha &= \frac{V_i}{R_i}(t_{i+1} - t_i) \end{aligned}. \tag{25}$$

The final heading angle ψ_{i+1} results as:

$$\psi_{i+1} = \psi_i + \alpha \tag{26}$$

Equations (16), (20), (22), (24) and (26) consist a simplified kinematics model, which can be used to simulate the flight behavior (forward, right and left turn) of a UAV on a nearly constant altitude, with small variations in speed V and roll angle φ. The inputs to the model are the initial position (x_0, y_0) and heading angle (ψ_0), along with the real airplane speeds V_i and roll angles φ_i, in each time t_i, provided by the telemetry. The outputs of the model are the airplane coordinates (x_{i+1}, y_{i+1}) and the corresponding heading angle ψ_{i+1} in each time t_{i+1}.

Several scenarios have been tested in order to examine the ability of the model to simulate the flight behavior of the UAV NEARCHOS.

In fig. 8 the trajectory of a flight path is presented, executed by the aircraft for 27 seconds. The altitude remains almost constant and the mean velocity of the aircraft is 55 m/s. The time intervals used for the simulation are equal to 1s. The solid line presents the original trajectory, whereas the discontinuous line describes the trajectory resulted using the kinematics model.

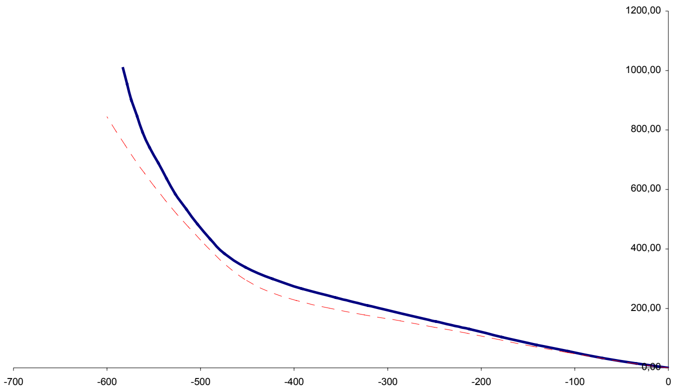

Fig. 8. Test case 1. Original Trajectory and Trajectory by kinematics model of the NEARCHOS.

Observing the results from test case 1, it seems that the kinematics model has a satisfactory behavior when the aircraft executes smooth turns. The mean deviation between the simulated and the actual trajectory is about 6 meters in the x-axis and 40 meter in the y-axis.

The 2nd test case presented in Fig. 9 is a more complex one. We should point out that in this test case the altitude was not constant, because of the complex maneuvers of the actual flight. However, the altitude variation was not more than 30 meters.

The duration of this maneuver was one minute and ten seconds and during this motion the aircraft executes right and left turns with medium and large roll angles. In addition, the mean velocity was 46 m/s and the mean altitude was 453 meters.

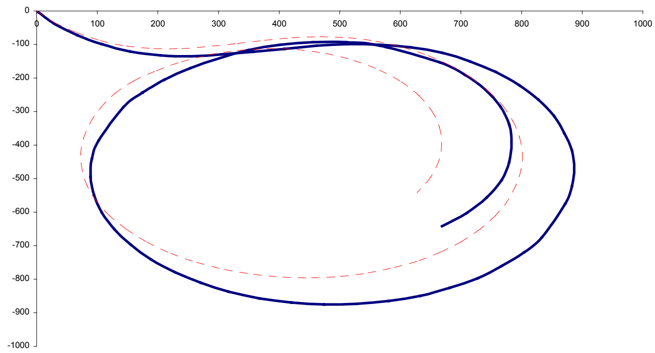

Fig.9 Test case 2. Original Trajectory and Trajectory by kinematics model of the NEARCHOS.

Observing the results from the second test case, it is verified that the simulated trajectory presents small deviations from the real one, even when the aircraft executes sharp maneuvers. Specifically, in this test case the deviation from the real trajectory is about 75 meters in the x-axis and 45 meters in the y-axis.

Considering the above, it seems that the kinematics model, which is simple in principle, has a satisfactory behavior regarding the simulation of the airplane flight. The deviations observed between the original trajectory and the simulated one, resulting from the simplifications of the kinematics model, could be interpreted by the following observations:

- Energy losses of the aircraft because of the sequential rotations. The total energy of the aircraft is reduced, when it executes maneuvers and as a result the altitude of the aircraft is reduced. In order to maintain the altitude invariable, the pilot should increase the throttle of the aircraft. In the cases under consideration the altitude of the actual flight was not constant and altitude variations of about 30 m were observed.
- Sideslip of the airplane because of the sequential turns. Using the kinematics model, it is supposed that the aircraft executes successive circular arcs. However, due to the speed and roll angle variations, the aircraft appears a sideslip. This was not taken into account during the implementation of the kinematics model and thus there are deviations form the real trajectory, especially when the airplane expresses steep variations of speed and especially roll angle, between successive time intervals.
- The wind speed during the actual flight was not taken into account in the simple model.

5. Design of the fuzzy control system

The basic purpose of the navigation system is the motion of the vehicle upon a predefined trajectory. In order to navigate the aircraft upon a trajectory, a fuzzy controller of the so-called Mamdani type, has been designed and implemented. The testing trajectories were developed by the kinematics model, which is described in section 4.

The developed control system has two inputs and one output. The inputs are the current roll angle and the heading error of the aircraft. The output, which is called, roll command, is the change of the roll angle.

5.1 Inputs of fuzzy logic control system

As previously mentioned, the fuzzy controller takes as inputs the current roll angle and the heading error of the aircraft. Even though the current roll angle takes values ranging from -90^0 to 90^0, the flight control system of the tested vehicle (NEARCHOS) functions safely in a range from -70^0 to 70^0. The linguistic variables that represent the current roll angle are: *Right_Big (rb), Right_Medium (rm), Right_Small (rs), Zero, Left_Big (lb), Left_Medium (lm), Left_ Small (ls).* The membership functions, which have been derived empirically from tests, are shown in Fig. 10.

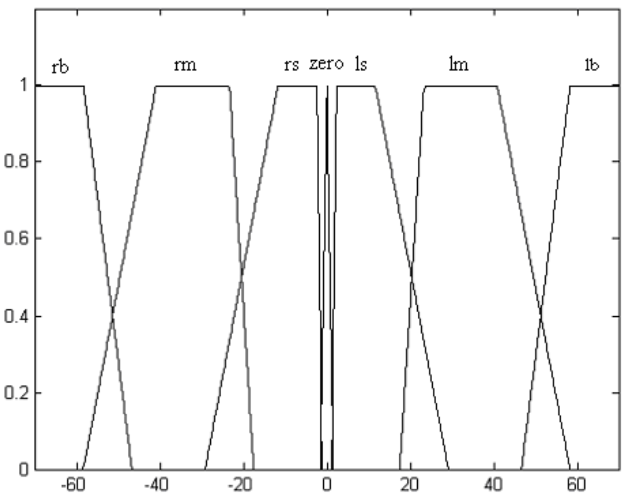

Fig.10. Membership function plot of input variable "Current Roll".

The second input to the fuzzy controller is the heading error, which is defined as the difference between the desirable and the factual direction of the aircraft. The factual direction is the heading of the aircraft, which is provided from the GPS. The desirable direction is the heading of a vector, with a starting point the current aircraft's position and ending point the desirable position.

The desirable and the heading direction take values ranging from 0^0 to 360^0, whereas the heading error takes values ranging from -180^0 to 180^0. However, in this implementation the heading error takes values in the region $[-100^0, 100^0]$. Negative (positive) values of heading error correspond to desirable right (left) roll.

The linguistic variables that represent the heading error are: *Negative_Big (nb), Negative_Medium (nm), Negative_Small (ns), Zero, Positive_Big (pb), Positive_Medium (pm), Positive_Small (ps).* The membership functions are shown in Fig. 11.

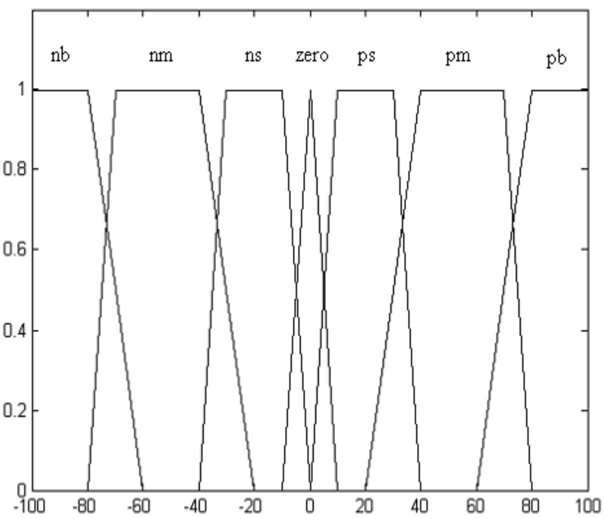

Fig. 11. Membership function plot of input variable "Heading_Error".

5.2 Outputs of fuzzy logic control system

The fuzzy controller has one output, which is the command for change-of-the-roll-angle of the aircraft. Similar to the current roll angle, the linguistic values that represent the roll command are: *Right_Big* (rb), *Right_Medium* (rm), *Right_Small* (rs), *Zero*, *Left_Big* (lb), *Left_Medium* (lm), *Left_ Small* (ls). The membership functions are shown in Fig.12.

The granularity level in the input and output variables is subjectively specified in an *ad hoc* manner from observation and experience. The criteria for selecting *linguistic variables and values* in the roll controller are:

1) Desired output behavior
2) Smoothness and consistency of the output,
3) Smallest possible number of rules in the rule base.

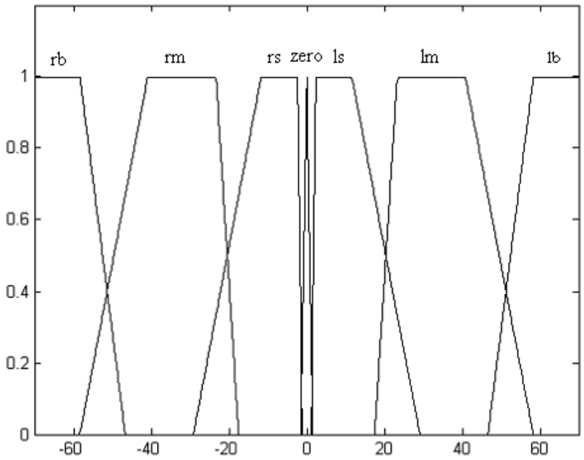

Fig.12. Membership functions of input variable "Current Roll".

5.3 The rule base

The controller has been developed using 49 IF-THEN rules. An example of rules is demonstrated: *IF Current_Roll is Right_Big AND Heading_Error is Negative_Big THEN Roll_Command is Zero.* The development of these rules is based on consecutive tests and their control output surface is shown in Fig. 13.

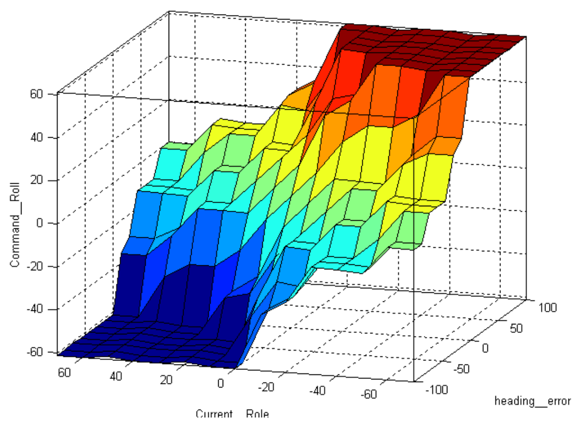

Fig.13. The control surface.

6. Results

The fuzzy logic control system has been designed and implemented using the *Fuzzy Logic Toolbox* of MATLAB. Several scenarios have been tested to study the controller's applicability. Initially, a desired trajectory is created, using the kinematics model with constant velocity and predefined roll angles, and then it is attempted to follow this trajectory (real) using the fuzzy logic control system.

In test case 1, the aircraft executed a trajectory for 165 seconds. The aircraft starts with zero roll angle, and a heading angle of -40^0. Then, it executes a number of maneuvers with roll angle ranging from -30^0 to 30^0. Fig. 14 presents the corresponding results, where the continuous and discontinuous lines represent the desired and the simulated trajectory respectively.

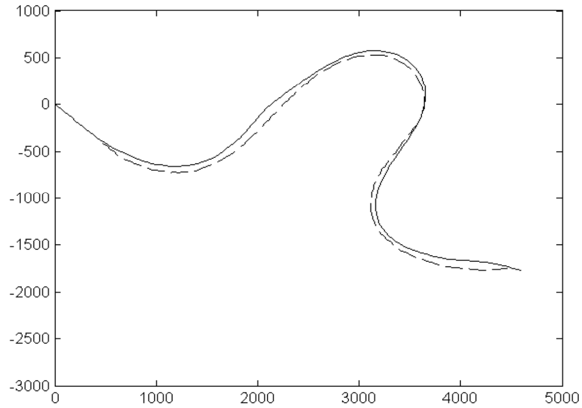

Fig. 14. Test case 1. The continuous and discontinuous lines represent the desired and the simulated trajectory, respectively.

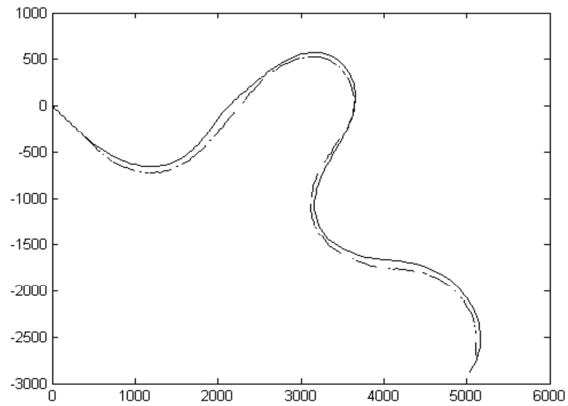

Fig. 15. Test case 2.

In the second test case, the aircraft executes a trajectory for 195 second. The roll angle varies between -30^0 to 40^0. The corresponding results are shown is Fig. 15.

In the third test case, the aircraft executed a trajectory for 185 seconds. The initial conditions of the aircraft were the same as in the previous cases. In this case, the roll angles during the flight varied between -40^0 and 40^0. The results of this case are presented in Fig. 16.

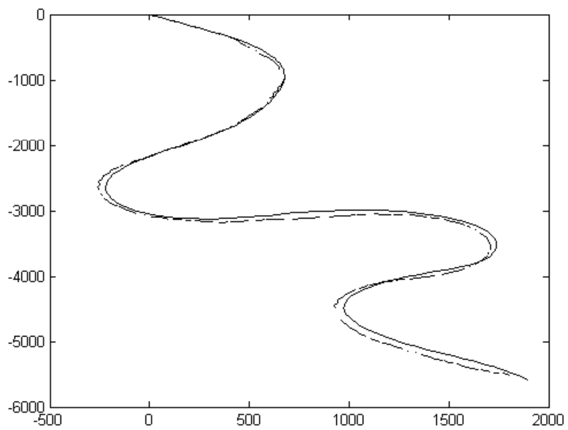

Fig. 16. Test case 3.

In test case 4, the aircraft executed a trajectory for 190 seconds. The coordinates of the starting point are (0, 0) with initial roll angle equal to zero, and a heading angle equal to 35^0. The corresponding results are presented in Fig. 17.

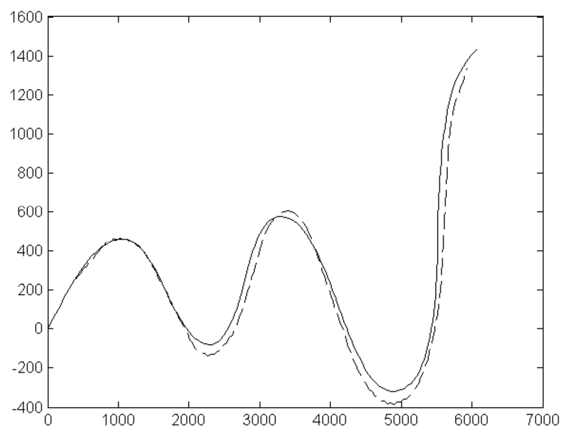

Fig. 17. Test case 4.

7. Discussion and Conclusions

We have presented a fuzzy logic control system for the roll control of an Unmanned Aerial Vehicle. Initially, we used the data from actual test flights of a real UAV, in order to develop the kinematics model of this aircraft. The corresponding model assumes that the flight takes place in a nearly constant altitude. Additionally, the actual flight with a varying speed and varying roll angle is modeled as a sequence of small flight turns, each one with constant speed and constant roll angle, but with different values between the successive flight path segments. Thus, the airplane motion is approximated as a sequence of lines and circular arcs, for short time intervals.

The results presented in Section 5 reveal the satisfactory behavior of the kinematics model even if the aircraft executes complicated maneuvers, with sharp variations of roll angle.

A fuzzy logic control system was designed, capable of following predefined trajectories at a constant altitude. The fuzzy controller has a very simple structure with two inputs and one output. The results presented in Section 7 show that the aircraft has the ability to follow predefined trajectories with small declinations.

The future directions of the research include the optimization of the rule base using evolutionary algorithms. The goal is to create a robust fuzzy logic control system in order to approximate better the ideal trajectory. In addition, the development of a kinematics model and the relevant controller for the longitudinal plane is attempted, in order to create a fully autonomous navigation system, based on fuzzy logic.

Acknowledgments

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References

[1] Y. Li, N. Sundararajan and P. Saratchandran, Neuro – Controller Design for Nonlinear Fighter Aircraft Maneuver using Fully Tuned RBF Networks, *Automatica*, Vol. 37, 2001, pp. 1293-1301.

[2] C. Schumacher and S. N. Singh, Nonlinear Control of Multiple U.A.Vs in Close-coupled Formation Flight, *Proceedings of the AIAA Guidance, Navigation, and Control Conference*, Denver CO, 2000, pp. 14-17.

[3] B. A. White, A. L. Blumel and E. J. Hughes, A Robust Fuzzy Autopilot Design using Multi–criteria Optimization, *International Journal of Fuzzy Systems*, Vol.2, No.2, 2000, pp. 129-138.

[4] M. G. Perhinschi, Parameter Optimization via Genetic Algorithm of Fuzzy Controller for Autonomous Air Vehicle, *Proceedings of the AIAA Guidance, Navigation, and Control Conference*, Portland OR, USA, 1999, pp. 790-797.

[5] R. C. Nelson, *Flight Stability and Automatic Control*, Mcgraw-Hill, Aerospace Series, 1990.

[6] E. M. Atkins, E. H. Durfee and K. G. Shin, Autonomous Flight with CIRCA–II, Autonomous Agents-99 Workshop on Autonomy Control Software, May 1999.

[7] P. Doherty, G. Granlund, K. Kuchcinski, E. Sandewall, K. Nordberg, E. Skarman and J. Wiklund, The WITAS Unmanned Aerial Vehicle Project, *Proceedings of the 14th European*

Conference on Artificial Intelligence, Berlin, 2000, pp. 747-755.

[8] A. J. Calise and R. T. Rysdyk, Nonlinear Adaptive Flight Control using Neural Networks, *IEEE Control Systems Magazine*, Vol. 18, No. 6, December 1998.

[9] Nguyen X. Vinh, *Flight Mechanics of High-Performance Aircraft*, Cambridge Aerospace Series 4, 1993.