FUZZY CONTROL FOR THE KADET SENIOR RADIOCONTROLLED AIRPLANE

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Abstract

Three control strategies for the longitudinal dynamics of a *Kadet Senior* radiocontrolled airplane are analyzed and compared through simulation of a global nonlinear mathematical model. The first strategy uses a PID controller for the speed and two PID cascade controllers for the climb rate and altitude. The second strategy is a control system based on fuzzy logic. The third strategy consists of a hybrid system with a PID controller for the climb rate and fuzzy controllers for the speed and altitude.

1 Introduction

Control systems for airplanes are usually designed through simulation of different strategies in order to select the most appropriate in terms of stability and response time with limits on oscillations [2]. The objective of these control systems is to execute stable and controlled flights, avoiding any dangerous maneuvers and landings under extreme conditions.

In this paper, a comparative analysis of three different control strategies for the *Kadet Senior* radiocontrolled airplane is presented. This work is developed using a global nonlinear mathematical model, which we first describe qualitatively. Then the control problem is formulated and three different solutions are proposed. Finally, the results of the simulation tests are presented and compared analytically.

2 Characteristics of the airplane

The *Kadet Senior* (figure 1) is a radiocontrolled airplane manufactured by Sig, with a wingspan of 1.98 m, which is large enough to lift the sensors. It also has great inherent stability and low flight speeds. It cannot execute aerobatics or complex maneuvers, because it doesn't have ailerons. These features make the *Kadet Senior* an excellent model for testing control systems for longitudinal dynamics.

3 Qualitative description of the mathematical model

The mathematical model for the longitudinal dynamics of the airplane used in this work is an analytical generic model [2], which employs the parameters obtained from the *Kadet Senior* radiocontrolled airplane plans. The block diagram of this model is shown in figure 2. The model consists on three nonlinear differential equations, and the manipulated variables are the elevator angle d_e and the engine duty cycle d_T. Both variables influence directly on the angular speed Q, horizontal speed U_A and the vertical speed W_A of the airplane. With a coordinate transformation on these three variables, the horizontal speed V_X and the vertical speed V_Z of the airplane on the ground reference system are obtained, as shown in the same figure.

Each of the forces acting on the airplane depends nonlinearly on the total speed of the airplane, its angle of attack, the manipulated variables d_e and d_T, the altitude, the air density, etc. This dependence is expressed as nonlinear functions, approached to simpler equations (truncated Taylor series in some cases, as in [3]) to reduce the computational requirements of the model. However, the model works properly for most possible operation points, including stalls and all normal (non-inverted) flight conditions.

Figure 1: Photograph of the *Kadet Senior*.

The model response is qualitatively good for changes on d_e and d_T. For example, an increment on d_T generates more thrust, which makes the airplane go faster. This means an increment of the aerodynamic forces and moments, including the lift, which also increases the climb rate. At the other hand, if the elevator angle is negative, the moment on the airplane tends to increase, generating a positive change on the pitch angle, then the airplane gains vertical speed and loses horizontal speed (nose up). This demonstrates the coupling between horizontal and vertical speeds.

4 Control objectives

The objective of the control systems considered in this paper is the control of the altitude and speed of the *Kadet Senior*, by means of acting on the manipulated variables d_e and d_T.

The altitude must be kept as close as possible to the reference value, without appreciable oscillations, in order to stabilize the flight and avoid bad landings. The response time for changes on the flight conditions must be as small as possible, and limiting the climb rate to normal values, in order to avoid dangerous dives or climbs.

5 General control strategy

The three control strategies presented in this paper must accomplish the previous objectives. The design of these strategies is not simple if only are employed the speed and altitude, because the altitude of the airplane is the integral of the climb rate, which depends on its horizontal and vertical speeds and the pitch angle. This can be changed moving the elevators if the speed is enough to do that. This means that a bad movement of the elevator can generate obtuse pitch angles, and then, undesired flight conditions. To solve this problem, it is proposed to employ an intermediate control variable, the climb rate, which must be limited to avoid flights in undesired conditions. To accomplish these objectives, the control strategies analyzed in this paper present the structure shown in the general block diagram of the figure 3.

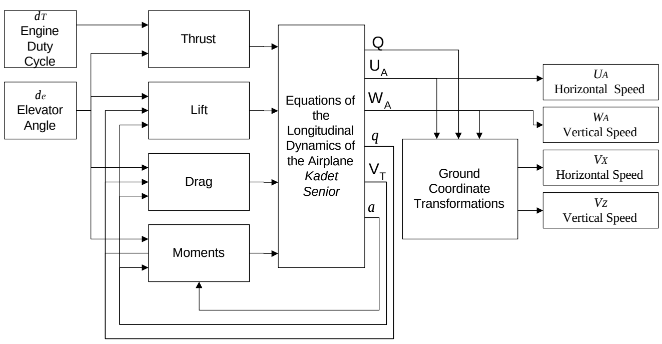

Figure 2: Block diagram of the mathematical model.

6 PID control strategy

This strategy consists on two independent PID control loops [1]: one for the speed and another for the altitude, as shown in figure 4. The first control loop has only one manipulated variable, the engine duty cycle d_T. The second one consists on two controllers in cascade; the outer loop compares the measured altitude with the reference, and generates the reference for the climb rate. The inner loop takes this reference, which is compared with the measured climb rate, and acts over the elevator to control it. Each of these control loops is described next.

6.1 PID control for climb rate

This controller calculates the error as the difference between the reference climb rate and the measured climb rate, and generates a value for the manipulated variable d_e, elevator angle. The controller gain is negative, because an increment on the elevator angle tends to diminish the climb rate of the airplane.

The parameters for this controller were adjusted through the method of trial and error, the same method used in all the PID controllers in this paper, due to the dependence between the airplane's behavior and the operating point, which makes it difficult to apply any analytic method. After some tests, the response of the system was fast and free of oscillations for the followings values of proportional, integral and derivative gains: KP=4, KI=3, KD=1.2. As in every other PID controller, the integral action is disconnected in order to get a better performance when the manipulated variable enters the saturation zone.

6.2 PID control for altitude

This control loop is the most important in the airplane flight, because a poor control may cause a crash with land. The controlled variable is the altitude and the manipulated variable is the climb rate. The controller was calibrated through trial and error, until the response oscillations-free and fast enough. The gains obtained for the controller were the following: KP=0.25, KI=0.1, KD=0.25. It was also necessary to saturate this controller's output out of the range (-3 m/s, 3 m/s) to avoid the execution of undesired maneuvers or inverted flights. The integral action is disconnected when the manipulated variable is out of the interval (-0.1 m/s, 0.1 m/s) to avoid any oscillation.

6.3 PID control for speed

This last control loop is the least important, because a bad control on the speed won't affect the performance of the other controllers, except in those situations when the speed is minimal.

In order to reach a good performance of this controller, it is necessary to control the climb rate first, because the speed is very sensitive to this variable. The parameters adjustment for this controller gave the following gains: KP=0.5, KI=1, KD=1. The integral action is disconnected when the manipulated variable is out of the interval (0,1).

7 Fuzzy control strategy

It has been considered important to try fuzzy control algorithms in this system [4, 5] due to the simplicity to be adapted to the airplane's flight in terms of fuzzy rules. This control strategy has two independent control loops, based on fuzzy logic, to control altitude and speed, as shown in figure 5. Figure 6 describes the structure of every fuzzy controller used in this work. These controllers have a Mamdani inference system, with centroid defuzzyfication method. Its inputs usually are the error of the controller and the derivative of the controlled variable, which gives the system a derivative action characteristic. Its output is integrated to reduce the stationary-state error. In this way, these controllers work as PID-like fuzzy controllers [4]. However, they are adjusted as expert systems, and also have nonlinear responses, which differentiate them from simpler PID controllers.

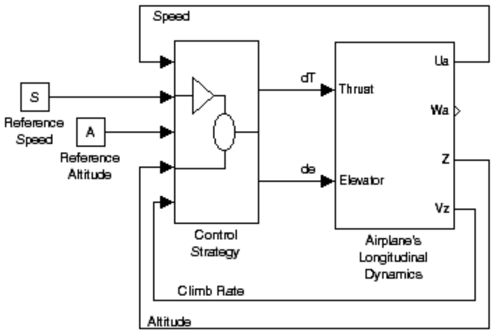

Figure 3: Basic control diagram used for the three strategies.

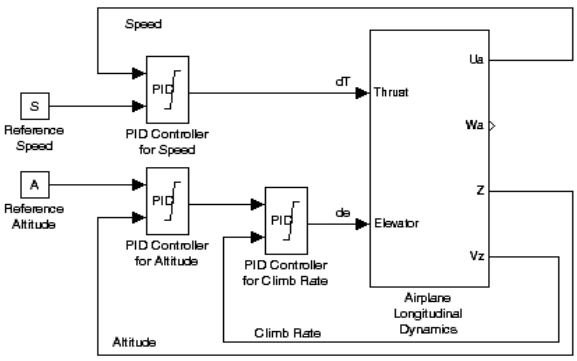

Figure 4: Block diagram of the PID controller system.

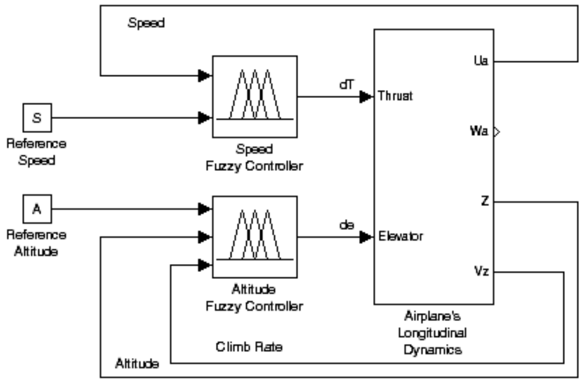

Figure 5: Block diagram of the fuzzy control system.

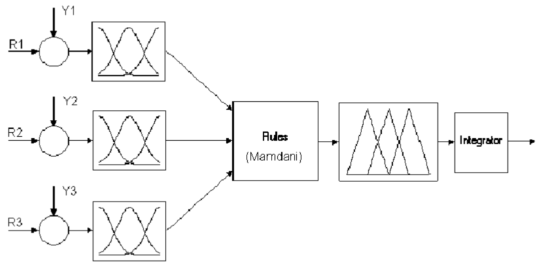

Figure 6: Fuzzy control structure.

7.1 Fuzzy control for speed

This controller works just like the controller shown in figure 6, but considering only one input variable, the speed of the airplane.

For the speed error there are 9 fuzzy sets with the membership functions shown in figure 7; these were adjusted by means of trial and error, obtaining a fast and oscillation-free response.

In order to act with better resolution when the error is next to zero, and then avoid oscillations, the membership functions of the central sets present a smaller base. The membership functions for the acceleration are defined uniformly, as shown in figure 8. Membership functions of the output are 9, they have the same shape and are defined in the interval [-1, 1]. The rules defined are those used by any pilot trying to control the speed of the airplane; the surface generated by the output of the controller for different inputs is shown in figure 9.

7.2 Fuzzy control for altitude

This system controls the airplane's altitude taking as inputs the climb rate, the measured altitude and its reference; the output is a signal for the elevator, whose membership functions are like those shown in figure 8, though they are defined in the interval [-15^o, 15^o]. The shapes of the membership functions for the climb rate, shown in figure 10, were obtained by means of trial and error.

There are three zones in each half axis; the closest to zero is the zone in which the vertical speed is small, and is used for approaching to the reference; the next zone, trapezoidal shaped, is bigger and is used for movements between distant altitudes; the last zone, extended over the rest of the range, takes the dangerous values for the performance of the airplane, and must be avoided.

Membership functions for the difference of altitudes, shown in figure 11, are asymmetrical around zero, because it has been considered the effects of the gravity that helps the airplane to go down. The surface formed by the output of this controller is shown in figure 12.

8 Hybrid control strategy

This control strategy is similar to the PID control system, because it utilizes two independent control loops to control speed and altitude (figure 13). The first of them is identical to the one used in the fuzzy controller for the speed. The altitude control system consists on two control loops in cascade. The inner one, which controls the climb rate, is the same used to control the climb rate in the PID system. The outer one uses a fuzzy controller slightly different to the rest of the fuzzy controllers utilized in this paper, because it doesn't integrate its output. This doesn't impede to get a null steady-state error, because this condition is obtained with the inner control loop.

Figure 14 shows the membership functions for the output of this controller; figure 15 shows the output-input function which characterizes the controller in steady state.

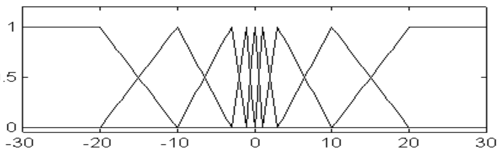

Figure 7: Membership functions for the speed error.

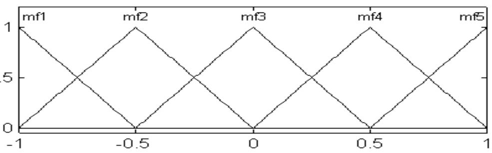

Figure 8: Membership functions for the acceleration.

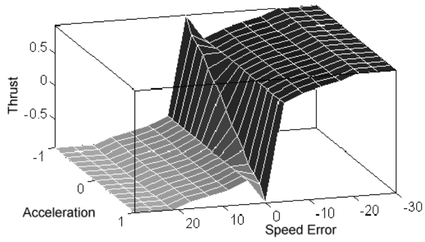

Figure 9: Surface formed by the output of the fuzzy controller for the speed.

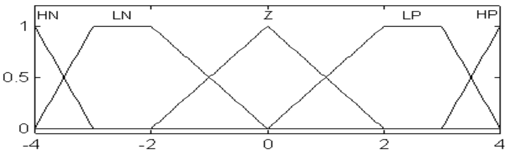

Figure 10: Membership functions for the climb rate.

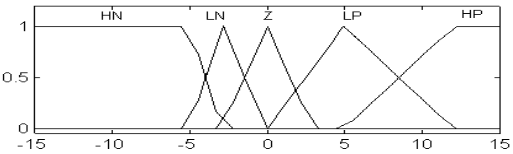

Figure 11: Membership functions for the altitude error.

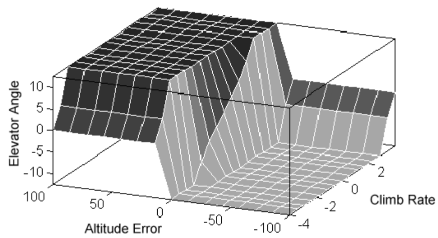

Figure 12: Surface formed by the output of the fuzzy controller for the altitude.

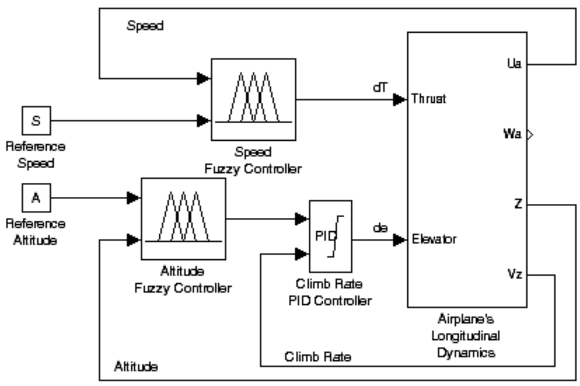

Figure 13: Block diagram of the hybrid controller system.

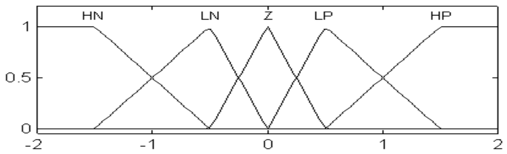

Figure 14: Membership functions for the climb rate.

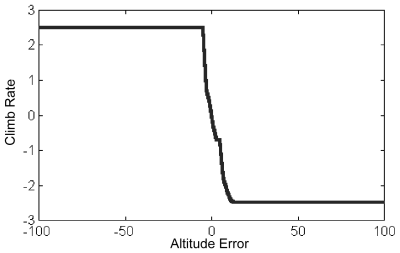

Figure 15: Output-input function for the altitude fuzzy controller.

9 Simulation tests and analysis of results

9.1 Conditions for the tests

All the tests consider the same initial conditions:

- Initial speed: 10 m/s.

- Initial altitude: 30 m.

- Initial climb rate: 0 m/s.

The changes in the references are the following:

The reference for the altitude is 20 m from t = 0 s until t = 35 s; after that, it increases to 40 m.

The reference for the speed is kept in 16 m/s from the beginning until t = 15 s; then, it is increased to 18 m/s.

9.2 PID control strategy

Figures 16 and 17 shown the performance of the PID controller. The altitude response is smooth, which agrees with the objectives planned; however, it is relatively slow when the reference increases. The speed control is bad due to the coupling with the altitude and its variation.

9.3 Fuzzy control strategy

Fuzzy controller shows a better performance for the altitude control (figure 18). It is observed that the fuzzy controller is the best in terms of response time; however, it is also observed an important fall in the speed of the airplane (figure 19). The speed controller is the same used in the other cases, so the only explanation for this fall is the low power of the engine. It is unable to maintain the climb rate required by the altitude controller, and then, the airplane loses speed. If the engine is unable to give enough power to keep a climb, this constitutes a serious problem in a real airplane.

9.4 Hybrid control strategy

The hybrid controller (figures 20 and 21) controls the altitude better than the PID, so it can be said that it has a better generation of reference for the climb rate. The speed control is slightly more sensitive to the altitude changes than the PID speed control; however, it tends faster to the reference than the PID.

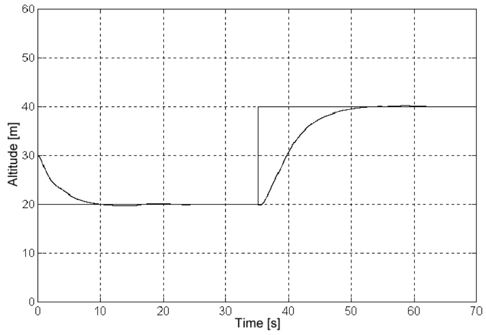

Figure 16: PID control of altitude.

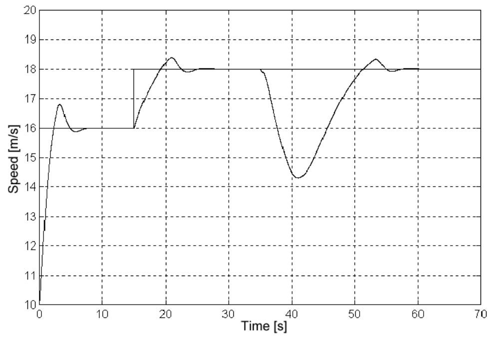

Figure 17: PID control of speed.

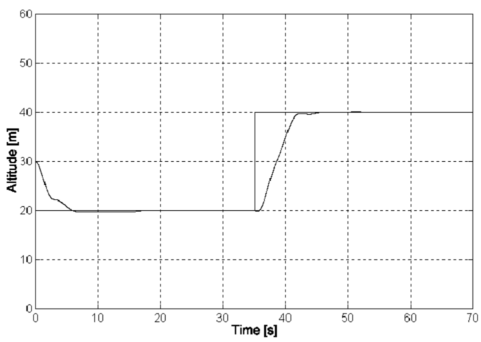

Figure 18: Fuzzy control of altitude.

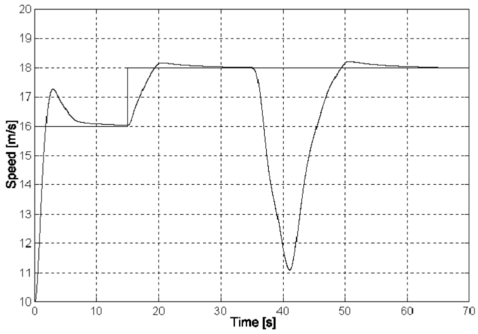

Figure 19: Fuzzy control of speed.

9.5 Comparative analysis of the strategies

In the figures it can be seen the relation between controlling the altitude as fast as possible and keep the speed. In all these control systems the objective has been to make faster the altitude response, minimizing oscillations; under these conditions, it is not possible to have a good control for the speed, due to the incapacity of the engine to support that.

Table 1 shows a quantitative comparison between the three strategies, based in the calculus of the root mean squared error of the altitude and speed. This demonstrates in quantitative terms that the fastest controller for the altitude is the fuzzy controller.

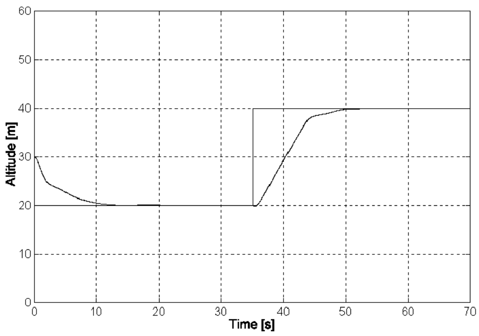

Figure 20: Hybrid control of altitude.

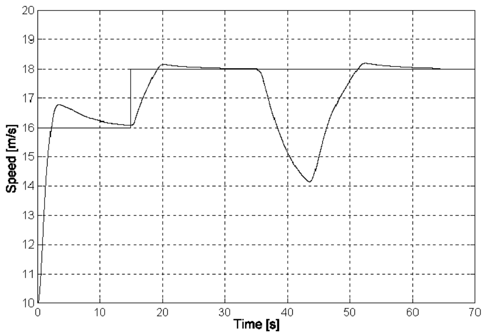

Figure 21: Hybrid control of speed.

Control System	Altitude RMSE (m)	Speed RMSE (m/s)
PID	4.79	1.27
Fuzzy	4.17	1.93
Hybrid	4.96	1.32

Table 1: Quantitative comparison between the three control strategies.

10 Conclusions and future works

In this work it has been used a mathematical model which describes the longitudinal dynamics of the airplane *Kadet Senior* to design a control system for that particular airplane. It has been compared, qualitative and quantitatively, the performances of three control strategies for the altitude and speed of the airplane. As a conclusion, it can be said that the fuzzy controller can be adapted in a better way to control the altitude in this system than the PID controller, due to the nonlinear behavior of the first one, which can generate faster actions on the nonlinear system of the airplane. However, the PID controller is simpler and has a better performance for the speed control of the airplane.

The next stage in this work is to test these control systems in the real airplane, comparing the results with those presented in this paper. In that case, the airplane will work as a experimentation platform oriented to testing different control systems. The data and the information obtained in those tests can be useful to develop real applications on unmanned air vehicles.

Acknowledgements

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