Automatic Landing in Adaptive Gain Scheduled PID Control Law

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Abstract: This paper deals with a problem of automatic landing guidance and control system design. The auto-landing control system for the longitudinal motion is designed in the classical PID controller. The controller gains are properly adapted to variation of the performance using fuzzy logic as a gain scheduler for the PID gains. This control logic is applied to the problem of the automatic landing control system design. From the numerical simulation using the 6DOF nonlinear model of the associated airplane, it is shown that the auto-landing maneuver is successfully achieved from the start of the flight conditions: 1500 ft altitude, 250 ft/sec airspeed and zero flight path angle.

Keywords: automatic landing control system, adaptive gain scheduled PID controller, fuzzy logic

1. INTRODUCTION

Recently the accident records of domestic aircrafts show that the pilot's mistake is one of the main sources of the accidents. Moreover more than 50% among the accidents occur in the approach and landing maneuver. This flight phase occupies only 4% overall flight times. In order to enhance safety in the approach and landing phase, some facilities have been built around the airport runway such as MLS and IBLS. One of the others is Instrument Landing System (ILS), which has been popularly used up to date. In this paper a guidance and control algorithm for the automatic landing flight control system is considered based on ILS. The overall schematics of ILS is depicted in Fig. 1. In recent years techniques for the gain scheduled control law design have been of great attention in many industrial applications to uncertain nonlinear systems. Capability of the gain adaptation is known to be able to improve robustness of control systems to uncertain environment under which the control system is operating. Airplane auto-landing maneuver is one of the most challenging flights under the uncertain environment that airplane flies at near stall speed around which aerodynamic characteristics may change abruptly and is vulnerable to the abrupt change of weather condition near the ground during the landing approach. In this paper the adaptive gain scheduled PID control law, which is realized in fuzzy logic, is developed to satisfy the maneuver performance of the precise trajectory following under gusty wind. It is supposed in this paper that the longitudinal motion of the associated airplane is only considered for automatic landing maneuver. In section 2, the guidance and control system for the approach and landing maneuver in ILS and the airplane associated with this problem are briefly introduced. In section 3 and 4, the automatic landing algorithm designed for the associated airplane in this paper is analyzed in the 6DOF nonlinear simulation of the airplane, followed by the conclusion in section 5.

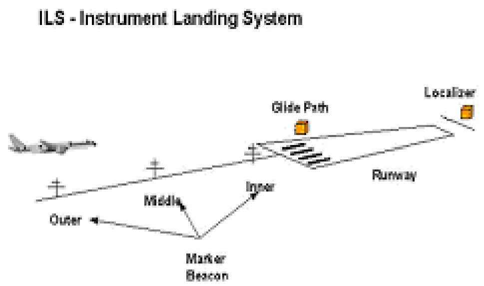

Fig. 1: Instrument Landing System (ILS)

2. GUIDANCE SYSTEN FOR THE APPROACH AND LANDING

In this paper only the longitudinal motion of the airplane is considered. The associated airplane has the center of gravity at 35%MAC, which means that the airplane has static instability in this condition. Control surfaces of the airplane have an elevator with ± 25 deg maximum deflection and a throttle (%). It is assumed that the airplane starts the approach at 1,500 ft altitude with 250ft/sec airspeed and the wing level. Also available measurements for feedback are assumed to be rate gyro, altimeter, and IMU. In this design the angle of attack sensor is not used for noise sensitivity. The actuator model in the elevator loop is assumed to be a 1^{st}-order system with 0.05sec time constant. According to MIL-8785C, the associated airplane belongs to Class-IV, Flight Phase Category 'C' and is required to satisfy the flying quality of Level '1' for the longitudinal motion. For the approach and landing maneuver in this paper, it is assumed that the glide slope beam is set 3.0 deg upward produced by ILS installed around airport runway, which starts at 1,500 ft altitude assumed in this paper. The geometry of the glide slope capture followed by the flare is depicted in Fig. 2.

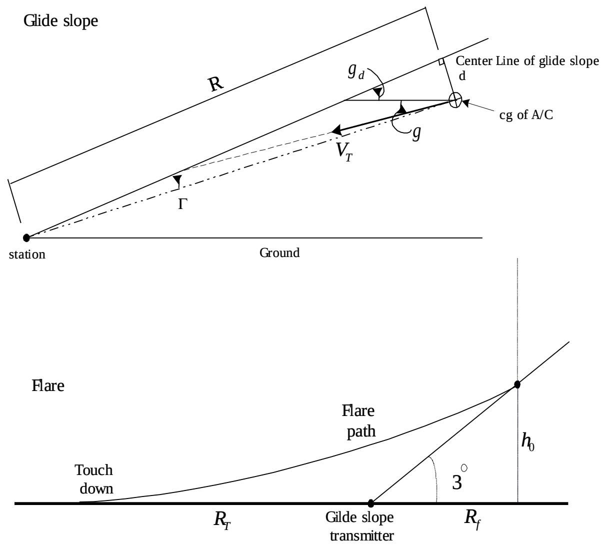

Fig. 2 : glide slope and flare

Moreover, the automatic landing control system to be designed should satisfy the requirements given in Table 1.

Table 1. Design Requirements

contents	specifications
ΔV_T	$\pm 10\, ft/\sec$
Δq	$\pm 5\deg$
Δa	$\pm 5\deg$
Sink rate for flare	$\leq 1\deg$

3. AUTOLANDING SYSTEM DESIGN

In this section the airplane to be considered in this paper is briefly introduced, and then the basic design technique in classical root-locus method for automatic landing flight control system is discussed. The control system designed in the basic design technique is scheduled in fuzzy logic which is briefly mentioned in this section. It is noted that the automatic landing system designed here is only for the longitudinal motion of the approach and landing maneuver.

3.1 The Associated Airplane Dynamics

The linear model of the associated airplane for the approach and landing maneuver is expressed in state space :

$$\dot{x} = Ax + Bu \tag{1}$$

where the actuator model given in section 2 is included in Eq.(1) and the state and input variables in Eq.(1) are given as follows:

$$x^T = \{V_T \quad a \quad q \quad q \quad d_e\} \tag{2}$$

$$u^T = \{d_{ec} \quad d_T\} \tag{3}$$

Here the aerodynamic coefficients and propulsive coefficients in the system matrices $\{A, B\}$ in Eq.(1) are given in the lookup table, obtained from the flight experiments. For example, the lift coefficient C_L is a function of $\{M, H, a, d_e\}$ where Mach number M, altitude H, angle of attack a, and elevator deflection d_e.

3.2 Gain Scheduled PID Control System Design

In general, the transfer function of a PID controller is defined in the following form:

$$K(s) = K_p + K_d\, s + K_i \frac{1}{s} \equiv \frac{u(s)}{e(s)} \tag{4}$$

where $u(s)$ and $e(s)$ means the input to the plant and the error signal between a reference and a feedback output, respectively. And K_p, K_i, and K_d are the proportional, integral, and derivative gains, respectively. A slightly different equivalent form as another useful expression is

$$K(s) = K_p\left(1 + \frac{1}{T_i s} + T_d\, s\right) \tag{5}$$

where $T_i = \dfrac{K_p}{K_i}$ and $T_d = \dfrac{K_d}{K_p}$. T_i and T_d are known as the integral and derivative time constants, respectively. The parameters of the PID controller K_p, K_i and K_d or K_p, T_i and T_d can be manipulated to produce various response curves from a given process. Finding optimum adjustments of a controller for a given process is not trivial. So in this paper a gain scheduled PID controller is proposed. The controller gains are properly adapted in real time to change of the system performance to satisfy the requirements specified. To accomplish the adaptation of the controller gains, fuzzy logic is introduced. The block diagram of the proposed controller structure is given in Fig. 3.

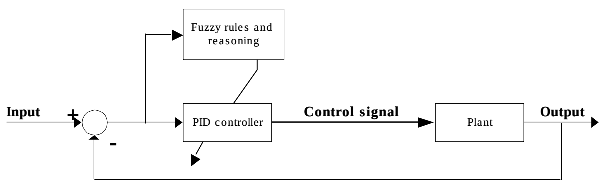

Fig. 3 : PID control system with a fuzzy gain scheduler

The approach taken here is to utilize fuzzy rule and reasoning to adaptively generate the PID controller parameters. It is assumed that the gains K_p and K_d satisfy the conditions:

$$\left.\begin{aligned} K_{P_{\min}} \leq K_P \leq K_{P_{\max}} \\ K_{d_{\min}} \leq K_d \leq K_{d_{\max}} \end{aligned}\right\} \tag{6}$$

where $\{K_{p_{\min}}, K_{p_{\max}}\}$ and $\{K_{d_{\min}}, K_{d_{\max}}\}$ can be obtained experimentally or analytically. It is noted that the parameter limits can be selected to keep on the satisfactory performances within the limits. For convenience, K_p and K_d are normalized by the following linear transformation:

$$K_j^n = \frac{K_j - K_{j_{\min}}}{K_{j_{\max}} - K_{j_{\min}}} \qquad (j = p, d) \tag{7}$$

Note that K_j^n is the range between zero and one. In the proposed PID controller, the integral gain is obtained from the integral time constant determined with reference to the derivative time constant.

$$T_i = k\, T_d \tag{8}$$

Thus the integral gain is obtained by

$$K_i = \frac{K_p^2}{k\, K_d} \tag{9}$$

Now, the parameters $\{K_p^n, K_d^n, k\}$ are determined by a set of fuzzy rules of the form

"If $e(t)$ is A_i and $\dot{e}(t)$ is B_i, then K_p^n is C_i, K_d^n is D_i, and $k = k_i$, for $i = 1,2,\ldots,N$ " (10)

Here, the values of $\{A_i, B_i\}$ are fuzzy sets to be defined in the common triangular membership functions. Also is a constant defined in the singleton membership functions. The membership functions of these fuzzy sets for $\{e(t), \dot{e}(t)\}$ are shown in Fig. 4.

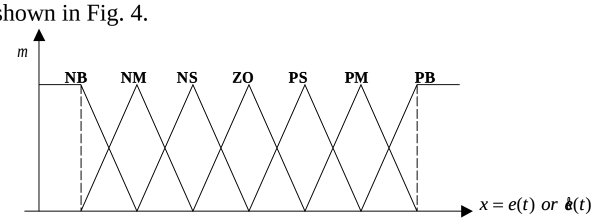

Fig. 4 : Membership functions for $e(t)$ and $\dot{e}(t)$

In this figure, N represents negative, P positive, ZO nearly zero, S small, M medium, B big. Thus NM stands for negative-medium, PB for positive big, and so on. The fuzzy sets of $\{C_i, D_i\}$ may be defined as either B or S and are specified by

$$\left.\begin{aligned} m_S(x) &= -\frac{1}{4}\ln(x) \\ m_B(x) &= -\frac{1}{4}\ln(1-x) \end{aligned}\right\} \qquad (11)$$

where x stands for $\{K_p^n, K_d^n\}$, respectively. The fuzzy rules of $\{C_i, D_i\}$ in Eq.(10) may be simply expressed in the characteristics of the step responses of a typical 2nd-order system. The tuning rules in this study are extracted from the designer's experiences obtained from the classical design of the automatic landing maneuver. Especially, whether the integral action should be strong or weak is determined by the well-known Ziegler-Nichols PID tuning rule. In this design, k is the parameter related with the tendency of integral action. This is determined from the singleton membership function shown in Fig. 5. It is noted that the parameter k from Fig. 6 may be properly corrected in the control loop of automatic landing system.

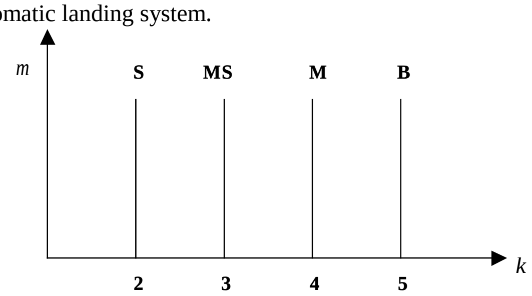

Fig. 5 : Singleton Membership Function

The truth value (m_i) of the i-th rule in Eq.(10) is obtained by the product of the membership function values in the antecedent part of the rule:

$$m_i = m_{A_i}(e(t)) \cdot m_{B_i}(\dot{e}(t)) \qquad (12)$$

where m_{A_i} is the membership function value of the fuzzy set A_i given a value of $e(t)$, and m_{B_i} the membership value of the fuzzy set B_i given a value of $\dot{e}(t)$. The implication process of a fuzzy rule along with Eq.(11)-(12) determines the values of $\{K_P^n, K_d^n\}$ for each rule from their corresponding membership functions. By using the membership functions in Fig. 5, it should be satisfied:

$$\sum_{i=1}^{N} m_i = 1 \qquad (12)$$

Then, the defuzzification yields the following conditions:

$$\left.\begin{aligned} K_P^n &= \sum_{i=1}^{N} m_i\, K_{P_i}^n \\ K_d^n &= \sum_{i=1}^{N} m_i\, K_{d_i}^n \\ k &= \sum_{i=1}^{N} m_i\, k_i \end{aligned}\right. \qquad (13)$$

Once $\{K_p^n, K_d^n, k\}$ are obtained, the PID controller parameters are calculated from the following equations that are due to Eq.(7)-(9):

$$K_j = (K_{j_{\max}} - K_{j_{\min}})K_j^n + K_{j_{\min}} \qquad j = p, d \qquad (14)$$

3.3 Stability Analysis

In a control system design, first of all, the system stability should be guaranteed. When the fuzzy logic is a part of the control system, it seems hard to prove the system stability because this is a nonlinear system. The gain scheduled PID controller designed in this paper is a class of nonlinear system because the PID controller properly adapts their gains in time according to variation of the performance. Hence it is difficult to prove the stability of the closed-loop system. However, in qualitatively speaking, the gain scheduled control system in this paper guarantees stability because the gain limit of PID is obtained from the root-locus in which the closed-loop system should be stable. This means that the mild start-up transients may be tolerable for this design problem. If wild start-up transients happen, instability of the system performance might be monitored. It is noted that this monitoring system is not yet involved in this system.

4. SIMULATION AND EVALUATION

In this section, the automatic landing guidance and control system designed for the longitudinal motion in the gain scheduled PID controller is simulated in 6DOF nonlinear simulation model. Here the elevator actuator model is included as a simple time-delay model and the throttle input(%) is transformed to thrust(lb) along with the delay effect. Also the actuation limits of the actuators are considered: $\pm 20\,\deg$ for elevator and 2~90% throttle setting. The associated airplane initially has the conditions of the straight level flight at 1500 ft altitude and 250 ft/s airspeed, and starts the approach and landing maneuver. The time responses of the guidance and control system for the automatic approach and landing maneuver are given in Fig. 6. From the pictures of the time responses, it is observed that the glide slope capture is achieved at less then 50 sec after the automatic landing logic on. The flare starts at 110 sec and the smooth touchdown takes place at less then 130 sec. During the approach and landing maneuver, the design results almost satisfy the design requirements except the moment of flare start. From the flight mechanics, just after accomplishment of the glide slope capture, the angle of attack gets reduced slightly because of the pitch angle change. It may change the airspeed to increase but the velocity feedback loop remains the airspeed unchanged with 250 ft/sec by reducing the throttle change. Also, adaptation of the PID gains for the glide slope capture and flare maneuver is shown as a typical example in Fig. 7. From the results, it is shown that the gains of PID controller are being properly adapted in time. The gain change of the PID controller takes place abruptly at the transient time period because of the big change of the airplane states from trim values. Because of the flare logic on, it is shown that the PID controller for flare logic adapt their gains properly in time.

5. CONCLUSION

So far the adaptive gain scheduled PID control law is designed for the automatic landing maneuver in ILS. In a practical point of view, PID control law is maintained as a base logic. For the adaptive gain scheduler of the PID controller, fuzzy logic is introduced. To illustrate the successful achievement of automatic landing maneuver, numerical simulation based on the 6DOF nonlinear model of the associated airplane is carried out. It is observed from the simulation results that the automatic landing maneuver in longitudinal axis is satisfactory with proper adaptation of the PID gains to variation of the performance.

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