VI IFSA World Congress, São Paulo, Brazil, 1995, Vol I.

Improved Automatic Landing by Fuzzy Sliding Mode Control

F. Mora-Camino*†, A.K. Achaibou*, R. Asep*†, T.J. Shen*†
(*)Laboratoire d'Architecture et d'Analyse des Systèmes du C.N.R.S.
7, Avenue du Colonel Roche, 31077 Toulouse Cedex - France
(†)Ecole Nationale de l'Aviation Civile
7, Avenue Edouard Belin, 31055 Toulouse Cedex - France
e-mail: mora@laas.fr

Abstract : We consider the problem of the control of the flight path of a landing aircraft. This nonlinear control problem is analyzed from a practical point of view, the limitations of its present solution are discussed as well as the usefulness of introduction of fuzzy concepts.

1. Introduction

In this communication we consider the problem of the control of the flight path of a landing aircraft. This nonlinear control problem is analyzed from a practical point of view, the limitations of its present solution are discussed as well as the usefulness of introduction of fuzzy concepts. Then a new control law design approach based on the combined application of fuzzy logic and nonlinear methods (model inversion and sliding mode techniques) is proposed to improve the efficiency of the existing automatic landing systems. The proposed solution is evaluated by numerical simulation.

2. The Problem Considered

In this communication we consider the problem of the design of autoland systems for civil transportation aircraft. One of the main goals of flight control technology has been to design all-weather automatic landing systems (CAT III in the ICAO terminology). The achievement of this goal has turned possible the landing of aircraft without visual reference to the runway. This is obtained by an airborne system which receives from a ground based Instrument Landing System(ILS) radio-electric information about lateral(Localizer) and vertical(Glide) deviations from a nominal glide path centered on the runway and of moderate rate of descent(2.5^0 to 3.5^0). This information is then processed by the airborne autoland system which guides the aircraft along the glide path and close to the ground causes its flare out and touch down at an acceptable rate of descent with the right attitude (main landing gears first). This type of system, experimented first during the sixties, has been now used for decades and has been continuously improved over the years while other solutions such as the two-segment approach system and the micro landing system (MLS), have been abandonned. However important difficulties remain and explain why some landings are quite rough, unconfortable for the passengers and damaging for the structure of the aircraft: The radio-electric glide path is not linear and presents imperfections related to the configuration of the ground and to the presence of moving vehicules such as taxiing aircraft and airport service vehicules. At ground level the wind, which is always during the different phases of a flight an important element to be taken in consideration (by the navigation and flight management system), becomes a crucial flight parameter: The detection of important variations of wind speed or wind direction (the "wind-shears") which perturb its aerodynamic field and modify its drag and lift forces right close to the ground. The adequate execution of the flare phase depends on the pre-setting of gains for the control law which depend on the mass centering and inertia of the aircraft which are not exactly known. Modern turbofans present rather long time constants (2 or 3 seconds) and are unable to produce rapid reactions to these varying situations.

3. Classical Solution Approaches

It is well known that the flight dynamics of an aircraft are non-linear, however, the classical approach to design flight control laws has been [1] to linearize and decouple the equations of motion to apply first linear feedback control theory and later linear state space methods. This approach is effective when the aircraft is operating around a slow varying equilibrium situation and when the required actions are small deviations of control surfaces or of the setting of the engines. However since a commercial aircraft has to climb to cruise level, to change repeatedly its heading and to descend for landing, manoeuvers and transients are common situations while important parameters such as mass and wind direction are imperfectly known. So, a lot of effort has been dedicated to overcome the limitations of this approach through the introduction, in general on an empirical ground, of corrections and limitations which denature the original control laws while concurrent objectives have been achieved with more or less success. More recently, nonlinear control techniques have been considered for flight control: Meyer et al.[2] made use of nonlinear transformations to achieve exact linearization of the flight dynamics, Lane and Stengel[3] have designed an inverse control law for decoupling input/output channels, Hedrick and Gopalswamy [4] introduced sliding methods for nonlinear flight control while Larkin [5] was the first to propose the application of fuzzy logic to the design of flight control laws. Each of these approaches present some advantages and some limitations: In general the methods based on inverse dynamics present various problems such as stability of the inner dynamics, speed saturation of the actuators, effect of modelling errors and of external perturbations although they can provide, in nominal conditions, perfect decoupling and desired output dynamics (for instance for an automatic flight path following mode). Sliding methods present a solution for modelling errors and robustness but they introduce a chattering effect on inputs which is not acceptable for flight control applications since structural modes can be activated while control actuators can be submitted to stressing conditions. Also, a direct design of a fuzzy flight control leads to the generation of a large set of rules whose use does not guarantee stability or the absence of a marked oscillatory behaviour.

4. The Proposed Solution Approach

The system under study presents three entries (flap deflection, elevator deflection and throttle setting) and three types of outputs (trajectory variables, speed and attitude angles). If we consider that the independent variable is the distance-to-go to the nominal touch down point on the runway, instead of time, the trajectory variables reduce to the height of the aircraft above the runway. With respect to attitude angles, if during the glide phase the angle of attack must remain limited to safe values, during the flare maneuvre the pitch angle becomes the variable of interest. So the system can be considered as square in any phase of the landing operation. In this study we consider that the setting of the throttle is fixed, so that two control channels are considered: aircraft height control from flap deflection and attitude control from elevator deflection. Using the distance-to-go, x, as the independant variable, the longitudinal equations of motion of the aircraft in still air are:

$$\frac{dh}{dx} = \tan(\gamma) \tag{1}$$

$$\frac{d\theta}{dx} = \frac{q}{V\cos(\gamma)} \tag{2}$$

$$\frac{dq}{dx} = \frac{M(V,\delta_e,\delta_f)}{V\cos(\gamma)} \tag{3}$$

$$\frac{d\alpha}{dx} = \frac{[q - L(V,\delta_e,\delta_f) + mg\cos(\gamma)]}{mV^2\cos(\gamma)} \tag{4}$$

where h is the aircraft height, γ is the path angle, V is the speed, θ is the pitch angle, q is the pitch rate, α is angle of attack ($\alpha = \theta - \gamma$), δ_e is the elevator deflection and δ_f the flap deflection, M is the reduced pitch moment and L is the aerodynamic lift while m is the mass of the aircraft. From the above equations we can write:

$$\frac{d^2h}{dx^2} = (1+\tan(\gamma))^2\frac{L - mg\cos(\gamma)}{mV^2\cos(\gamma)} \tag{5}$$

$$\begin{aligned}\frac{d^2\theta}{dx^2} = {} & \frac{M}{V^2\cos^2(\gamma)} \\ & + \frac{q}{V}\frac{L - mg\cos(\gamma)}{mV^2\cos^2(\gamma)}\tan(\gamma)\end{aligned} \tag{6}$$

So if the aircraft height follows a reference trajectory $h_r(x)$ with second order dynamics ω_h, z_h (ω_h = natural undamped frequency ,z_h = damping ratio). L must be such that:

$$\begin{aligned}h_r = {} & \frac{(1+\tan(\gamma)^2)}{\omega_h^2}\frac{L - mg\cos(\gamma)}{mV^2\cos(\gamma)} \\ & + 2\frac{z_h}{\omega_h}\tan(\gamma) + h\end{aligned} \tag{7}$$

In the same way we get for the pitch angle:

$$\begin{aligned}\theta_r = {} & \frac{1}{\omega_\theta^2}(\frac{M}{V^2\cos^2(\gamma)} \\ & + \frac{q}{V}\frac{L - mg\cos(\gamma)}{mV^2\cos^2(\gamma)}\tan(\gamma)) \\ & + 2\frac{z_\theta}{\omega_\theta}\frac{q}{V\cos(\gamma)} + \theta\end{aligned} \tag{8}$$

Since the system (7-8) is inversible $((1+\tan(\gamma))^2/(\omega_h^2\omega_\theta^2 mV^4\cos^3(\gamma)) \neq 0)$ it is always possible to find input linearizing complexes L and M or equivalently δ_e and δ_f. Let $\overline{h}(z)$ and $\overline{\theta}(x)$ be the resulting nominal height and pitch trajectories. Suppose now that mass, centering and inertia are missestimated and that wind and ground effects are no more negligeable. We can write the output accelerations under the form:

$$\frac{d^2y}{dx^2} = f(x) + \Delta f(x) + (g(x) + \Delta g(x))(\overline{u} + \Delta u)$$

or

$$\frac{d^2y}{dx^2} = \frac{d^2\overline{y}}{dx^2} + \Delta f(x) + \Delta g(x)\overline{u} + (g(x) + \Delta g(x))\Delta u$$

with $x^{'} = (h, \theta, q, \alpha)$ $\quad y^{'} = (h, \theta)$ $\quad u^{'} = (\delta_e, \delta_p)$ *so*

$$\frac{d^2\Delta y}{dx^2} = \varphi(x) + \psi(x)\Delta u$$

with

$$\varphi(x) = \Delta f(x) + \Delta g(x)\overline{u}$$

$$\psi(x) = g(x) + \Delta g(x)$$

and

$$\Delta y = y(x) - \overline{y}(x)$$

Let:

$$\sigma = \tau\frac{d\Delta y}{dx} + \Delta y$$

Height and pitch will be in a first order sliding motion if: $\sigma = 0$ with $\sigma \in \Re^2$ and $\tau \in \Re^{+2}$.
Δu should be chosen such that:
$\sigma\dot{\sigma} \leq -\lambda\sigma$ with $\lambda > 0$ to get a sliding motion.
In this case, Δu should be such as:

$$\Delta u = -K\psi^{-1}sgn(\sigma)$$

where K is taken such as:
$\tau(K - \phi_{max}) \geq \Delta\dot{y}_{max}$
and $\lambda = \tau(K - \phi_{max}) - \Delta\dot{y}_{max}$
However, important difficulties arise: ϕ and ψ are not exaltly known and the sign function must be tackled with care since it can induce unacceptable chattering effects. Also, the choice of τ is not independant of the tracking error and of its tendency. So here we propose to use a fuzzy sets representation for the uncertainties about the system dynamics and fuzzy rules to chose the parameters of the considered corrective control (Δu).
A fuzzy supervisor provides a safe estimate of maximum values for φ according to fuzzy sets associated with variations of the parameters (mass (Δm), ground speed (ΔV) and wind speed (Δw)) and with sensitivity functions $f_i = \frac{\partial f}{\partial p_i}$ where p_i is the i^{th} influencing parameter.

Note that if the sliding motion is effective since time t_0, $\Delta\dot{y}_{max}$ is equal to $\mid \Delta\dot{y}(t_0) \mid$. The required time constant for the sliding mode control must be chosen in accordance with the nominal position and speed tracking errors $\overline{y} - y_r$ and $\dot{\overline{y}} - \dot{y}_r$.
Most often, the sign function is replaced by a saturation function such as:

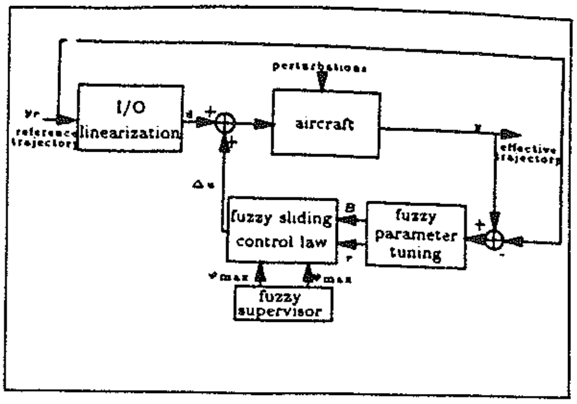

Figure 1: Fuzzy sliding mode control structure

$sat\ x = x/B$ if $|x| < B$
$sat\ x = +1$ if $x > B$ $\quad sat\ x = -1$ if $x < -B$
and B should be chosen in accordance with τ to avoid limit oscillations around the reference values. So a set of fuzzy rules can be established to chose τ and B through scaling, fuzzification and defuzzification techniques. So, we get the sliding mode control structure of Figure 1. Figures 2 and 3 show simulation results obtained using the full flight dynamics of a general aviation aircraft (TB20). Specialized knowledge has been extracted using the ICARE software which allows for varying situations the computation of flight qualities and the testing of different control schemes. The proposed control approach appears to be robust with respect to parameter uncertainties and external perturbations (wind).

5. Conclusion

In this communication the problem of path control for a landing aircraft has been considered. The proposed approach is based on advanced techniques from non-linear control theory and makes use for its effective implementation of the power of fuzzy logic to tackle with uncertain knowledge about the behavior of non-linear systems.

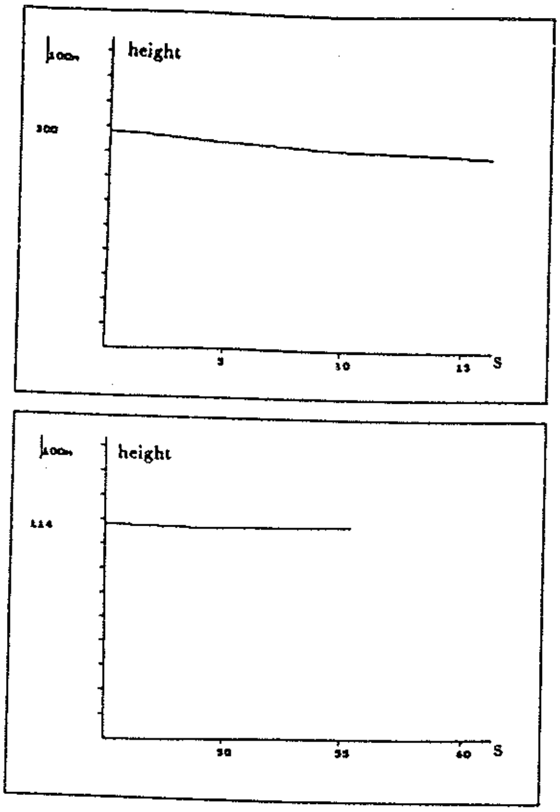

Figure 2: Evolution of height during landing

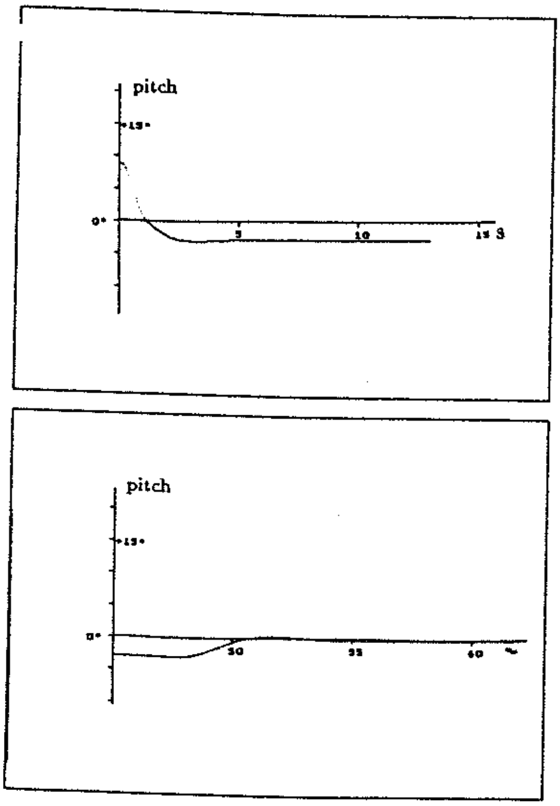

Figure 3: Evolution of pitch angle during landing

REFERENCES

1. McLean, D., " Automatic Flight Control Systems ", Prentice Hall. 1990.
2. Meyer, G., Sui, R. and Hunt, " Application of Nonlinear Transformations to Automatic Flight Control ", Automatica, Vol.20, Jan, 1984, pp. 103-107.
3. Lane, S.H., Stengel , R.F. , " Flight Control Design using Nonlinear Inverse Dynamics ", Automatica, Vol.24, 1988, pp.471-483.
4. Hedrick, J.K., Gopalswamy, S., " Nonlinear Flight Control Design via Sliding Methods ", Journal of Guidance, Control and Dynamics, Vol.13, 1990, pp. 850-858.
5. Larkin, L.I., " Fuzzy Logic Controller for Aircraft Flight Control ", in Industrial Applications of Fuzzy Control, Sugeno M. Editor, North Holland,1985.
6. Palm, R., " Robust Control by Sliding Mode ", Automatica, Vol.30,1994, pp. 1429-1437.
7. Tai, H.M., " Chattering Reduction in Sliding Mode Control via Fuzzy Control Approach ", 9th International Conference on System Engineering, Las Vegas, 1993, pp. 528-532.
8. Mora-Camino, F., Achaibou, A.K., " From Flight Qualities to Flight Control Law Design: A Simulation Tool ", SCS Multiconference, Las Vegas , Jan.1995.
9. Achaibou, A.K., Mora-Camino, F., " A Fuzzy Approach to Flying Qualities Enhancement ", Tempus Impact Workshop, Fuzzy Duisburg'1994.