A LATERAL DIRECTOR AUTOPILOT DESIGN FOR CONFLICT RESOLUTION ALGORITHMS

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Abstract: Conflict resolution, namely avoidance of aircraft crushes, is one of the main problems to be solved in a free flight based air traffic system. The researches on conflict resolution are mainly performed in simulative environments. In the work presented here, a simple lateral director autopilot is designed for conflict resolution studies. Using such a simple autopilot, real aircraft dynamics can be incorporated to conflict resolution techniques and the simulation results can be made closer to real situations.

1 INTRODUCTION

In studies on the problem of conflict resolution, the airplanes are considered to be single points able to go in any direction pointed by the conflict resolution algorithm (Alliot et al., 1992; Bicchi and Pallottino, 2000; Clements, 1990; Erden, 2001; Erden, 2002; Petrick and Felix, 1998; Pappas, 1997; Tomlin, 2000). These applications are based on the assumption that the aircrafts can be piloted in any commanded direction, which is not the case in reality. It is possible that the results of conflict resolution studies might be made closer to reality by using some simplified aircraft dynamics and autopilots. In this study a simple lateral autopilot (Rauw, 1998; Sachs, 1999) is designed for conflict resolution studies in order to serve as an interface between the dynamics and the guiding mechanisms.

2 LINEARIZED LATERAL DYNAMICS OF AIRCRAFT

The linearized lateral dynamics equations are given as follows (McLean, 1990):

$$\begin{aligned}
\dot{\beta} &= Y_v\beta - r + \frac{g}{U_0}\cos\gamma_0\phi + Y^*_{\delta_r}\delta_r \\
\dot{p} &= L'_\beta\beta + L'_p p + L'_r r + L'_{\delta_a}\delta_a + L'_{\delta_r}\delta_r \\
\dot{r} &= N'_\beta\beta + N'_p p + N'_r r + N'_{\delta_a}\delta_a + N'_{\delta_r}\delta_r \\
\dot{\phi} &= p + r\tan\gamma_0 \\
\dot{\psi} &= r\sec\gamma_0
\end{aligned} \tag{1}$$

In these equations U_0 denotes the speed of the aircraft in the x axis direction of the aircraft body frame, pointing forward out of the nose of the aircraft. The subscript 0 shows that this speed is used as the trim (linearization) condition. β denotes the sideslip angle, namely it is an indication of the angle between the x axis of the body frame and direction of flight in the lateral plane. It is given by ($\beta = v/U_0$) for small β values, where v stands for the velocity component of the aircrfat in the y direction of the body frame, pointing out through the right wing. If β is not zero, then the aircraft nose direction is not pointing to the direction of flight in the lateral plane. p and r denote the angular velocities (roll and yaw rates) of the aircraft with respect to the x and z axis of the body frame; and ϕ and ψ are the corresponding roll and yaw angles. δ_a and δ_r stand for the aileron and rudder deflections, respectively. These two are used as the control parameters of the lateral dynamics. γ_0 is the angle between the relative wind (the direction of flight) and the horizontal plane (McLean, 1990, p.36). The subscript 0 denotes the value used for trimming. The primed stability derivatives appearing in the equations are dependent on some parameters of the aircraft (surface area of the wing, mean aerodynamic chord, wing span), density of air, and aerodynamic coefficients of the aircraft that are obtained from wind tunnel tests. (McLean, 1990, pp.51-55; Stevens and Lewis, 1992, pp.65-80)

In the simulations of this research a very large, four-engined, passenger jet aircraft, named Charlie, is used. The stability derivatives for lateral motion are given in Eq 2. These values are given for a flight condition of $U_0=158m/s$, $\gamma_0=0^0$, in a height level of *6100m*. These data are taken from (McLean, 1990, pp.559-561).

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$$\begin{array}{ll} Y_v : -0.082 & L'_{\delta_r} : 0.15 \\ Y^*_{\delta_r} : 0.014 & N'_\beta : 0.42 \\ L'_\beta : -2.05 & N'_p : -0.07 \\ L'_p : -0.65 & N'_r : -0.14 \\ L'_r : 0.38 & N'_{\delta_a} : 0.018 \\ L'_{\delta_a} : 0.13 & N'_{\delta_r} : -0.39 \end{array} \quad (2)$$

When these stability derivatives are substituted in Eq.1, the A and B matrices of the linear system,

$$\bar{x} = \begin{bmatrix} \beta \\ p \\ r \\ \phi \\ \psi \end{bmatrix} \qquad \dot{\bar{x}} = A\bar{x} + B\bar{u} \qquad u = \begin{bmatrix} \delta_a \\ \delta_r \end{bmatrix} \quad (3)$$

are as follows:

$$A = \begin{bmatrix} -0.082 & 0 & -1 & 0.062 & 0 \\ -2.05 & -0.65 & 0.38 & 0 & 0 \\ 0.42 & -0.07 & -0.14 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \end{bmatrix} \qquad B = \begin{bmatrix} 0 & 0.014 \\ 0.13 & 0.15 \\ 0.018 & -0.39 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \quad (4)$$

3 STRUCTURE OF THE LATERAL DIRECTOR AUTOPILOT

Control of the lateral motion of aircraft is managed by manipulating the roll angle with the aileron deflections. Therefore, Roll Attitude Hold mode (RAH) is the basic autopilot mode for lateral autopilots. The deviation of the actual roll angle from the desired roll angle is fed to the ailerons. Heading Hold mode (HH) is the lateral autopilot mode that functions to maintain a certain heading of the aircraft. It uses the difference between the actual yaw angle and desired yaw angle as the feedback. This feedback is used to determine the magnitude of the roll angle necessary to manage the desired heading of the aircraft. Then it uses the RAH as the inner loop to sustain that roll angle. Besides these two modes, turn-coordinator is another important part of the lateral autopilot. During turnings of aircraft an undesired sideslip angle may occur if the flight is not coordinated. The function of turn-coordinator is to suppress the sideslip angle with appropriate deflections of rudder. Fig. 1 shows the block diagram of the described lateral autopilot model.

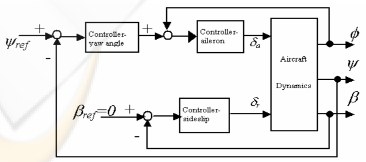

Figure 1: Basic lateral autopilot block diagram

4 TURNING AND COORDINATED TURN

The basic maneuver in lateral motion is the turning maneuver in constant level. In this maneuver the aircraft maintains a bank angle (roll angle). Since the body frame is banked with respect to the Earth fixed frame the lift force in the direction of (–*z*) axes of the body frame (opposite to the gravity direction if it is not banked) is also banked. The horizontal component of the lift force maintains the centrifugal force (f_c) necessary for turning, and the vertical component balances the weight. The situation is shown in Fig. 2.

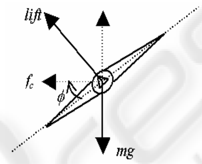

Figure 2: The centrifugal force due to banking of the lift force

An analysis of Fig.2 with the physical laws relating the centrifugal force to the turning radius will reveal that, for a constant speed flight with velocity U_0, the bank angle required for a turning of w radians per second is given with the formula in Eq. 5. This formula shows that a larger banking is required for a sharper turn.

$$\phi = tan^{-1}\left(\frac{U_0 w}{g}\right) \quad (5)$$

Due to the banking of the lift force, its vertical component decreases and is no more sufficient to balance the weight. More deflection of the elevator is needed for compensating the decrease in the vertical component; otherwise the aircraft will loose height. This is achieved by the turn-compensator in lateral autopilots. In the analysis above and in the simulations of this research it is assumed that the compensation for the loss of lift is achieved by a hypothetical turn-compensator. Therefore, the vertical component of the lift force is always equal to the weight, sustaining the aircraft stay in the same level in any maneuver.

A turn is said to be ‘coordinated’ when the lateral acceleration and the sideslip velocity (v), hence the sideslip angle (β), are zero. The condition for a coordinated turn is that the rate of change of the sideslip angle ($\dot{\beta}$) is zero. The necessary condition for that is given by, (McLean, 1990, p.335).

$$r = \frac{g}{U_0}\sin(\phi) \quad (6)$$

In any turn sideslip angle occurs if the rate of yawing (r) is different from the value given by Eq.6. The turn will not be coordinated in that case. If a turning is not coordinated the derivations made on Fig. 2 will not be valid, because the velocity vector and the heading of the aircraft will not be pointing to the same direction. The autopilot designed in this work has the sideslip suppressor component as shown in Fig. 1. This suppressor maintains the sideslip angle close to zero during any maneuver with proper rudder deflections. Therefore, in any turn in simulations, Eq.6 is sustained very closely, hence the turns may be considered to be coordinated.

5 DIRECTION CONTROL AND LOCALIZER

In case of coordinated turns, the heading of the aircraft can be taken as the yaw angle. This is equivalent with the sideslip angle, β, being zero. For small bank angles we can drop the 'sin' in Eq.5, and write,

$$\dot{\psi} = r = \left(\frac{g}{U_0}\right)\phi \quad (6)$$

As Eq.6 reveals, the rate of turn of aircraft is approximately proportional to the bank angle. A simple direction controller for the aircraft can be in the form,

$$\phi_{comm} = K_{\psi}(\psi_{ref} - \psi_{act}) \quad (7)$$

For this control law, the 'controller-yaw angle' block in Fig. 1 should be filled with K_{ψ}.

Localizing the aircraft in a desired direction is the main concern for lateral motion control systems. When an aircraft approaches to the airport for landing, it should have been aligned to the direction of runway. VHF-omni range (VOR) navigation is the most commonly used system for this purpose. Fig. 3 shows a graphical representation of the system.

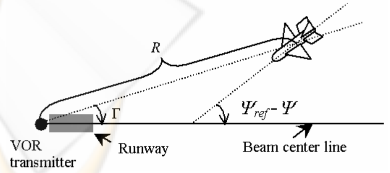

Figure 3: Graphical representation of VOR system

VOR navigation system makes use of the radio navigation systems to generate the steering commands to put the aircraft in the runway's bearing direction. (Nelson, 1998, pp.314-318; McLean, 1990, p.381). The information of $(\Psi_{ref} - \Psi)$ and R are used to generate the angle Γ. The output signal of the VOR transmitter is proportional to the angle Γ, and this signal is used to generate the Ψ_{com} command for the director autopilot to make the Γ angle zero.

6 DESIGN OF LATERAL DIRECTOR AUTOPILOT

The aim in this section is not to design a sophisticated lateral autopilot, rather, to design a suitable one sufficient to incorporate the linearized lateral dynamics of an aircraft with any conflict resolution algorithm. The RAH and HH modes of the lateral autopilot will be incorporated in PID controllers. There will be a sideslip suppressor to strengthen the coordinated turn assumption, and the principles of the VOR navigation system will be utilized in a modified form.

In more concrete terms, the aim can be stated as 'to design an autopilot to put the aircraft in any direction in its flight level'. It is assumed that the position and heading of the aircraft, and the direction it should go are input to the control system, as shown in Fig. 4.

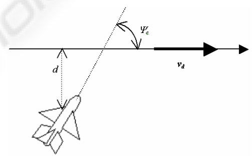

Figure 4: Position of the aircraft and the direction it should go in

What differs the situation in Fig. 4 from the situation in Fig. 3 is that there is no runway, no VOR transmitter, and no radio signal communication. The data for the reference direction is already available in the aircraft from the conflict resolution algorithm without a communication process. Since there is no VOR transmitter it is meaningless to use an angle of Γ as in Fig. 3. It is more practical to use the information of d and $\boldsymbol{v_d}$. Any ordered two points in space determines a directed line. Let us denote this direction with the vector $\boldsymbol{v_d}$ and name it as the 'direction of the line'. $\boldsymbol{v_d}$ gives the information of reference yaw angle. The difference between the reference yaw and actual yaw of the aircraft will be one of the control signals of the director. When the heading of the aircraft is in the direction of $\boldsymbol{v_d}$, the line aircraft follows will be parallel to the reference directed line. However, these two lines are desired to be coincident, not to be in parallel. Therefore the information of d should be utilized to coincide the path of the aircraft with the reference line. The second control signal of the director will be *d*. The controller should manage to make ψ_e and *d* zero simultaneously. In the director, the two control signals produce two aileron deflection (δ_a) commands and these are fed to the dynamics of the aircraft with a weighted sum. The block diagram is given in Fig. 5.

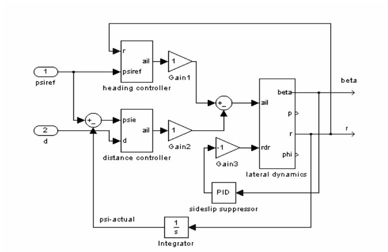

Figure 5: Block diagram of the lateral director

The three main parts of the lateral director autopilot are seen in Fig. 5: Heading controller, distance controller, and sideslip suppressor. The aileron deflection command of the heading controller is multiplied by a weight factor and added to the command of distance controller, which is also multiplied with a negative weight (these weights are arranged to be *1* for the aircraft used in simulations). These weighting factors may be obtained by ad-hoc methods for different aircrafts. The rudder deflection should be negative in order to suppress a positive sideslip angle. PID controllers are used for all control blocks. The sideslip suppressor is simply a PID controller. The heading controller and distance controller blocks are shown in Fig. 6.

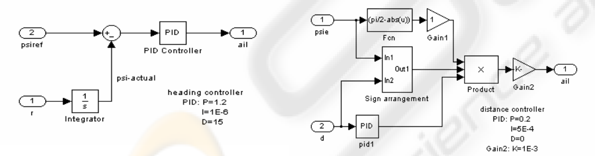

Figure 6: Block diagrams of the heading and distance controllers

The PID parameters of the heading controller are determined by ad-hoc methods. The distance controller takes the error yaw angle (psie) with the distance (d) and generates an aileron command. The parameters of the PID controller and the gains in distance controller are obtained again by ad-hoc methods. In fact the controller is not a PID but a PI controller since the D parameter is zero. The function block labeled as 'Fcn' determines the distance command according to the heading of the aircraft with respect to the reference direction. Considering Fig. 4., when the ψ_e is near 90^0 there is not much need for aileron deflection to decrease the distance, because the aircraft is already heading in the direction to decrease the distance. On the other hand it needs a strong aileron deviation when the angle ψ_e approaches to zero. The sign arrangement block is necessary for arrangement of sign of distance. When the aircraft passes to the other side of the directed line (refer to Fig. 4) the sign of the distance becomes negative. The initial sign of the distance should be determined properly according to the aircraft being above or below the line, and consistency should be attained so that the system works properly in any configuration.

The outputs of the lateral director are taken as the yaw angle rate (*r*) and the sideslip angle (β). These are the necessary information to determine the path the aircraft follows in the two dimensional lateral plane. Although the sideslip angle is very close to zero as a result of the sideslip suppressor, this small value is still used in simulations. The yaw angle of the aircraft is simply the integral of the yaw rate. The aircraft flies with constant speed in the direction of $\psi_{actual}+\beta$. The subsection performing these calculations is called the 'position tracker'.

7 A SAMPLE RESULT

The integration of the autopilot, dynamics of the aircraft and the position tracker is shown in Fig. 7, with a plot of the route that the aircraft follows in an example situation. In this example situation, the commanded directed line is the *y=0* line with the direction of increasing *x*. Accordingly, the psiref command is made $\pi/2$ taking the *+y* direction as the north. The *d* command is equal to the y position of the aircraft. All the ad-hoc parameter arrangements are made considering the configuration in Fig. 7. The path is arranged to be fast enough to catch the directed direction with little overshoot.

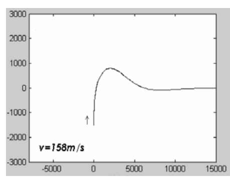

Figure 7: Autopilot, lateral dynamics, and position tracker system; the path followed by the aircraft for a 90^0 right turn in 1500m ahead

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