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NONLINEAR INVERSE DYNAMIC CONTROLLER FOR THE CONFLICT RESOLUTION OF FREE FLYING AIRCRAFTS

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ABSTRACT

The problem of congestion in air traffic route due to the development of today's booming air traffic can be solved by the concept of Free Flight. An aircraft under free flight condition is prone to conflicts with other aircrafts. The conflict detection and resolution of a free flying aircraft is considered in this paper. By considering the various modes, the aircraft is modelled in hybrid form based on conflict free maneuvrings. The control of lateral dynamics of a mode based flight is addressed in this work. A control law for velocity, heading angle and inertial position tracking is developed using Nonlinear Inverse Dynamic controller.

KEYWORDS: Conflict Detection, Free Flight, Hybrid Systems, Nonlinear Inverse Dynamics, Resolution

INTRODUCTION

Air traffic all over the world is growing at a rapid rate. This leads to the problem of congestion in air traffic routes. In order to solve this congestion, today’s air traffic controllers provide ground holds and airborne delays. This built in delays reduces the efficiency of our air traffic system and creates inconvenience to passengers as well as the flight crew. The structure of today’s air traffic controller (ATC) is blamed for all these delays. Wholly centralized control is adopted in our ATC systems now. The information from aircrafts is sent to a humanly operated air-traffic control station; they manually reroute the aircraft along certain predefined well-travelled routes using ground based navigation and surveillance equipment; thus avoiding conflict between aircrafts. As the air-traffic becomes congested, the workload of air-traffic controllers increases. Since the air traffic controllers detour the aircraft through predefined routes, the aircraft cannot fly along a route which ensure short flight time, minimum fuel consumption and inclement weather avoidance.

The idea of *free flight* in which each aircraft is free to decide its own route is a potential solution to the problem of air traffic congestion. The only condition for free flight is that the aircraft should keep at least a minimum distance between other aircrafts. In free flight scenario the pilot is free to choose their own routes, altitude, and speed. Several new technologies now available are fuelling a change in current air traffic management leading to the concept of *free flight*. Instead of a centralized control as used by current ATC systems, free flight follows a decentralized control scheme. Techniques like Global Positioning System (GPS) and a data link communication protocol called Automatic Dependent Surveillance (ADS) supports the new control scheme.

While talking about free flight an important term to be discussed with is conflict detection and resolution. In the aviation environment, each aircraft is surrounded by two virtual cylinders, the protected zone and alert zone [1]. The radius and height of the protected zone depends on some separation standards; the size and shape of the alert zone depends on various factors including airspeed, altitude, accuracy of sensing equipment, traffic situation, aircraft performance and average human and system response times. A conflict or loss of separation between aircraft occurs when their protected zones overlap. The system of aircraft is defined to be safe if the aircraft trajectories are such that their protected zones never overlap. Once a conflict is detected, necessary resolution measures have to be adopted to avoid the conflict.

The aircraft in a steady and level flight trajectory needs to maneuvre to another conflict free trajectory (by changing heading angle, velocity or both) when a conflict is detected. Thus the problem of conflict detection and resolution can be modelled as a hybrid system, in which the discrete state (distance between aircrafts) determines the continuous dynamics of the aircraft. A method to synthesize provably safe conflict resolution maneuvres is presented by Claire Tomlin, George J. Pappas, and Shankar Sastry in [1].

Tomlin, Claire, Ian Mitchell, and Ronojoy Ghosh present the problem of generating provably-safe conflict resolution maneuvres for aircraft in uncertain environments [2]. The time at which the maneuvres have to be initiated so that the conflict is avoided is also an important aspect in free flight scenario. Baojun Huang, Rui Zhou, Xiaohao Xu in [3] intend to provide the methods of computing the optimal time for conflict detection and resolution. Another technique of potential-field models by which aircraft may simultaneously and independently determine collision-free routes in a free flight operational environment is discussed in [4].

The concept of free flight is only realizable if the information about the neighbouring aircraft is made available. There are many modern technologies which help in the identification and state estimation of aircrafts in the vicinity. In [5] the authors present an Automatic Dependent Surveillance - Broadcast (ADS-B) which allows aircraft to broadcast identification, state, and intent information to neighbouring aircraft and nearby ground stations.

Conflict resolution by means of rerouting the flight paths which can be realized by sufficient maneuvring of the aircraft has been discussed in the literature. But the controllers required by aircraft's autopilot which enable the aircraft to take different maneuvring and desired trajectory tracking are not dealt with adequately. For the tracking of required heading angle and velocity in each mode of flight, suitable controllers are required.

In this paper, Nonlinear Inverse Dynamics (NID) control methodology [6] has been applied to achieve suitable maneuvring and desired trajectory for free flying aircraft. The designed control law has been applied to all the flight modes in order to have conflict free path. Simulation results that verify the performance are also presented. By incorporating a proper sequence of each discrete flight mode, this control methodology is capable of ensuring a conflict free path.

MODELLING OF CONFLICT RESOLUTION MANEUVRES

Hybrid automata are systems which exhibit both continuous state dynamics and discrete-state dynamics. In the conflict resolution problem, the trajectories of each aircraft are assumed to be sequences of flight modes, in which each flight mode has associated to it the continuous dynamics of the composite aircraft system. Our goal is to design conflict-free trajectories for each aircraft in a system of aircraft. Assume that a conflict occurs when a pair of aircraft incurs a lateral spacing of less than 5 nautical miles. Consequently, we surround each aircraft with a 2.5 nautical mile radius disk to represent the protected zone. We assume that each aircraft's desired trajectory is a finite sequence of segments, each corresponding to one of four *flightmodes* [1].

- **Mode 1: Velocity and Heading Hold:** In which the aircraft flies straight and level with a given constant velocity and a constant heading.
- **Mode 2: Velocity Capture, Heading Hold:** In which the aircraft flies straight and level with a constant heading and a velocity profile which is a pre-determined function of time.

- **Mode 3: Velocity Hold, Heading Capture:** In which the velocity is held at a prescribed constant value and the heading is a pre-determined function of time.
- **Mode 4:** ***Transition Mode:*** In which velocity and heading are both pre-determined functions of time.

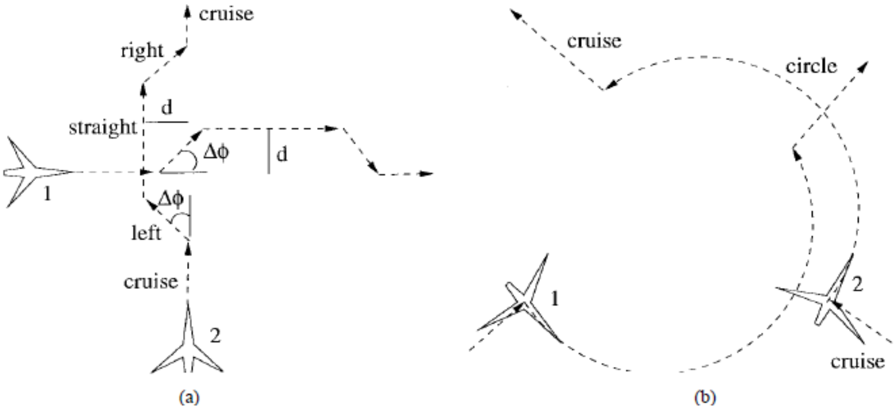

Figure 1: Two Different Conflict Resolution Maneuvres, with Associated Modes

The different flight modes for a conflict free maneuvre are being assigned by considering the discrete states of the hybrid system. For example, consider the two-aircraft examples of Figure 1. In the first, the aircraft avoid each other by transitioning through a sequence of heading changes: “left,” “straight,” “right,” and then back to the original “cruise” mode; in the second the conflict is avoided by both aircraft transitioning to a “circle” mode from a “cruise” mode. Each mode has associated with it the relative aircraft configuration dynamics.

AIRCRAFT MODEL

The dynamics used here are derived by Etkin and Reid in [7]. Assuming linear aerodynamic and inertia effects and an exact representation of gravity effects. The governing differential equations are given by the following system:

Longitudinal Dynamics

$$\dot{u} = \frac{\Delta X}{m} - g\sin\theta \tag{1}$$

$$\dot{w} = \frac{\Delta Z}{m} - g(1-\cos\theta\cos\phi) + u_0 q \tag{2}$$

$$\dot{q} = \frac{\Delta M}{I_y} \tag{3}$$

$$\dot{\theta} = q\cos\phi - r\sin\phi \tag{4}$$

Lateral Dynamics

$$\dot{v} = \frac{\Delta Y}{m} + g\cos\theta\sin\phi - u_0 r \tag{5}$$

$$\dot{p} = \frac{\Delta L}{I_x^{'}} + I_{zx}^{'}\Delta N \tag{6}$$

$$\dot{r} = \frac{\Delta N}{I'_x} + I'_{zx}\Delta L \tag{7}$$

$$\dot{\phi} = p + (q\sin\phi + r\cos\phi)\tan\theta \tag{8}$$

$$\dot{\psi} = (q\sin\phi + r\cos\phi)\sec\theta \tag{9}$$

Forces and Moments

$$\Delta X = X_u(u - u_0) + X_w w + \gamma_1(\delta_r, \delta_e) \tag{10}$$

$$\Delta Y = Y_v v + Y_p p + Y_r r + \gamma_2(\delta_r) \tag{11}$$

$$\Delta Z = Z_u(u - u_0) + Z_w w + Z_{\dot{w}}\dot{w} + Z_q q + \gamma_3(\delta_e) \tag{12}$$

$$\Delta L = L_v v + L_p p + L_r r + \gamma_4(\delta_r, \delta_a) \tag{13}$$

$$\Delta M = M_u(u - u_0) + M_w w + M_{\dot{w}}\dot{w} + M_q q + \gamma_5(\delta_e) \tag{14}$$

$$\Delta N = N_v v + N_p p + N_r r + \gamma_6(\delta_r, \delta_a) \tag{15}$$

where *u:* velocity along *x* direction in body axes, *v:* velocity along *y* direction in body axes, *w:* velocityalong *z* direction in body axes, *p:* roll rate, *q:* pitchrate, *r:* yaw rate, *Φ:* bank angle, *Ψ:* yaw angle, *θ:* pitch angle, $\delta_T$thrust, δ_e: elevator angle, δ_r: rudderangle, δ_a: aileron angle, *g:* acceleration due to gravity, u_0: initial value of *u*, ($X_{(.)}$, $Y_{(.)}$, $Z_{(.)}$, $L_{(.)}$, $M_{(.)}$, $N_{(.)}$): given constants for the aircraft, and $\gamma_1 \ldots \gamma_6$:known functions of the control inputs. Let the aircraft position (in inertial coordinates) in terms of the state variables $x = [u\ v\ p\ r\ \Phi\ \Psi\}]^{T}$:

$$\dot{x}_{inertial} = u\cos\psi - v\sin\psi\cos\phi \tag{16}$$

$$\dot{y}_{inertial} = u\sin\psi + v\cos\psi\cos\phi \tag{17}$$

REVIEW OF NON-LINEAR INVERSE DYNAMICS CONTROLLER

Since the controller design is based on NID, this section reviews the theory behind this methodology [7]. Consider the system of the form,

$$\dot{x} = A(x) + B(x)u \tag{18}$$

$$y = C(x) \tag{19}$$

where A(*x*) = (n x 1) vector, B(*x*) = (n x m) matrix, C(*x*) = (m x 1) vector. Since the aircraft dynamics take the general non-linear form,

$$\dot{x}' = f(x', u') \tag{20}$$

$$y = Cx^{'} \tag{21}$$

where $x^{'}$ = (n x 1) state vector, $u^{'}$ = (m x 1) control vector, y = (l x 1) constant matrix. The aircraft dynamics are linearised using input output feedback linearization method. This involves the construction ofthe inverse dynamics of (18) and (19) by differentiating the individual elements of ‘y’ a sufficient number of times until a term containing a ‘u’ appears. Since only ‘m’ outputs can be controlled independently with ‘m’ inputs, it will be assumed that dim(y) = dim(u) = m. Introducing the kth order differentiation operator, $L_A^k(\bullet)$, such that,

$$L_A^k(x) = \left[\frac{\partial}{\partial x} L_A^{k-1}(x) \right] A(x) \tag{22}$$

$$L_A^0(x) = x \tag{23}$$

Simplifies the subsequent development. Using this notation to differentiate the ith component of ‘y’ yields,

$$y_i^{(d_i)} = C_i x^{(d_i)} = C_i \left[\frac{\partial}{\partial x} L_A^{d-1}(x) \right] A(x) + C_i \left[\frac{\partial}{\partial x} L_A^{d-1}(x) \right] B(x) u \tag{24}$$

where d_i is the order of the derivative of y_i necessary to ensure that,

$$C_i \left[\frac{\partial}{\partial x} L_A^{d-i}(x) \right] B(x) \neq 0 \tag{25}$$

After differentiating the ‘m’ elements of ‘y’ repeatedly, the output dynamics can be represented as,

$$y^{(d)} = \begin{bmatrix} y_1^{(d_1)} \\ y_2^{(d_2)} \\ \cdot \\ \cdot \\ \cdot \\ y_m^{(d_m)} \end{bmatrix} = \begin{bmatrix} C_1 L_A^{d_1}(x) \\ C_2 L_A^{d_2}(x) \\ \cdot \\ \cdot \\ \cdot \\ C_m L_A^{d_m}(x) \end{bmatrix} + \begin{bmatrix} C_1 \frac{\partial}{\partial x} L_A^{d_1-1}(x) \\ C_2 \frac{\partial}{\partial x} L_A^{d_2-1}(x) \\ \cdot \\ \cdot \\ \cdot \\ C_m \frac{\partial}{\partial x} L_A^{d_m-1}(x) \end{bmatrix} B(x) u \tag{26}$$

Let,

$$A_i^*(x) = C_i \left\lfloor L_A^{d_i}(x) \right\rfloor \tag{27}$$

$$B_i^*(x) = C_i \left[\frac{\partial}{\partial x} L_A^{d_i-1}(x) \right] B(x) \tag{28}$$

$$y^{(d)} = A^*(x) + B^*(x) u \tag{29}$$

A sufficient condition for the existence of an inverse system model to (18) and (19) is that B^* in (29) be non-singular. If this is the case, then the inverse system model takes the form,

$$\overset{\bullet}{x} = \left\lfloor A(x) - B(x) F(x) \right\rfloor + B(x) G(x) v \tag{30}$$

where $v=y^{(d)}$ is the input to the inverse system.

$$G=\left[B^*(x)\right]^{-1} \tag{31}$$

$$F=\left[B^*(x)\right]^{-1}A^*(x) \tag{32}$$

Applying the NID control law,

$$u=-F(x)+G(x)v \tag{33}$$

To the original system of (18) and (19) leaves it in the integrator-decoupled form,

$$y^{(d)}=v \tag{34}$$

Setting,

$$v=-\sum_{k=0}^{d-1}P_k y^{(k)}+P_0 w \tag{35}$$

Where $y^{(k)}$ the kth derivative of the output vector y, and the P_k chosen as (m x m) constant diagonal matrices, gives the original system. The decoupled linear, time invariant dynamics is:

$$y^{(d)}+P_{d-1}y^{(d-1)}+P_0 y=P_0 w \tag{36}$$

NONLINEAR INVERSE DYNAMICS (NID) CONTROLLER FOR AIRCRAFT LATERAL MOTION

The division of the entire flight envelope of an aircraft into various modes depending upon other aircrafts in its vicinity has already been explained. On the detection of another aircraft within a predefined range the flight mode has to switch to a conflict free path. An aircraft following a steady and level path indicates mode 1. On the detection of another aircraft, it changes its mode to mode 3 via mode 4, thus following a curved- conflict free path. Once the collision is avoided, it has to be brought back to mode 1 via mode 4. The control δ_T, δ_r and δ_a which controls the aircraft to ensure this conflict free maneuvre are obtained by applying NID control. The input values (δ_T, δ_r, δ_a) computed as:

$$\delta_T=\frac{1}{c_0}\left\{\dot{u}_d+a_1(u_d-u)\right\} \tag{37}$$

$$\delta_r=-\frac{1}{c_1}\left\{\left(g\sin\phi_d-u_0 r\right)-\dot{v}_d+a_1(v_d-v)\right\} \tag{38}$$

$$\delta_a=\frac{c_2}{c_1c_3}\left\{(g\sin\phi_d-u_0 r)-\dot{v}_d-a_1(v_d-v)\right\}+\frac{1}{c_3}\left\{\ddot{\phi}_d+b_1(\dot{\phi}_d-\dot{\phi})+b_2(\phi_d-\phi)\right\} \tag{39}$$

where $c_0,\dots,c_5$: given constants for the aircraft [7].

Where u_d and v_d are desired values and We design Φ_d in terms of $\dot{\psi}_d$,Ψ_d,Ψ:

$$\phi_d=\frac{1}{2}\sin^{-1}\left(\frac{2u_0}{g}\dot{\psi}_d\right)+K_p(\psi_d-\psi) \tag{40}$$

The desired bank angle for required heading changes is given by (40).

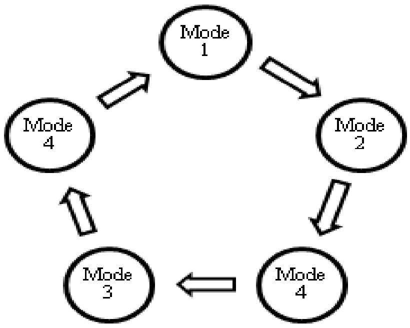

Figure 2: Hybrid Modes of a Free Flying Aircraft

SIMULATIONS AND DISCUSSIONS

Simulation results are presented from Figure 3 to Figure 6. Mode 1 is the altitude, speed and heading holdmode. The aircraft flies straight and level with zero bank angle. This is the normal cruise condition for a commercial transport aircraft. Results in figure 3 show the trajectory and state variables of the aircraft in this mode. In the results it is seen that velocity and heading angle remains constant. An aircraft in free flight condition follow this mode unless a conflict is detected.

In mode 2 the altitude and heading are maintained but the velocity profile is a pre-determined continuous function of time. The aircraft flies straight and level but the velocity varies. This mode helps in velocity capture without deviating from the cruise condition flight path. Figure 4 shows the relevant trajectory and state variables for this mode. Once a conflict has been detected, the flight trajectory has to be switched to this mode so that chance of collision can be avoided. Even if the flight wants to take a manoeuvre for collision avoidance, the heading change can be initiated through this mode only.

In mode 3, the forward speed and bank angle is held at some prescribed constant value depending on the turn radius. The mode is used to capture heading, i.e change from one heading angle to a desired heading angle. The trajectory in this mode is plotted in Figure 5. From the X-Y plot it can be seen that the flight is taking a curved path to avoid conflict.

Mode 4 also can be called as transition mode in which velocity, bank angle and heading are all predefined functions of time. The purpose of this mode is to capture a desired bank angle, velocity and heading simultaneously. Modes 2 and 3 always have to be separated by the transition mode to ensure continuity. This mode is essential for complex manoeuvres because it helps to discretize a space-time trajectory of an aircraft. Figure 6 gives the trajectories in this mode.

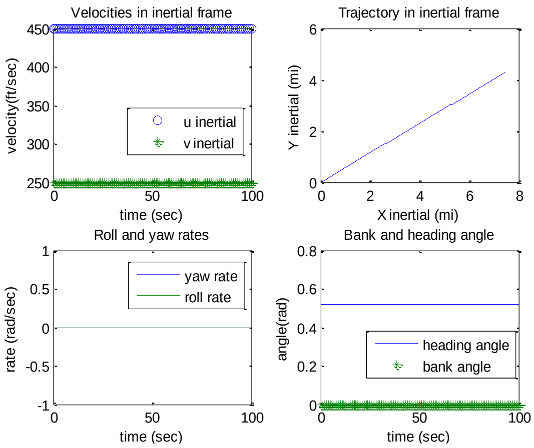

Figure 3: Mode 1 Trajectories

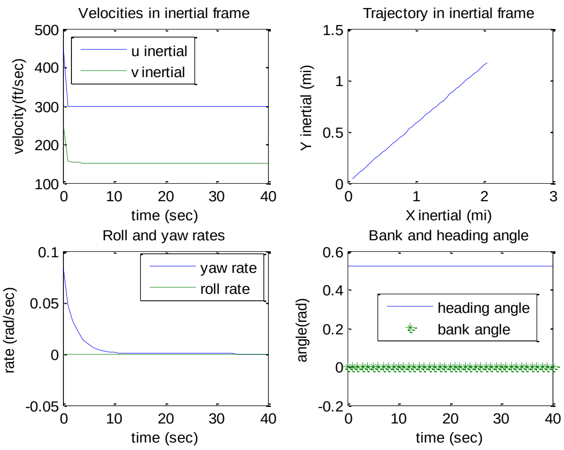

Figure 4: Mode 2 Trajectories

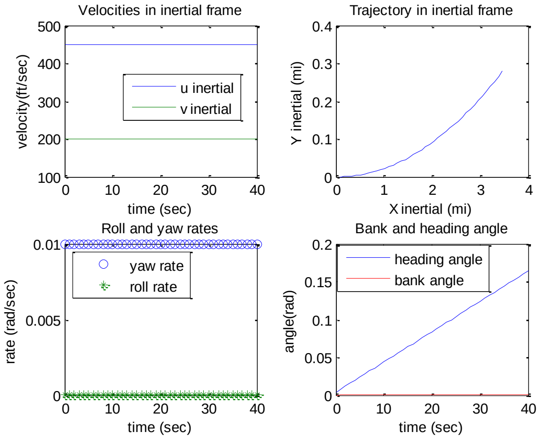

Figure 5: Mode 3 Trajectories

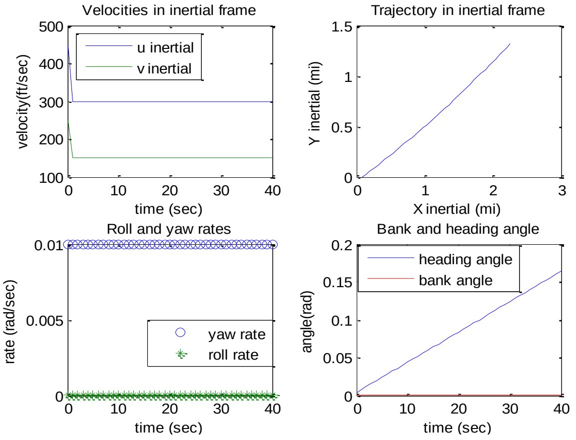

Figure 6: Mode 4 Trajectories

CONCLUSIONS

A control law that is applicable for all flight modes is developed using Nonlinear Inverse Dynamics methodology. Simulation results show that the designed controller is capable of tracking all the four modes involved in ensuring conflict free maneuvre.

The next part of the research will focus on designing a controller that will also incorporate adequate sequencing of each discrete flight mode based on the parameters of the protective zone

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