REQUIRED ACTION TIME IN AIRCRAFT CONFLICT RESOLUTION

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Heming Chen

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Yiyuan Joseph Zhao, Advisor

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Dedication

This work is dedicated to my parents and Yao.

ABSTRACT

Due to limitations in their performance capabilities, aircraft must begin avoidance maneuvers well before specified minimum separation standards are reached. In other words, there is a time ahead of a predicted conflict at which aircraft must start to act. This paper presents the concept and a systematic procedure for determining the REquired ACtion Time, or REACT, for pairwise conflict resolutions. REACT marks the least advance time necessary for successful avoidance maneuvers and defines the minimum lookahead window for reliable trajectory predictions. In this paper, the process of conflict detection and resolution is divided into a series of segments, and typical times associated with these segments are estimated. Pairwise conflicts in different encounter geometries are considered. Aircraft flights are described with a dynamic point-mass model that uses position and velocity components as states, and excess thrust, lift, and bank angle as controls. Motion constraints due to both aircraft performance limitations and passenger comfort considerations are imposed. In resolving a potential conflict, it is assumed that one of heading change, altitude change, or speed change is used. Both cooperative and non-cooperative maneuvers are studied. Uncertainties in onboard trajectory state measurements, pilot response delays and behaviors, as

well as initial aircraft speeds are represented as random variables. Monte-Carlo numerical simulations are conducted to establish trends of REACTs over different encounter angles for every single control authority. The effectiveness of different control authorities in resolving conflicts are compared.

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(C_L, C_D)	(lift, drag) coefficient
D	aerodynamic drag
$D_{\min}$	horizontal separation requirement
g	gravitational acceleration
h	inertial altitude
$H_{\min}$	vertical separation requirement
K	control parameters
L	aerodynamic lift
m	aircraft mass
r	horizontal distance between two aircraft
S	vehicle reference area
T	engine thrust
t	time

V_t	true airspeed
(W_x, W_y)	(east, north) wind component
(x, y)	(east, north) position
γ_a	air-relative flight path angle
μ	bank angle
ν	normalized separation standard
ω	natural frequency in closed-loop response
ψ_a	air relative heading angle measured clockwise from the North
Ψ_a	air relative heading angle between two aircraft
ρ	air density
σ	variance
ζ	damping ratio in closed-loop response
$\bar{(\ )}$	normalized variable
$(\ )_0$	initial value
$(\ )_c$	commanded value
$(\ )_f$	final value
$\dot{(\ )}$	time derivative

Chapter 1

Introduction

In the Air Traffic Control (ATC) system, aircraft must maintain sufficient separations at all times during flight. The Federal Aviation Administration (FAA) defines different minimum separation requirements for different phases of flights. A major task of the air traffic controllers is to enforce these separation standards. This is a considerable undertaking because each day, the nation's ATC system facilitates thousands of commercial flights and enables millions of passengers to travel to their destinations. Air traffic has increased significantly in the last century, and is expected to grow further. In particular, the Next Generation Air Transportation System (NextGen) may need to accommodate up to three times the current traffic level by 2025[1].

This paper examines two fundamental issues in the development of conflict

resolution strategies. Because of limited aircraft performance capabilities, constraints on aircraft flights, and human operator response delays, aircraft cannot change their trajectories instantaneously. Particularly, either one or both aircraft involved in a potential conflict must begin appropriate avoidance maneuvers **well before** specified minimum separation standards are reached. The **first issue** is to determine the least advance time in a potential conflict at which correct avoidance maneuvers **must** begin in order to maintain the minimum separation standards. In resolving a potential conflict, controllers and/or pilots may employ one, two or all three of heading, altitude, and/or speed control authorities. The **second issue** is that under similar conditions, which control authority would be the most effective for resolving a conflict, measured by a small advance time required to resolve the conflict. Solutions of these two questions are highly useful in understanding the scopes and limits of conflict resolution strategies and algorithms. In addition, the required least advance time effectively sets the lower limit on the lookahead window for reliable trajectory predictions.

In the past, practical algorithms have been developed and applied successfully in the ATC system. The Center/TRACON Automation System (CTAS) developed at NASA Ames Research Center[2–5] uses computer algorithms of conflict detection and resolution to resolve aircraft conflicts. By providing flight

advisories of heading, speed and/or altitude instructions, it assists air traffic controllers in ensuring safe separations among all aircraft as well as in constructing a smooth and efficient flow of air traffic. In comparison, the Traffic Alert and Collision Avoidance System (TCAS) was developed for airborne use on individual aircraft[6−9]. TCAS is able to detect potential collision with a nearby aircraft, and to issue maneuver advisories to avoid the collision. In addition, considerable research has been conducted on the analysis and development of algorithms for efficient conflict detection and resolution in different phases of flight, and for various conflict scenarios that involve both two or more aircraft[10−35].

Directly related to the current paper, the concept of required action range is introduced in Ref. 36, where a two-step procedure based on optimization methods is presented. However, the iterative optimization procedure is not convenient to use. In addition, the effects of various uncertainties are not considered. In Refs. 37 and 38, numerical simulations are used to study the required action time and to compare the effectiveness of different control authorities. However, uncertainties in pilot behaviors, navigation system, and surveillance are not addressed either. The concept of required action time is also discussed in Ref. 39.

This paper focuses on pairwise conflict scenarios in order to develop a fundamental understanding of these concepts. The concept of REquired ACtion Time (REACT) is introduced as the least advance time required to successfully resolve

a predicted conflict, and a systematic procedure for estimating REACTs is presented. In this procedure, aircraft flights are described with a dynamic point-mass model reflective of typical commercial transports. Different encounter geometries are examined. In resolving a conflict, it is assumed that a single trajectory control authority of heading, speed, or altitude change is used. A model of closed-loop trajectory tracking is developed with the method of feedback linearization. Motion constraints due to both aircraft performance limitations and passenger comfort considerations are imposed. In particular, representative sources of uncertainties in the conflict detection and resolution process are modeled. Monte-Carlo numerical simulations are then conducted to evaluate the effects of various uncertainties on REACTs. The effectiveness of these different control authorities are compared. Both cooperative and non-cooperative maneuvers are considered.

Chapter 2

The Concept and Components of Required Action Time

In the air traffic system, sufficient separations must be maintained between any pair of aircraft at all times. The specific separation requirements depend on flight phases and the types of aircraft involved. During en route flight, the FAA currently specifies that any two aircraft must be separated by at least $D_{\min} = 5$ nautical miles (nmi) horizontally or $H_{\min} = 1,000$ ft vertically. For the convenience of discussions, the minimum separation requirements are mathematically expressed as

$$\frac{r}{D_{\min}} \geq 1 \quad \text{or} \quad \frac{|\Delta h|}{H_{\min}} \geq 1 \tag{2.1}$$

where r and Δh are respectively the horizontal and vertical distance between two aircraft.

$$\nu = \sqrt{\left(\frac{r}{D_{\min}}\right)^2 + \left(\frac{\Delta h}{H_{\min}}\right)^2} \geq 1 \tag{2.2}$$

In numerical or analytical studies, it is often convenient to combine these two criteria into one ellipsoidal approximation. A pairwise conflict occurs if Eq. (2.2) is violated. The applicable expression in Eq. (2.2) depends on the trajectory control authority used in resolving a conflict.

In practice, the ATC system constantly monitors all aircraft as their flights progress. In order to ensure safe separations among these aircraft, their flight trajectories are predicted and any likely potential conflicts are detected. If a potential conflict is projected to occur beyond a reasonable doubt, aircraft will be directed to start appropriate conflict avoidance maneuvers. Because they cannot make instantaneous trajectory changes due to limitations on their performance capabilities, aircraft should begin conflict resolution maneuvers **after** a potential conflict is detected and **well before** the specified minimum separation standards are reached.

Fig. 2.1 illustrates this concept through a potential head-on conflict and the use of heading control. In this case, in order to maintain the minimum separation, either one or both aircraft must start avoidance maneuvers **before** the minimum horizontal separation distance is reached. The **smallest** advance time $(t_f - t_r)$

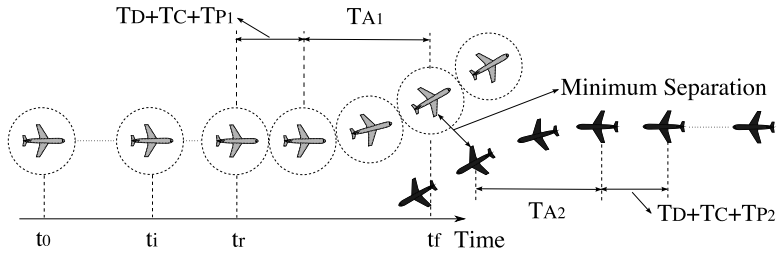

Figure 2.1: Concept of REquired ACtion Time (REACT).

at which correct avoidance maneuvers must begin in order to avoid the potential conflict constitutes the REquired ACtion Time, or REACT. The REACT concept quantifies the minimum time it takes to resolve a pairwise conflict.

Mathematically, the boundary conditions for estimating REACTs can be stated as follows. Initially at some time t_0, two aircraft involved in a potential conflict are approaching each other but their relative separation still far exceeds the minimum standards, or

$$\nu(t_0) > 1, \quad \dot{\nu}(t_0) < 0 \tag{2.3}$$

At some time $t_i > t_0$, the potential conflict is first detected via trajectory predictions. From this time on, predicted fight trajectories of the two aircraft are periodically updated and carefully monitored. At some time $t_r > t_i > t_0$, the potential conflict is considered likely and proper conflict avoidance maneuvers are initiated. Finally, a conflict is considered to be resolved if the relative separation

between the two aircraft is larger than or equal to the specified minimum separation and the rate of separation increases. Mathematically, at the time t_f when the conflict has been successfully resolved

$$\nu(t_f) \geq 1, \quad \dot{\nu}(t_f) \geq 0 \tag{2.4}$$

The conflict detection and resolution process requires surveillance data. Ground-based surveillance currently uses primary and secondary radar systems. In addition, with the increased use of the Global Positioning System (GPS) and digital data link, individual aircraft may periodically broadcast their state information to both ground stations and neighboring aircraft in an Automatic Dependent Surveillance-Broadcast (ADS-B) scheme. The radar cycle is about 5 seconds in TRACON areas and 12 seconds for the en route flight phase. ADS-B has an update frequency of once per second. Airborne-based surveillance can use either airborne radar, ADS-B, or ground-based information sharing system.

In order to develop a systematic procedure for estimating REACTs for various traffic scenarios, the process of conflict detection and resolution is divided into a series of segments. Conflict detection and avoidance may be performed by a ground station, an individual aircraft, or by their appropriate combinations. We first consider ground-based system.

1. **Decision Time**: The surveillance information is processed and/or displayed

to assist controllers and/or Decision Support Tools (DSTs) in making decisions on if there is a potential conflict, when to initiate conflict avoidance maneuvers, and what maneuvers to use. For the purpose of estimating REACTs, the decision process can be described by the amount of time needed to process the information as well as to make the decision: T_D. Normally, the party responsible for making decisions need to monitor and evaluate the traffic for several surveillance cycles. In addition, the decision to act could be made in the middle of a particular surveillance cycle. For consistency in this study, it is assumed that the decision time, T_D, is measured from the beginning of the cycle in which a decision of action is made.

In the current ATC system, controllers need to assess the flights of many aircraft by mentally constructing their future trajectories to detect potential conflicts. The time required for this human decision-making process depends on the traffic density, ambient conditions, location of the region being considered, controller skills, as well as controller personalities. In comparison, computer-based DSTs employ mathematical models to predict future aircraft trajectories and to check for potential conflicts. When a potential conflict is detected, they can calculate alternative trajectories to avoid the conflict. The time needed for DST decisions depends on the algorithms, the amount of computations, and the computer system.

2. **Communication Time**: The communication time, T_C, accounts for the process of giving instructions to the pilots by controllers, and for the pilot to confirm the instructions. This process may contain back and forth clarifications between pilots and controllers. In actual flights, pilots may negotiate with controllers. The time spent on negotiations can be considered part of the decision process.

   The time required for a single communication consists of broadcast time, propagation time, and reception time. The propagation time for voice or data signal to traverse the air media at the speed of light is extremely small compared with typical aircraft flight dynamics, and can therefore be neglected. As a result, the communication time covers the start of the transmission to the complete reception of an intended message, and is proportional to the amount of information communicated divided by the rate of communication.

3. **Pilot Response Delay**: The pilot response delay, T_P, represents the time to comprehend and respond to controller instructions and to physically alter aircraft control effectors while maintaining other nominal duties in flying the aircraft.

4. **Aircraft Maneuver Time**: Once pilot controls are applied, the aircraft

requires finite time to achieve necessary trajectory changes that avoid the conflict. The aircraft maneuver time T_A accounts for the time from the initiation of appropriate control actions by pilots to the time at which the conflict is successfully avoided, as stated in Eq. (2.4).

In a given conflict geometry, the aircraft maneuver time depends the mode of collaboration. Specifically, the two aircraft are cooperative if both maneuver to avoid the conflict, non-cooperative if only one aircraft maneuvers whereas the other maintains its original trajectory, or adversary if one of the aircraft has a failure and thus may move to worsen the potential conflict. The maneuver time also depends on which control authorities are used by individual aircraft, their conflict resolution strategies, their performance capabilities, their initial flight conditions, navigation errors, and pilot behaviors. In addition, the aircraft maneuver time is influenced by disturbances in the flight environment and atmospheric conditions. More importantly, the maneuver time is a direct function of the specified minimum separation standards.

Based the above discussions, REACT is defined as the sum of the four segment times:

$$T_{\text{REACT}} = T_D + T_C + T_{P_1} + T_{A_1} = T_D + T_C + T_{P_2} + T_{A_2} \tag{2.5}$$

Note that while individual aircraft may have different pilot response times and

maneuver times, the total of pilot response delay and aircraft maneuver time remains the same for both aircraft, because a successful conflict resolution is based on the relative separation between the two aircraft, as indicated by Eq. (2.4).

The above division of the conflict detection and resolution process can be simplified to describe airborne-based systems. In particular, the decision time and pilot response delay may be combined, and the communication time can be omitted. However, the basic functions of these segments shall still be present.

The concept of REACT has some important applications. If a conflict is declared early, aircraft will have sufficient times to respond and can employ smooth, gradual maneuvers to avoid the conflict. However, a conflict declared far in advance may not materialize due to uncertainties and the resulting trajectory prediction errors. On the other hand, if the conflict is declared late in the process, the occurrence of conflict is more certain, but the aircraft will have less time to respond and thus may need to make more drastic maneuvers in order to avoid the conflict. If a conflict is declared too late, the aircraft may not have sufficient time to adequately maintain the minimum separation requirements. Desirably, a conflict avoidance maneuver should be initiated at the "right" time. The REACT concept defines the **least** advance time necessary for a successful conflict resolution.

$$t_f - t_r \geq T_{\text{REACT}} \tag{5}$$

In addition, the first instant at which a potential conflict is declared must be sufficiently early. This puts a requirement on the **minimum** lookahead window over which reliable trajectory predictions must be made in order to detect and confirm a potential conflict. In general, the minimum lookahead time for reliable trajectory predictions is determined by their intended applications in DSTs. The maximum lookahead time for trajectory predictions, on the other hand, depend on the propagation of trajectory prediction errors.

Chapter 3

Equations of Motion

In this paper, a dynamic point-mass model is used to describe aircraft motions. Aircraft mass is assumed constant. The equations of motion for a single aircraft are given by[40].

$$m\dot{V}_t = T - D - mg\sin\gamma_a \tag{3.1}$$

$$mV_t\cos\gamma_a\dot{\Psi}_a = (T\sin\alpha + L)\sin\mu \tag{3.2}$$

$$mV_t\dot{\gamma}_a = (T\sin\alpha + L)\cos\mu - mg\cos\gamma_a \tag{3.3}$$

$$\dot{x} = V_t\cos\gamma_a\sin\Psi_a \tag{3.4}$$

$$\dot{y} = V_t\cos\gamma_a\cos\Psi_a \tag{3.5}$$

$$\dot{h} = V_t\sin\gamma_a \tag{3.6}$$

Lift and drag are given by

$$L = \frac{1}{2}\rho V_t^2 S C_L, \quad D = \frac{1}{2}\rho V_t^2 S C_D \tag{3.7}$$

In these equations, trajectory state variables of an aircraft include $[V_t, \psi_a, \gamma_a, x, y, h]^T$ and trajectory control variables are $[\bar{T}, \bar{L}, \mu]^T$, where the normalized excess thrust and normalized lift are defined as

$$\bar{T} = \frac{T - D}{mg} \quad \bar{L} = \frac{L}{mg} \tag{3.8}$$

Aircraft motions must satisfy constraints due to performance limitations, passenger comfort considerations, as well as ATC regulations. General constraints applicable to the process of conflict resolution may be stated as

$$\bar{T}_{\min} \leq \bar{T} \leq \bar{T}_{\max} \tag{3.9}$$

$$C_{L_{\min}} \leq C_L \leq C_{L_{\max}} \quad |\mu| \leq \mu_{\max} \tag{3.10}$$

$$V_{\min} \leq V \leq V_{\max} \quad \gamma_{\min} \leq \gamma \leq \gamma_{\max} \tag{3.11}$$

Appropriate values of these bounds are discussed below when specific trajectory control laws are presented.

Motions of the two aircraft in a potential conflict can be studied by combining the two sets of equations for both aircraft. The complete set of state variables

describing the motions of two aircraft include

$$[V_1, \psi_1, \gamma_1, x_1, y_1, h_1, V_2, \psi_2, \gamma_2, x_2, y_2, h_2]^T \tag{3.12}$$

and controls are

$$[\bar{T}_1, \bar{L}_1, \mu_1; \bar{T}_2, \bar{L}_2, \mu_2]^T \tag{3.13}$$

Then, the relative horizontal and vertical separations for use in Eq. (2.1) can be obtained from

$$r = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2} \tag{3.14}$$

$$\Delta h = h_2 - h_1 \tag{3.15}$$

In addition, the relative heading of the two aircraft can be defined as

$$\Delta\Psi = \Psi_2 - \Psi_1 \tag{3.16}$$

Specifically, $\Delta\Psi_0 = \Psi_2(t_0) - \Psi_1(t_0)$.

Chapter 4

Conflict Geometries and Avoidance Strategies

To obtain numerical solutions, we consider potential conflicts between two aircraft during en route flight. For consistency, it is assumed that the two aircraft are originally flying at the same altitude with similar speeds. Fig. 4.1 illustrates conflict geometries with different encounter angles from zero (trailing) to 180 degrees (head-on). If there were no conflict avoidance maneuvers, the two aircraft would collide at the center point.

To resolve the conflict, one or more of the three trajectory control authorities need to applied: the change of heading, speed, and/or altitude. The three control authorities can be effected by the use of bank angle, thrust and lift respectively.

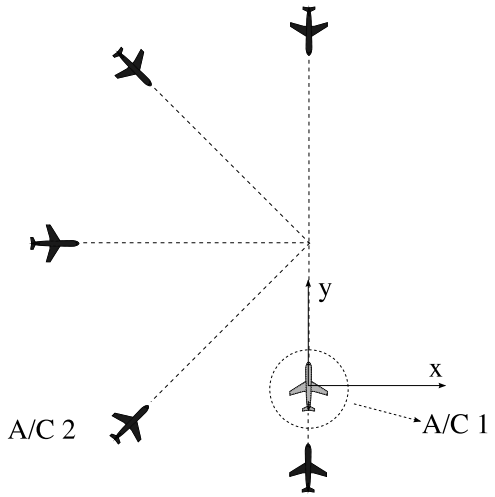

Figure 4.1: Encounter geometries.

When used alone, each control authority has its advantages and limitations. For example, an adjustment in speed requires the least spatial deviations from the original trajectories but it may not be able to avoid a head-on conflict. The change of heading angle can resolve conflicts of different geometries, but it requires a large horizontal space to accomplish. It is also possible to use more than one control authorities at a time. For example, an aircraft could change both heading angle and speed simultaneously to avoid a conflict.

This paper examines on the use of only one trajectory control authority at each time in order to study their fundamental properties. REACTs for each control authority are determined for different encounter geometries and then compared. For each case, the conflict resolution strategy and the corresponding trajectory

tracking logics are defined below.

4.1 Conflict Resolution with Heading Control

In a cooperative heading control maneuver, both aircraft involved in the potential would change their heading angles, as indicated in Fig. 4.2. In a non-cooperative maneuver, on the other hand, only one aircraft changes its heading whereas the other remains along its original course.

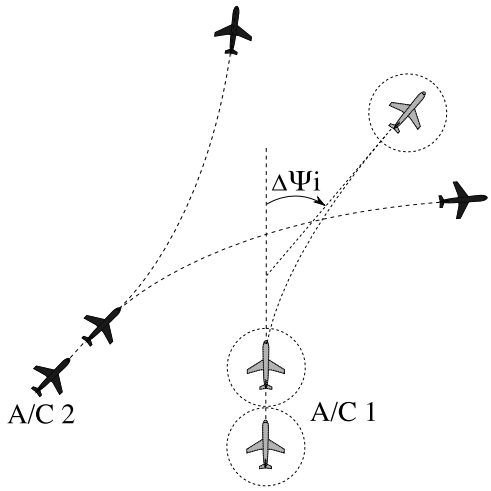

Figure 4.2: Conflict resolution with heading control.

A straightforward heading strategy for resolving a conflict would requires the

aircraft to change its heading by a certain fixed amount, $\Delta\Psi$.

$$\Psi_c = \begin{cases} \Psi_0 & t \leq t_r, \\ \Psi_0 \pm \Delta\Psi & t > t_r. \end{cases} \tag{4.1}$$

where the $\pm$ indicates the direction of turning, and $\Delta\psi = 0°$ corresponds to the non-manuvering aircraft in a non-cooperative resolution. An appropriate amount of heading angle change for a maneuvering aircraft depends on the traffic situation as well as controller/pilot preferences. Since aircraft would continue toward their destinations after a conflict is resolved, the maximum amount of heading change should balance the need to resolve the conflict and the desire to stay close to the original trajectories. In this paper, it is assumed that $\Delta\psi = 30°$. The appropriate direction of turning for a given aircraft depends on the encounter geometry and will be studied below.

In actual flights, pilots or autopilots fly the aircraft to follow the heading change command. The actual trajectory-tracking logics can be quite complicated. In this paper, the method of feedback linearization is used to model closed-loop trajectory tracking[41]. This method requires the specification of desired closed-loop dynamics. For the tracking of a heading angle command using the bank angle, the resulting closed-loop system is of first order and a desired response dynamics

can be specified as

$$\dot{\Psi} + K_{\Psi}(\Psi - \Psi_c) = 0 \tag{4.2}$$

We obtain

$$\mu \approx \sin^{-1}\left[\frac{V_0}{g}\dot{\Psi}_c - \frac{K_{\Psi}}{g}V_0(\Psi - \Psi_c)\right] \tag{4.3}$$

Aircraft bank angle μ is limited by aircraft performance capabilities, the load factor constraint, and passenger comfort. Typically, the maximum bank angle is about 30 degrees for en route flight and 40 degrees for terminal area operations. in this study, it is assumed that $|\mu| \leq 30°$.

4.2 Conflict Resolution with Speed Control

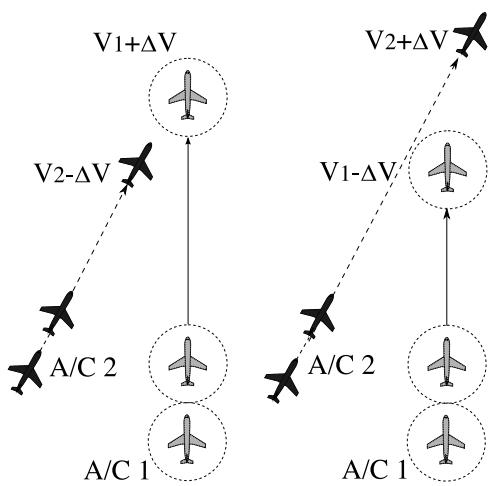

Figure 4.3: Conflict resolution with speed control.

In using speed control to resolve a pairwise conflict in a cooperative manner, one aircraft speeds up whereas the other slows down, or vice versa, as shown in Fig. 4.3. In a non-cooperative maneuver, one aircraft speeds up or slows down, whereas the other maintains its original speed. The speed control command for one aircraft can be stated as

$$V_c = \begin{cases} V_0 & t \leq t_c, \\ V_0 \pm \Delta V & t > t_c. \end{cases} \tag{4.4}$$

where it is assumed that $\Delta V = 50$ knots if the given aircraft is directed to maneuver, and $\Delta V = 0$ if it is not.

Speed command tracking via throttle is also of first-order. The desired closed-loop dynamics may be specified as

$$\dot{V} + K_V(V - V_c) = 0 \tag{4.5}$$

which leads to

$$\overline{T} \approx \sin\gamma + \frac{\dot{V}_c}{g} - \frac{K_V}{g}(V - V_c) \tag{4.6}$$

In practical flights, aircraft are not able to make instantaneous speed changes because of their limited thrusting capabilities especially during en route flight. Ref. 18 estimates based on aircraft performance limitations alone that the maximum acceleration possible for commercial jet transports is about 0.63 ft/sec^2 and the maximum deceleration is about -2.1 ft/sec^2. Considerations of passenger

comfort further limit the maximum deceleration to about -0.73 ft/sec^2. Consequently in this paper, we assume -0.73 ft/sec$^2 \leq \dot{V} \leq 0.63$ ft/sec^2.

4.3 Conflict Resolution with Altitude Control

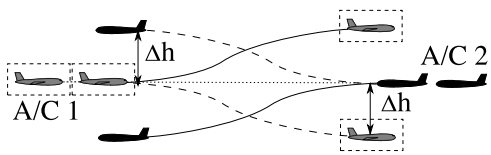

Figure 4.4: Conflict resolution with altitude control.

In using altitude control to resolve a potential conflict in a cooperative manner, one aircraft climbs, whereas the other aircraft descends, or vice versa, as shown in Fig. 4.4. In a non-cooperative maneuver, one of the two aircraft climbs or descends, whereas the other maintains its original flight level. The altitude command for one aircraft can be expressed as

$$h_c = \begin{cases} h_0 & t \leq t_c \\ h_0 \pm \Delta h & t > t_c \end{cases} \tag{4.7}$$

where in a non-cooperative maneuver, $\Delta h = 1,000$ ft for the maneuvering aircraft, and in a cooperative resolution, $\Delta h = 500$ ft for both aircraft.

Altitude control through lift is of second order, and the desired response dynamics can be expressed as

$$(\ddot{h} - \ddot{h}_c) + 2\zeta_V \omega_V (\dot{h} - \dot{h}_c) + \omega_V^2 (h - h_c) = 0 \tag{4.8}$$

Obtaining $\ddot{h}$ from Eqs. (3.1)-(3.6) and substituting it to Eq. (4.8), the required lift can be obtained as

$$\overline{L} = \frac{1}{\cos\mu}\left[1 - \frac{2\zeta_V \omega_V}{g}\dot{h} - \frac{\omega_V^2}{g}(h - h_c)\right] \tag{4.9}$$

Once again, the ability of the aircraft to ascend or descend is constrained by aircraft performance capabilities as well as passenger comfort. Based on estimates in Ref. 18, it is assumed that $-3.0^\circ \leq \gamma \leq 1.1^\circ$.

With appropriate choices of the coefficients, the above trajectory tracking laws can be used to represent either human pilots or autopilots. In their current forms, the heading and speed command tracking laws represent non-path trajectory controls, whereas the altitude command tracking represents path control. In general, the use of path control results in higher accuracy of position tracking compared with non-path control, whereas non-path controls are easier to implement. These two non-path control laws can be updated to path control by including lateral and longitudinal position errors.

Chapter 5

Modeling of Uncertainties and Variations

The aircraft flight process is full of uncertainties. Meaningful quantifications of REACTs must take into consideration various uncertainties in aircraft flights and the conflict resolution process. Below, mathematical expressions of these uncertainties used in estimating REACTs in this paper are discussed.

5.1 Navigation System Errors

To account for the effects of imprecise onboard navigation measurements, random errors are introduced to the measured values of airspeed, heading angle, altitude

rate, and altitude for use in the trajectory command tracking logics. Correspondingly, all the state variables in Eqs. (4.3), (4.6) and (4.9) represent measured values.

Modern day commercial transports can use a combination of different navigation systems. Perhaps all commercial aircraft are currently equipped with navigation grade GPS receivers that can receive WAAS corrections. Normally, GPS positioning errors are time-correlated with a time constant on the order of 1 minute. For the convenience of analysis in this paper, navigation errors are assumed to be uncorrelated random variables with zero means and truncated Gaussian distributions. Position errors are truncated to $\pm 2\sigma$, whereas speed errors are truncated to $\pm 1\sigma$. The following values are used in the simulations.

$$\sigma_x = \sigma_y = 0.5 \text{ m}, \sigma_h = 2.5 \text{ m}, \sigma_V = 5 \text{ cm/s}, \sigma_{\dot{h}} = 10 \text{ cm/s} \tag{5.1}$$

In comparison, It is assumed that the heading angle is measured with magnetic compass combined with computer compensations, and a similar distribution is used. The maximum heading angle error is $\pm 0.7^\circ$ that corresponds to $\pm 1\sigma$.

$$\sigma_\Psi = 0.7^\circ \tag{5.2}$$

5.2 Group Pilot Model

Different pilots have different response behaviors in tracking the same flight commands. For example, in responding to conflict avoidance commands, some pilots may be cautious while others can be relatively aggressive. Estimations of REACTs should consider likely variations among the pilot population. A simple and effective approach to model variations in the pilot population is to treat the trajectory tracking coefficients as well as the pilot response time as random variables[42].

In order to properly model the probabilistic features of these coefficients and times, some observations of the human operator behaviors are helpful. Pilots are professionals who receive considerable training and practices. Therefore, it can be assumed that all pilots possess the minimum level of proficiency. On this basis, the percentage of pilots who act substantially more rapidly is small, as is the percentage of pilots who perform significantly more slowly. In between these extremes, pilot behaviors may be caused by differences in experiences, company procedures, personalities, and emotional states.

Based on these discussions, it is assumed that coefficients in the trajectory tracking logics, K_V, K_Ψ, and ω_h, are modeled as random variables with a modified Rayleigh distribution[42]. The corresponding probability density function is given

by

$$f(x;s) = \frac{(-x+x_1)}{s^2} \exp\left[\frac{-(-x+x_1)^2}{2s^2}\right] \tag{5.3}$$

In comparison, the damping ratio ζ_h is depicted by truncated Gaussian distribution within $\pm 2\sigma$.

The modified Rayleigh density function is determined by two parameters: s and x_1, where s defines the shape of the curve and x_1 is the upper limit of the random variable x. It is further assumed that $s = (x_1 - x_0)/4$, where $[x_0, x_1]$ is the range of the random variable x. This approximation allocates over 95% of the x values into the interval $[x_0, x_1]$. The corresponding mean is $\mu = -s\sqrt{\pi/2} + x_1$. Fig. 5.1 illustrates this modified Rayleigh distribution.

For a typical human pilot population, ranges of the trajectory tracking coefficients are defined as:

$$\omega_h \in [0.05, 0.5], K_V \in [0.05, 0.1], K_\Psi \in [0.05, 0.1], \zeta \in [0.5, 0.8] \tag{5.4}$$

Performances of autopilots are expected to be more consistent compared with human pilots, but their model parameters should vary similarly. Therefore, parameters in Eq. (5.4) are used in the simulation studies.

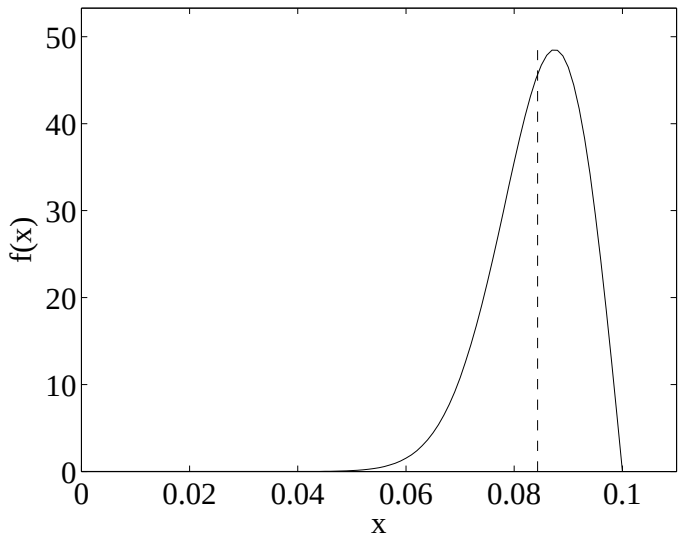

Figure 5.1: Modified Rayleigh probability density function for K_V.

5.3 Initial Speed Uncertainties

While it is assumed that the two aircraft involved in a potential conflict have similar initial speeds, the exact values of their initial speeds are likely to be different. Uncertainties are introduced to account for likely variations in their relative airspeeds. Define

$$\eta = \frac{V_{2,0}}{V_{1,0}} \tag{5.5}$$

Then, η is modeled as a random parameter varying in $[0.8, 1.2]$ with a uniform distribution.

5.4 Random Time Elements in REACT

Each of the four components of REACTs: T_D, T_C, T_P and T_A, contains different types of uncertainties. While T_D and T_C both vary with controllers and circumstances, they merely delay the issuing motions. Accordingly, their likely worst values can be used in estimating REACTs. In this paper, $T_D = 20$ seconds and $T_C = 3$ seconds are assumed for human controllers based on Refs. 43 and 44. The decision times for DSTs are expected to be smaller, e.g. $T_D = 5$ seconds.

The pilot response delay T_P has similar properties as coefficients of the closed-loop trajectory tracking logics. Because better performances in this case correspond to smaller delays, a reflected Rayleigh distribution is used to model T_P.

$$f(x; s) = \frac{(x + x_0)}{s^2} \exp\left[\frac{-(x + x_0)^2}{2s^2}\right] \tag{5.6}$$

This function is also determined by two paramters, s and x_0, where s defines the shape of the curve and x_0 is the lower limit of the random variable x. Again, it is assumed that $s = (x_1 - x_0)/4$, where $[x_0, x_1]$ is the likely range of the random variable x. The corresponding mean is $\mu = s\sqrt{\pi/2} + x_0$. In this paper, it is assumed that $T_P \in [1.5, 3.5]$ seconds, therefore x_0 here is 1.5 seconds, and he corresponding mean is about 2 seconds.

Finally, the aircraft maneuver time T_A depends on dynamic aircraft flights in

the conflict resolution process and thus all the uncertainties associated with this process. Below, Monte-Carlo simulations of dynamic aircraft flights are used to estimate T_A.

Chapter 6

Numerical Solutions by Simulations

Monte-Carlo simulations are now used to simulate the dynamic aircraft flight process in various conflict scenarios. In each simulation, random variates for the various uncertainties along the entire integration interval are first generated using appropriate MATLAB functions in accordance to their probabilistic properties described above. These values are then stored for use in the numerical integration process. The dynamic equations for both aircraft are integrated using a fourth-order Runge-Kutta scheme by calling the *ode*45 function in MATLAB. In integrating these equations, trajectory controls are determined from the corresponding trajectory tracking logics. The pilot response delays for the two aircraft

are assumed independent. Numerical integrations begin when one or both pilots start to act, and end when Eq. (2.4) is satisfied. Because of potentially different pilot response times, the resulting T_A can be different for the two aircraft. However, $T_P + T_A$ is the same for both aircraft.

Because of the uncertainties, the satisfaction of Eq. (2.4) must be carefully verified in a Monte-Carlo simulation. It is observed that sometimes, the relative separation exhibits a non-monotonic behavior. In this paper, REACTs are measured when fluctuations in the simulated relative distance have stabilized and Eq. (2.4) is confirmed.

For each conflict scenario, simulations are repeated for $N_{\max} = 10,000$ times. This is found to be a threshold at which simulated aircraft maneuver time T_A stabilizes. In each simulation, the resulting value of $T_P + T_A$ is recorded if the minimum separation standards in Eq. (2.2) are satisfied during the entire flight process.

Chapter 7

Numerical Results

We consider both cooperative and non-cooperative resolution maneuvers. For the convenience of discussions, the two aircraft are named as A/C_1 and AC_2, where AC_1 is called the own vehicle, and A/C_2 the intruder. The initial relative heading angle between the two aircraft is systematically varied. To simplify the descriptions, we assume that A/C_1 always has a zero initial heading angle where A/C_2 can have different initial heading angles ranging from zero to 180 degrees, as illustrated in Fig. 4.1. In addition, A/C_1 always has an initial speed of 550 mph, whereas the speed of A/C_2 is determined by the initial speed ratio η, which is generated randomly in the given range.

7.1 REACT with Heading Control

In a cooperative heading maneuver, each aircraft can turn either left and right with respect to its current course; resulting in four possibilities. Due to the geometric symmetry, there are essentially two independent options. In option one, the two aircraft both turn left or right (same-direction turn). In option two, one aircraft turns left whereas the other turns right, or vice versa (opposite turn). In this paper, the heading angle is measured clockwise from the North. A left turn decreases the heading angle whereas a right turn increases it.

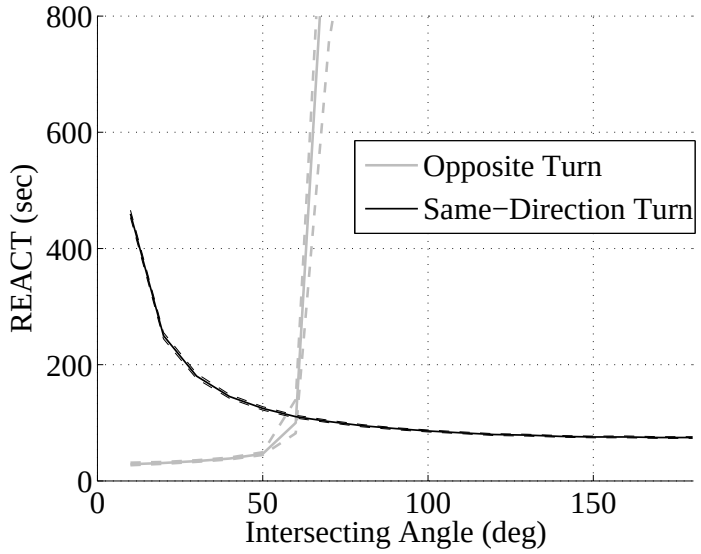

Figure 7.1: REACT with cooperative heading control.

Fig. 7.1 presents the effects of the encounter angle $\Delta\Psi_0$ on REACTs in these

two maneuver options. The two solid lines represent the average values for each option, whereas the contours defined by the dashed lines contain 90 % of the simulated values. For small encounter angles or merging conflicts, the REACTs are smaller when the two aircraft turn in opposite ways than if they turn oppositely. In the limiting chase of a tail-chasing conflict, the two aircraft should turn in opposite ways in order to avoid the conflict quickly. As the encounter angle increases to a certain critical value, around 60 degrees in Fig. 7.1, it becomes more efficient for the two aircraft to turn the same way. This is clearly true in the limiting case of a head-on conflict. In fact for large encounter angles, opposite turns would not help to resolve the conflict as the two aircraft would head toward each other again. This fact causes the spike of REACTs in Fig. 7.1 when opposite turns are used.

Fig. 7.2 shows the resulting REACTs when only one aircraft turns to avoid the conflict in a non-cooperative maneuver. In this case, in referring to Fig. 4.2, A/C_1, the own aircraft, maintains its original course whereas A/C_2, the intruder, turns either left or right. At small encounter angles, a left turn by A/C_2 is intuitively meaningful, as this would increase the relative separation between the two aircraft. Correspondingly, the REACTS are small. In comparison, a right turn would decrease the relative distance at least initially; resulting in larger REACTs. At the encounter angle increases, however, a right turn by A/C_2 becomes increasingly more efficient as evidenced by decreasing REACTS, whereas a left turn becomes

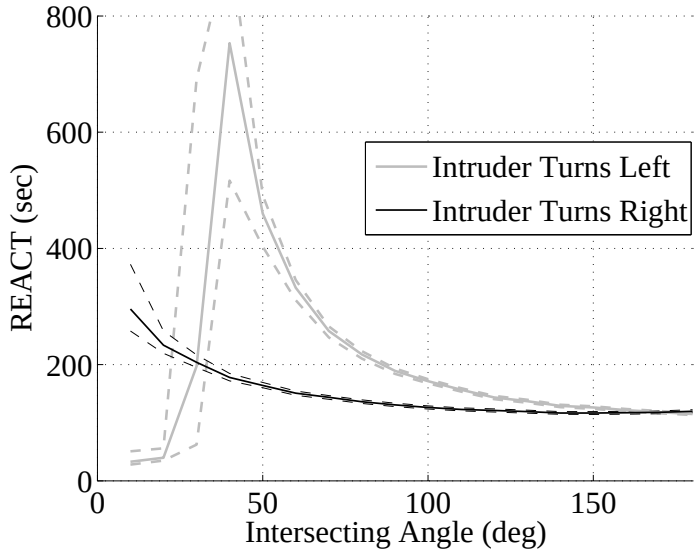

Figure 7.2: REACT with non-cooperative heading control.

increasingly inefficient. In particular, AC_2 with a left turn would almost be chasing A/C_1 when the encounter angle is around 40-60 degrees. As the encounter angle further increases, left turns by A/C_2 become gradually more efficient again. In the limiting case of a head-on conflict, it does not matter which way A/C_2 turns and the corresponding REACTS with either a left turn or a right turn become the same.

Comparisons of the cooperative vs. non-cooperative heading maneuvers reveal an interesting phenomenon. In both cases, one type of turning option becomes more efficient than the other as the encounter angle increases beyond a certain critical value. In cooperative maneuvers, the same-direction turning becomes more

efficient than opposite turning as the encounter angle exceeds about 60 degrees. In non-cooperative maneuvers, a right turn by AC_2 becomes more efficient as the encounter angle exceeds about 40 degrees. The opposite is true at lower encounter angles. For larger encounters angles or near head-on conflicts, cooperative maneuvers are about 50% more efficient than non-cooperative maneuvers in terms of REACTS (100 seconds vs. 150 seconds.) At smaller encounter angles, however, non-cooperative maneuvers can be more efficient than cooperative maneuvers. In other words, for conflicts close to tail-chasing configurations, it may be better to vector one aircraft only. Over the range of different encounter angles, REACTS vary from a fraction of a minute to about 10 minutes in both cooperative and non-cooperative maneuvers.

7.2 REACT with Speed Control

Aircraft may also employ speed changes to resolve a potential conflict. In a cooperative speed control, one aircraft speeds up whereas the other slows down or vice versa. Fig. 7.3 presents REACTs for cooperative speed control, where the solid lines again represent the average values and the dashed lines contain 90 % of the simulated values in each case. It shows that the mean values are basically the same. The small differences in the 90% containment regions are caused by

the fact that the random initial speed ratio makes one aircraft slightly faster than the other. The maneuver option where the slightly faster aircraft decelerates and the slower one accelerates produces REACTs that are slightly larger than those of the other option. After the encounter angle exceeds about 30 degrees, it does not make much difference which aircraft accelerates or decelerates.

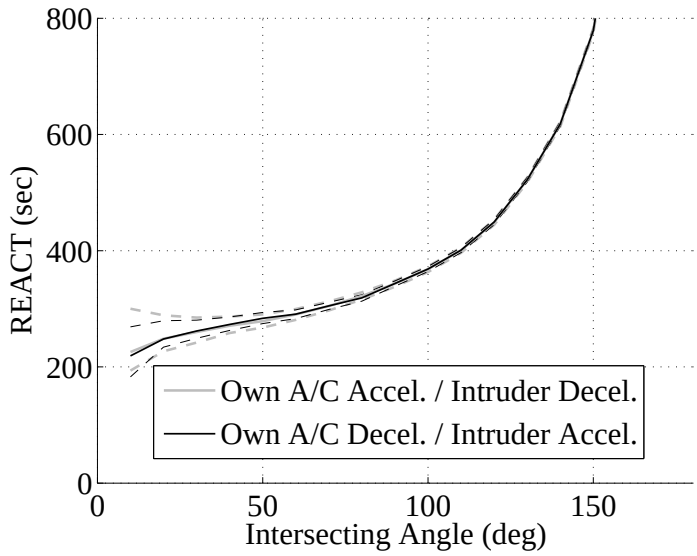

Figure 7.3: REACT with cooperative speed control.

Fig. 7.3 shows that as the encounter angle increases, REACTs increase non-linearly. As the encounter angle approaches 150 degrees, REACTs become significantly large; suggesting that the use of speed change alone becomes gradually infeasible to resolve the conflict in these cases. In the limiting case of a head-on conflict, the pure use of speed change will not be able to resolve the conflict and

the corresponding REACTs approach infinity. For encounter angles up to 150 degrees, the REACTs vary from 3 minutes to 14 minutes.

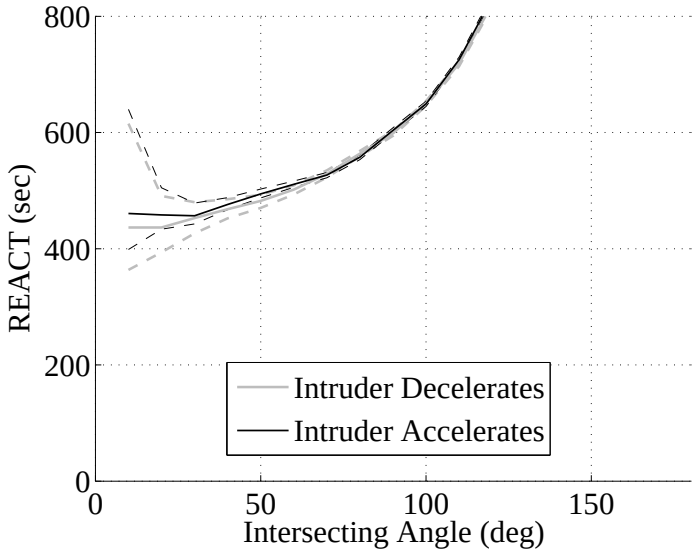

Figure 7.4: REACT with non-cooperative speed control.

In a non-cooperative speed control, one aircraft speeds up or slows down whereas the other maintains its original speed. Fig. 7.4 shows that the non-cooperative speed control exhibits a similar trend as in cooperative maneuvers. On the other hand, the overall REACTs with non-cooperative speed control are almost twice as high as those with cooperative maneuvers. Because it is assumed that AC_2 is behind AC_1 in merging conflicts, the gray solid line, representing the case where AC_2 slows down, has somewhat smaller REACTs.

7.3 REACT with Altitude Control

Finally, aircraft in a potential conflict may change their altitudes to avoid the conflict. In a cooperative maneuver, one aircraft climbs to a higher altitude whereas the other descends to a lower altitude. Depending on which aircraft would climb or descend, there are also two maneuver options, as shown in Fig. 4.4.

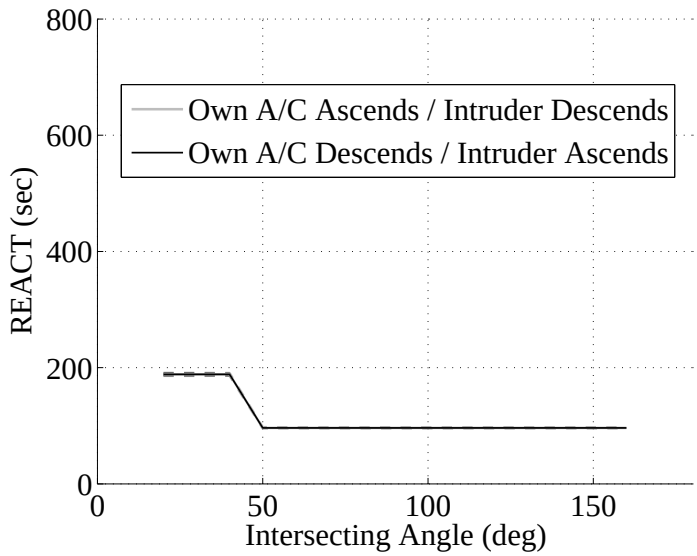

Figure 7.5: REACT with cooperative altitude control.

Fig. 7.5 shows that it does not matter which aircraft climbs and which descends in a cooperative maneuver. In addition, uncertainties within the assumed ranges seem to have little effect. The corresponding REACTs depend on the encounter angle in a distinct way. For encounter angles smaller than about 40 degrees, the

REACTs are about 200 seconds and remain constant with respect to the angle. For encounter angles beyond 50 degrees, on the other hand, the REACTs drop to about 100 seconds and then remain relatively constant with respect to the angle. The higher REACTs at smaller encounter angles are caused by the fact that the relative aircraft separation decreases initially even after the aircraft begin their altitude changes. In cooperative altitude controls, the REACTs vary from about 2 to 4 minutes over the range of all likely encounter angles.

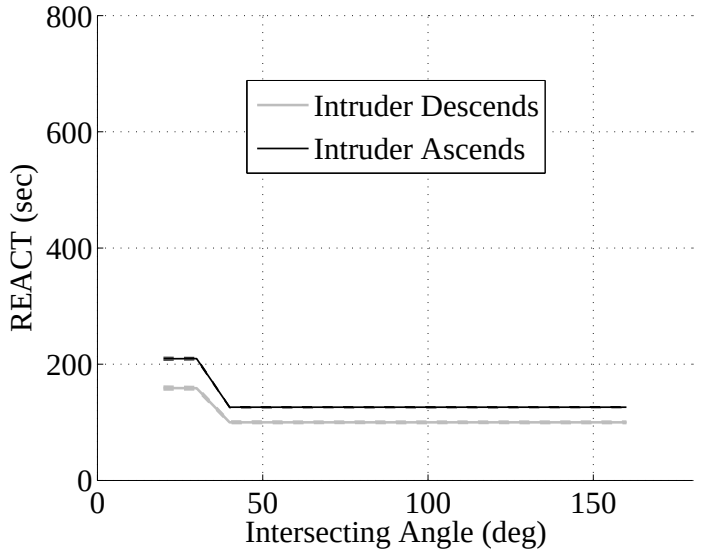

Figure 7.6: REACT with non-cooperative altitude control.

In non-cooperative altitude maneuvers, only one aircraft climbs or descends whereas the other aircraft maintains its original altitude. Fig. 7.6 shows that REACTs in non-cooperative altitude maneuvers exhibit a similar trend as those

in cooperative maneuvers. The critical encounter angle at which REACTs start to drop as the encounter angle increases becomes smaller. In addition, descending flight is somewhat more effective than climbs in resolving the conflict. This is because the magnitude constraint on the flight path angle is larger for descent than for climb. Overall, the REACTs are higher than those with cooperative altitude control, as expected, by about 30%. Again, the REACTs range around 2-4 minutes.

D. Control Effectiveness

In general, a smaller REACT means that the conflict resolution process would take less time and/or a smaller space to accomplish. It would give controllers more time to make a decision. It is important to realize that other conditions may need to be considered in selecting a control authority to resolve conflicts, such as keeping all aircraft in the same flight level or availability of usable airspace.

Fig. 7.7 compares REACTs obtained by using different control authorities in a cooperative maneuver. Clearly, speed control is the least effective because it requires the largest REACTs to accomplish a resolution. In addition, the sole use of speed control is not feasible in resolving a conflict when the encounter angle exceeds about 150 degrees, especially in a head-on conflict. Overall, cooperative heading control is the most effective of the three, especially at small encounter

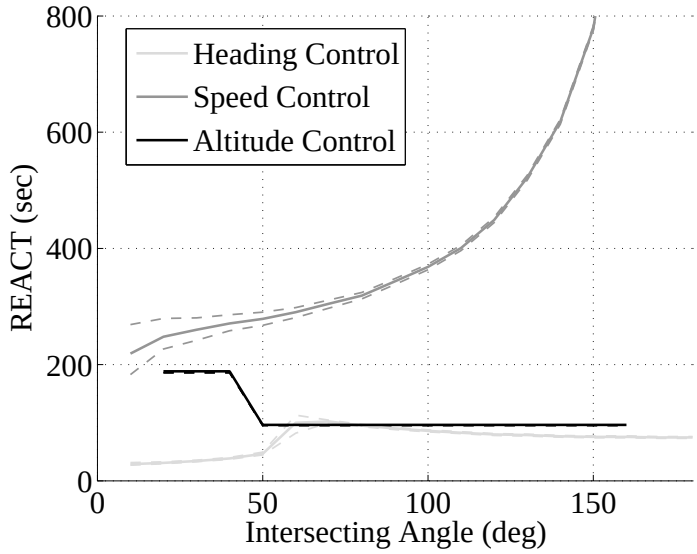

Figure 7.7: Comparison of control effectiveness in cooperative control.

angles. For encounter angles beyond about 60 degrees, cooperative heading control and altitude control are similarly effectively.

Things change somewhat for non-cooperative maneuvers. While speed control is still the least effective of the three, non-cooperative altitude control becomes more effective for encounter angles exceeding about 30 degrees. At lower encounter angles or in a merging conflict, non-cooperative heading control is still more effective.

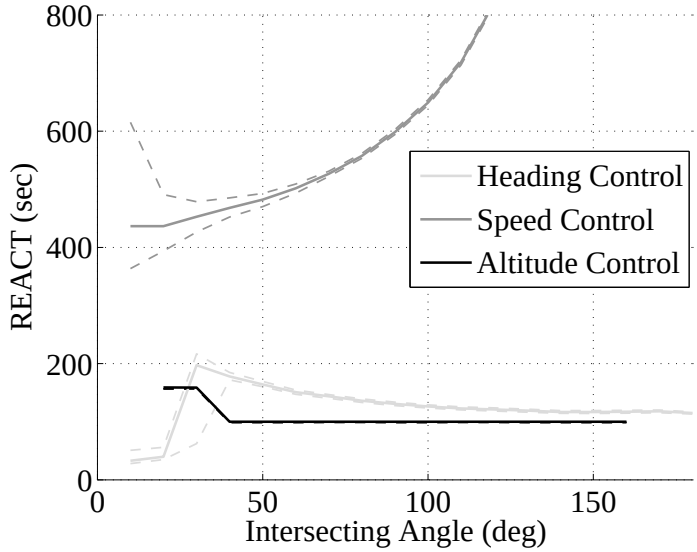

Figure 7.8: Comparison of control effectiveness in non-cooperative control.

Chapter 8

Discussions

Because a REACT represents the least advance time it requires to resolve a pairwise conflict, it provides a lower bound on the lookahead window for reliable trajectory predictions. The above results indicate that reliable trajectory predictions for use in en route pairwise conflict detection and resolution should be made with at least 5-10 minutes of lookahead window. This number will certainly increase when multiple aircraft need to be considered in conflict detections.

Generally speaking, the minimum lookahead windows for reliable trajectory predictions should be determined by their intended use, as advocated in this paper. The maximum meaningful lookahead windows, on the other hand, are determined by the propagation and characteristics of trajectory prediction errors. Beyond a certain lookahead time, prediction errors become so large that predicted

trajectories are no longer meaningfully useful for precision applications, such as scheduling and conflict probing. This is beyond the scope of the current paper.

In the calculations of this paper, wind effects are neglected. In reality, both the local wind patterns and wind measurement errors can affect the conflict resolution process and thus the resulting REACTs. Preliminary results indicate that REACTs vary with both the direction and magnitude of wind errors, as well as the forms of trajectory tracking strategies. It seems that whenever possible, the planned trajectories for resolving conflicts should take into consideration the local winds. In addition, the tracking of inertial quantities or path control is more robust to wind errors than that of air-relative quantities. However, the tracking of inertial quantities may cause additional control activities. A systematic study of the wind effect requires considerably more efforts beyond the results of the current paper, and shall be presented separately in the future. The results obtained under zero wind conditions in this paper can serve as benchmarks for comparisons.

Finally in this paper, it is assumed that the two aircraft would collide along their original flight paths if no resolution maneuvers are taken. In actual flights, potential conflicts may more likely result in losses of separations than direct collisions. In these cases, the geometric symmetry used in this paper no longer exists. As a result, there are more maneuver options in each conflict scenario. On the other hand, the REACTs when appropriate resolution maneuvers are used should

be smaller than those calculated in this paper.

Chapter 9

Conclusions

This paper presents a systematic approach to estimating the REquired ACtion Time, or REACT, for resolving pairwise aircraft conflicts. REACT represents the least advance time when the conflict resolution process must begin in order to maintain specified minimum separation standards. In estimating REACTs, the process of conflict detection and resolution is divided into four segments, and flight times associated with each segment are estimated either empirically or through numerical simulations. To accomplish this task, aircraft motion is modeled with a dynamic point-mass that uses position and velocity components as states, and excess thrust, lift, and bank angle as controls. In this work, pairwise conflicts in different encounter geometries are considered. In resolving a potential conflict, it is assumed that one of the control authorities: heading change, speed change

and altitude change is used individually. Aircraft performance limitations and passenger comfort considerations are imposed to bound the motions. In addition, representative sources of uncertainties in the process of conflict detection and resolution are modeled. Monte-Carlo numerical simulations are then conducted to calculate REACTs. Both cooperative and non-cooperative resolution maneuvers are considered.

Results indicate that heading control is the most effective at small encounter angles. It is reasonably effective for all encounter angles. Altitude control is effective when the encounter angle is reasonably large. In comparison, speed control is the least effective of the three. In particular, it cannot resolve head-on conflicts. Cooperative maneuvers where both aircraft take avoidance actions produce smaller REACTs than non-cooperative maneuvers where only one aircraft changes its state to resolve a conflict. However, at small encounter angles, non-cooperative heading control can require comparable REACTs with cooperative heading control. Overall, REACTs vary around 5-10 minutes for pairwise conflict resolutions, which set the lower bound on the lookahead window of reliable trajectory predictions for use in pairwise conflict detection and resolution.

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