A PARAMETRIC SENSITIVITY STUDY OF ULTRA CLOSELY SPACED PARALLEL APPROACHES

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Introduction

Commercial air traffic is projected to grow approximately 5% per year over the coming decades. This means that the world's airports and airspace will need to handle an increase of traffic by a factor of two to three over the next two decades. Many airports are near or at capacity now for at least portions of the day, making it clear that major increases in airport capacity will be required in order to support the projected growth in air traffic. This can be accomplished by adding airports, adding runways at existing airports, or increasing the capacity of the existing runways.

With the current approved technology for independent parallel approaches at an airport under Instrument Meteorological Conditions (IMC), parallel runways must be set at least 3400 ft apart[1,2]. In clear weather (Visual MC or VMC), parallel runways can be used that are 750 ft apart with air traffic control (ATC) passing responsibility for separation to the two pilots[3]. If technology can be developed that would allow 750 ft separation between parallel runways in IMC, the capacity of a large portion of today's airports equipped with parallel runways would be doubled during IMC. This would be a major benefit to airport capacity with no increased airport land area requirements and thus minimal impact on the surrounding communities.

In the longer term, technology that allows use of ultra closely spaced (750 ft to 2500 ft) parallel approaches (UCSPA) would have a huge impact on the environmental impact of airport capacity increases. To support airport capacity increases by a factor of two or three over the next two decades, new runways will be required. As the required spacing between runways decreases, the required additional land on which to build runways is reduced, thus reducing the environmental impact and cost. If technology can be developed to support a 750-ft separation in IMC, it is possible that no new airports or current airport real estate expansions would be required for decades.

Goals of the Study

Expected near-term advanced navigation sensors and data links have been successfully demonstrated on a B-757 at a runway spacing of 2500 ft [4,5]. In anticipation of future advanced navigation technology and practices that may permit parallel IMC approaches to runways less than 2500 ft apart, it is the goal of this investigation to determine the sensitivity of an ultra low runway separation to seven parameters which impact the successful resolution of a blunder/escape scenario: (1) safety buffer, (2) evader aircraft delay time, (3) difference between evader and blunderer roll rates, (4) difference between evader and blunderer maximum roll angles, (5) total system error (TSE), composed of navigation sensor error and flight technical error, (6) differences in airspeed, and (7) variation in initial longitudinal spacing. The relative sensitivities will then rank the parameter(s) which impact the successful completion of a blunder/escape maneuver during an ultra closely spaced parallel approach. In turn, this information will define future auto-pilot, data link, and approach guidance specifications.

General Sensitivity Analysis

The goal of sensitivity analysis is to estimate the change in output of a model with respect to the change in inputs [6]. In this case, let us define a dynamic, deterministic, continuous process of the form

$$\{L_t : t > 0\} \qquad (1)$$

where the output $L_t = L_t(Y_t)$ is a function of the

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input vector, $Y_t = (Y_1, Y_2 \dots Y_t)$ which is a history of the input process up to time t. $\{L_t(\bullet)\}$ is a sequence of real-valued functions[7]. The goal is then to estimate the expected performance of the system with respect to various parameters, $\bar{\upsilon}$,

$$f(\bar{\upsilon}) = E_{\bar{\upsilon}}\{L(\bar{Y})\} \quad (2)$$

and to examine the system sensitivities, $\nabla^k f(\bar{\upsilon}), k \geq 1$. For this investigation, only the first order gradients, k = 1, were examined. The parameter, $\bar{\upsilon}$, is comprised of the seven variables of interest. This sensitivity analysis was performed about a set of baseline parameters, $\bar{\upsilon}_0$, with variation in $\bar{\upsilon}$.

Ultra Closely Spaced Parallel Approach Model

The model created for the sensitivity analysis defines a continuous, two-dimensional, nonlinear, time-dependent trajectory for two point masses possessing kinematic airplane properties. All properties of the "airplanes" are deterministic. One airplane is designated the blundering aircraft or "blunderer", the second is designated as the evading aircraft or "evader". Two virtual "runways" are defined in an inertial reference frame while the aircraft trajectories are propagated in a leader/follower, translating, rotating, relative reference frame. The origin of the runway-referenced frame is placed at the approach end of the runway of the evader; the origin of the relative reference frame is the center of mass of the evader aircraft. After numerical integration of the equations of motion, a coordinate transform is performed at each time step to calculate both the relative and inertial positions and velocities of the airplanes.

The input vector, Y, contains initial conditions and maximum allowable values of the state vector. Additional conditions included in Y are timing specifications and threshold values for maneuver initiation and termination. The model output is the complete time dependent trajectory of the state vector, the closest point of approach of the two airplanes, and the time at which the closest point of approach occurred.

Dual Airplane Kinematic Equations

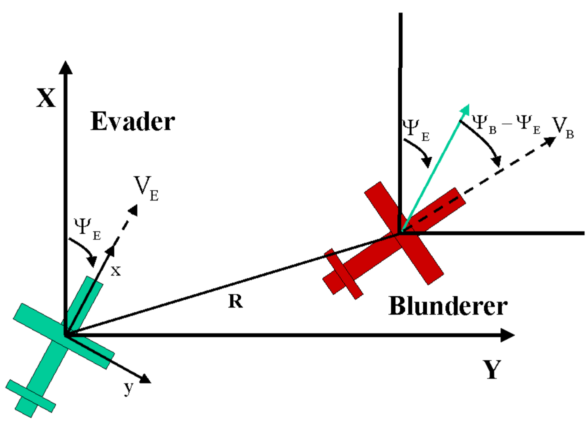
Using the evader airplane-referenced frame, the position of the blunderer relative to the evader is first calculated. Independently, the position of the evader relative to the runway is determined in the runway-referenced coordinate frame. A coordinate transform is then performed to rotate the blunderer airplane into the runway-referenced frame.

Evader Airplane-Referenced Frame Equations of Motion

The evader airplane referenced coordinate frame is a lead/trail concept[8]. The origin of the relative frame is the translating and rotating center of mass of the evader airplane, shown in Figure 1. The x-direction is out the nose, the positive y-direction out the right wing of the evader aircraft.

Ignoring the earth's rotation and without loss of generality, the inertial frame (denoted by capital X and Y) is translating with the evader airplane. The local body referenced frame (denoted by lowercase x and y) is used for intermediate calculations involving the relative rotation rates of the two airplanes.

Figure 1. Evader-reference relative frame



Using this geometry, the differential equations of motion of the blunderer airplane relative to the inertial frame of the evader airplane are presented in Eqns (3) to (4)

$$\dot{Y}_{B,\,Rel} = V_B \sin(\psi_B - \psi_E) - \dot{\psi}_E X \quad (3)$$

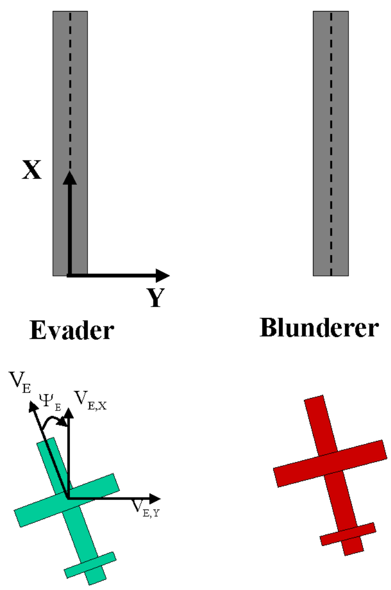
$$\dot{X}_{B,\,Rel} = V_B \cos(\psi_B - \psi_E) - V_E + \dot{\psi}_E Y \quad (4)$$

$$\dot{\psi}_B(t) = \int \frac{g \tan\phi_B(t)}{V_B} dt \qquad \dot{\psi}_E(t) = \int \frac{g \tan\phi_E(t)}{V_E} dt$$

Runway-Referenced Equations of Motion

In order to position the aircraft relative to a fixed set of runways, an inertial runway-referenced coordinate frame is presented in Figure 2 with a fixed origin at the threshold of the evader's intended runway. The along track coordinate down the runway centerline is X while the crosstrack dimension is Y. With prescribed initial conditions, the evader aircraft's trajectory is calculated in this frame using Eqns (5) and (6).

Figure 2. Runway-referenced coordinate frame



$$\dot{X}_E(t) = V_E(t)\cos(-\psi_E(t)) \quad (5)$$

$$\dot{Y}_E(t) = V_E(t)\sin(-\psi_E(t)) \quad (6)$$

Blunderer's Position in Runway-Referenced Coordinates

Once the runway-referenced position of the evader and the relative position of the blunderer to the evader are calculated, the position of the blunderer relative to its runway may be calculated by rotating and translating its position into the runway frame using Eqns (7) and (8).

$$X_B(t) = X_E(t) + X_{B,\,Rel}(t)\cos-\psi_E(t) + Y_{B,\,Rel}(t)\sin(-\psi_E(t)) \quad (7)$$

$$Y_B(t) = Y_E(t) + (-X_{B,\,Rel}(t)\sin(-\psi_E(t)) + Y_{B,\,Rel}(t)\cos(-\psi_E(t))) \quad (8)$$

The state vector is formed from Eqns (3) to (8) and is numerically integrated at each time step using a fourth order Runge-Kutta method.

Sensitivity Studies

Baseline Case

The baseline trajectory chosen for this generalized model of ultra closely spaced parallel approaches to dual runways is based on the 30 deg blunder scenario used in NASA's Airborne Information for Lateral Spacing program [9]. Initially, the two airplanes are exactly abeam each other at matched airspeeds of 140 kts and matched headings aligned with the runways. Each airplane has a 100 ft TSE toward the other airplane, which means the airplanes are initially 200 ft closer to each other than if they were each aligned with their respective runway. The blunderer then rolls at a rate of 10 deg/s to a maximum bank angle of 30 deg toward the evader and a maximum heading change of 30 deg. After a 2 sec delay from the initial blunderer roll, the evader performs an escape maneuver consisting of a roll rate of 10 deg/s to a maximum bank angle of 30 deg and a maximum heading change of 45 deg. This is similar to the trajectory proposed in [10], but in two-dimensional form. A summary of the baseline trajectory is presented in Table 1.

Table 1. Baseline trajectory

	start time (sec)	Roll rate (deg/s)	Max roll angle (deg)	Max heading change (deg)	Air-speed (kts)	TSE (ft)	Initial longitudinal separation (ft)
Blunderer	t_0	10	30	30	140	100	0
Evader	$t_0 + 2$	10	30	45	140	100	0

Parameter Variation

Three runway separation distances were investigated: 750, 1100, and 1500 ft. The baseline values of the sensitivity parameters are presented in Eqn 10. The blunderer and evader had matched airspeeds and roll rates, resulting in a “delta airspeed” and “delta roll rate” of 0 kts and 0 deg/s, respectively. The safety buffer refers to the distance beyond a wingtip to wingtip collision (assuming B-747-400 dimensions). The delay time encompasses the on-board collision detection algorithm, the air-to-air data link, airplane roll performance, and the pilot/auto-pilot response time. The TSE of each airplane includes error due to the navigation sensor system (such as an ILS or GLS) and the pilot path following error.

$$\upsilon_0 = \begin{bmatrix} TSE_{each} = 100\text{ ft} \\ \Delta\text{airspeed} = 0\text{ kts} \\ \Delta\dot{\phi} = 0\text{ deg/s} \\ \text{delay} = 2\text{ sec} \\ \Delta\phi = 0\text{ deg/s} \\ \text{Longitudinal spacing} = 0\text{ ft} \end{bmatrix} \tag{9}$$

Around this baseline trajectory, the six parameters of $\bar{\upsilon}$ were then individually varied over the ranges defined in Eqn 10 to create a six-dimensional spatial field composed of thousands of trajectories.

$$\bar{\upsilon} = \begin{bmatrix} TSE_{each} = 0\text{ to }200\text{ ft} \\ \Delta\text{airspeed}_{Evader} = -20\text{ to }+20\text{ kts} \\ \Delta\dot{\phi}_{Evader} = -5\text{ to }+10\text{ deg/s} \\ \text{delay} = 0\text{ to }5\text{ sec} \\ \Delta\phi_{Evader} = -30\text{ to }+30\text{ deg} \\ \text{Longitudinal spacing} = -500\text{ to }+500\text{ ft} \end{bmatrix} \tag{10}$$

From this six dimensional spatial field, the first order gradient of the performance, $\nabla^k f(\bar{\upsilon}), k = 1$, where performance is defined as the distance between the airplanes at the closest point of approach, was determined for each parameter by taking an effective partial derivative with respect to that parameter in the vicinity around the baseline trajectory. Determining the first order gradient (or partial derivative) was done by plotting the variation in the particular parameter versus the closest point of approach, fitting a straight line to the curve using a least squares fit over the selected range of variation, and then quantifying the slope of that line. Prior to fitting the line, the coordinates of each parameter were transformed into a normalized coordinate system. The gradients of each parameter may then be compared directly, with the steepest slope indicative of the greatest sensitivity over the range of variation. Since the gradient is directly related to the range of parameter variation, it is critical for this range to be composed of reasonable values. The performance metric for the safety buffer parameter, the effective margin, is defined as

$$\text{Effective margin} = \text{CPA} - \text{safety buffer}\,. \tag{11}$$

where the safety buffer was varied from 0 to 500 ft.

Comparison of the Relative Sensitivities

For the seven parameters of interest, composite, relative sensitivities are presented for runway spacings of 750, 1100, and 1500 ft in Figure 3. The percentages indicate the relative mulipliers between the parameters, i.e., at 1100 ft, the closest point of approach is three times more sensitive to delay time than to the “evader faster” roll rate difference. Two of these parameters with large effects, TSE and the safety buffer, are independent of the second aircraft. Other significant parameters such as the maximum roll angle and rates are directly dependent upon the information in and update rate of the data link.

Individual Parametric Gradients

An example of individual parametric data is presented in Figure 4 for the 1100 ft case. For the parameters exhibiting linear behavior, the gradient is the slope of the best-fit line. Four of the parameters exhibit nonlinear sensitivities with global minimums. In order to accurately estimate the first order gradients for these parameters, the parameter was divided into two regions that each exhibit linear behavior and plotted separately.

Collision Limits

Given the baseline trajectory, the zero crossing of the closest point of approach defines the critical value of that individual parameter at which collision (of the modeled B-7474-400s) occurs, with all other parameters of the baseline trajectory remaining unchanged. The zero crossings for each parameter are presented in Table 2. The double dashes indicate no collisions within the range of values of that parameter (shown in Eqn 10) about the baseline trajectory.

Figure 3. Relative sensitivities at 750, 1100, and 1500 ft

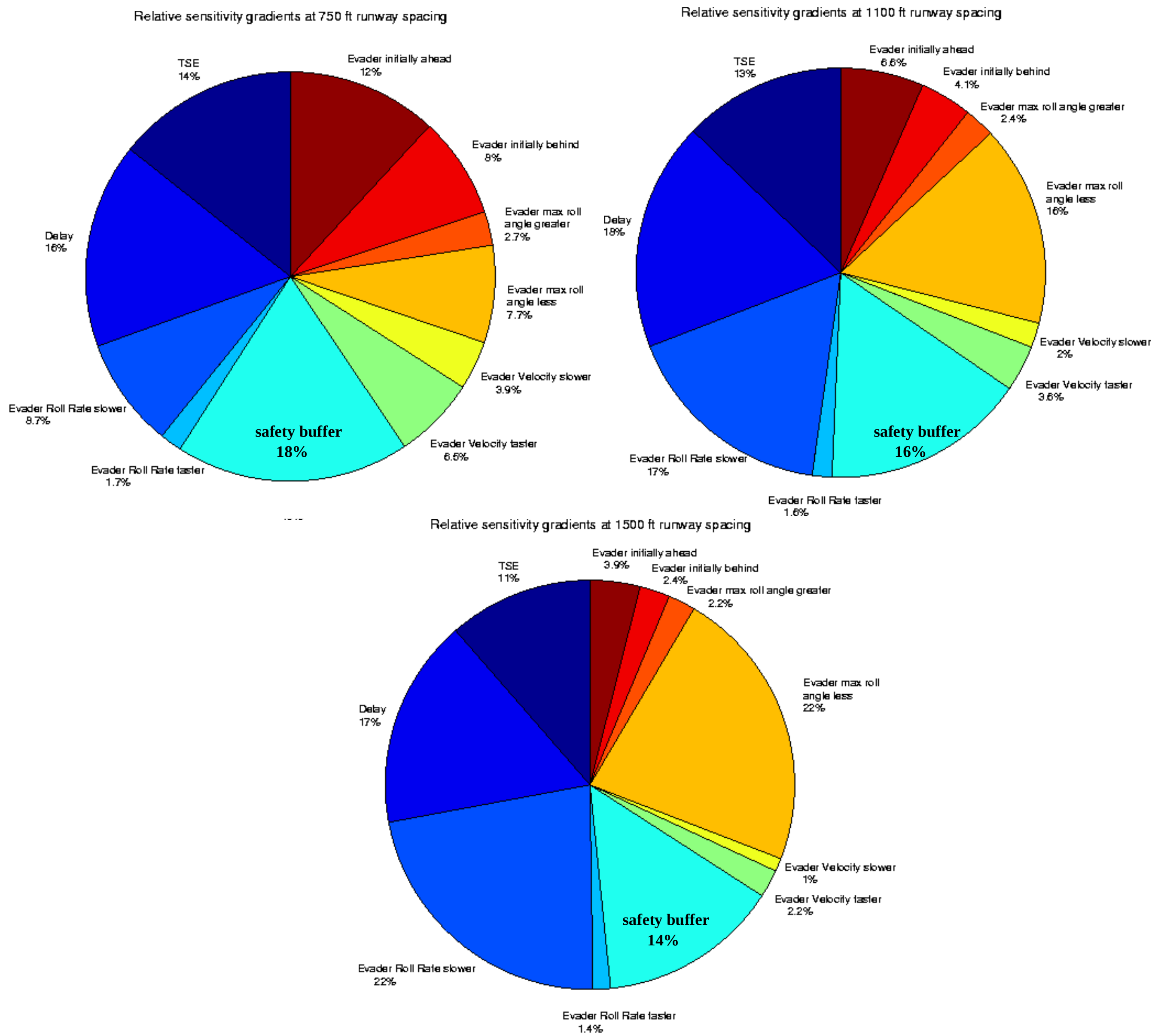
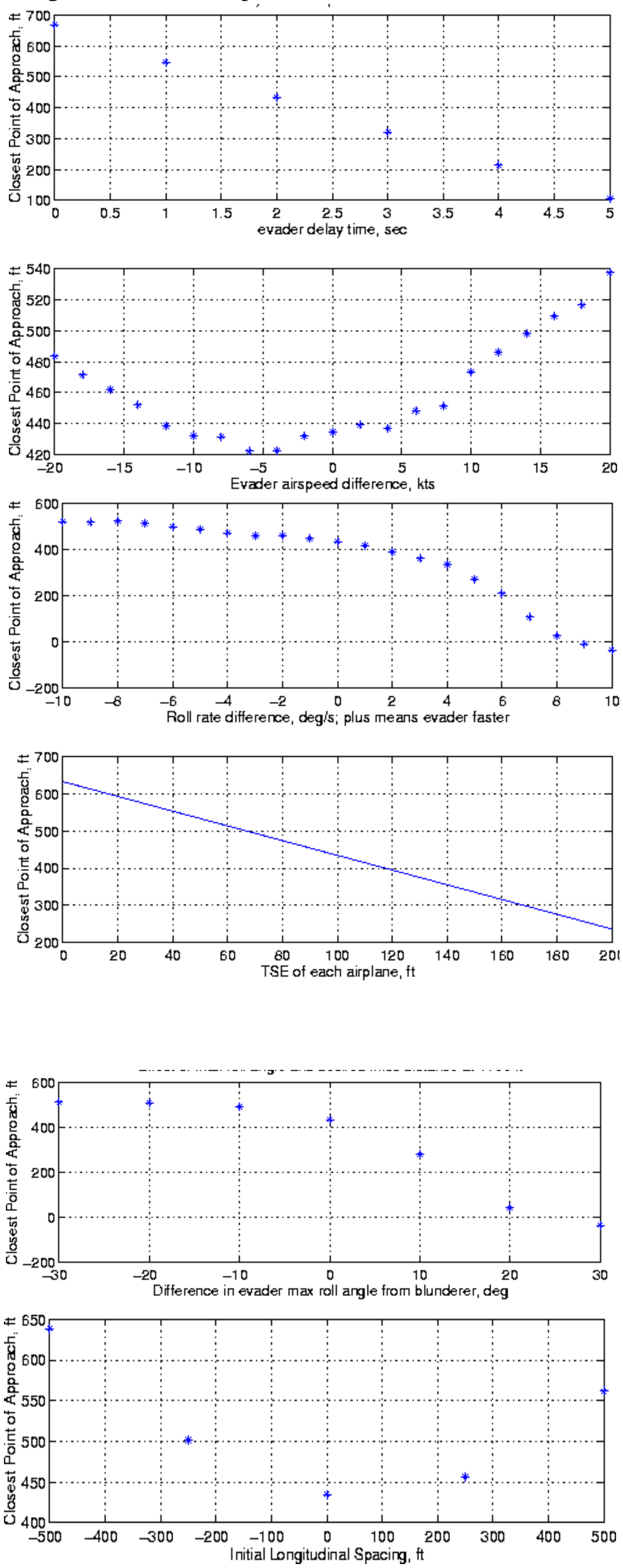


Table 2. Values at which a collision occurs, varied from the baseline case

Parameter	750 ft	1100 ft	1500 ft
TSE	147 ft	--	--
Δairspeed	--	--	--
$\Delta\dot{\phi}$	3.8 deg/s slower than the blunderer	8.8 deg/s slower	--
delay time	2.9 s	7 sec	--
maximum $\Delta\phi$	7 deg less bank than the blunderer	26 deg less bank	
Initial longitudinal spacing	--	--	--

Figure 4. Individual parametric sensitivities at 1100 ftt



Discussion

TSE

Maintaining a small TSE (composed of navigation sensor error and flight technical error, FTE) is critical to the success of UCSPA and can be done by using a GPS-based Landing System (GLS) such as the Wide Area Augmentation System (WAAS) or Local Area Augmentation System (LAAS), similar to those used in [11]. Demonstrated flight technical error in [11] for a pilot manually flying a Beechcraft Queen Air using WAAS and a tunnel in the sky display was under 40 ft, 95% of the time. Preliminary results from flight test data provided to Stanford by NASA Langley indicate that a B-757 on auto-pilot can maintain an FTE of less than 25 ft, 95% of the time. In this case, a local area DPGS system imitated the ILS approach. Typical navigation sensor errors for WAAS and LAAS are 3m and 1m, respectively. These FTE values are much better than those used by the FAA for approach analysis: 759 ft, 95%, for an LNAV approach with the auto-pilot coupled[12] and the TSE of 600 ft, 95%, measured in the Precision Runway Monitor program in Memphis [13]. While the FTEs from the AILS flight and in [11] are not representative of the current fleet-wide FTE, they represent a technically achievable goal with existing DGPS accuracy and an existing auto-pilot.

Safety buffer

Although visual formation flying is safely performed every day, it because of the large amount of information that the trail pilot has about the lead aircraft that this maneuver may be safely accomplished. In IMC, the safety buffer, typically 500 ft, is factored into maneuvers in order to compensate for a lack of high fidelity information about the neighboring aircraft. While any blunder is a fundamentally dangerous scenario for neighboring aircraft, this event occurs so rarely that no cases of a blunder during an IMC parallel approach has ever been officially documented. Anecdotal evidence suggests that blunders have occurred and therefore two fundamental capabilities must be given to pilots performing UCSPA: 1) the ability to fly a very precise, high integrity approach to landing and 2) the activities of the adjacent aircraft to sufficient detail that a successful escape maneuver may be accomplished should the other aircraft blunder. When these two capabilities exist, then the safety buffer may be reduced.

Heading Change

Although the maximum allowable heading change was 45 deg for the evader, the closest point of approach typically occurred near the point where both aircraft were on parallel courses with a 30 deg heading change. Therefore, it is important that the evader aircraft match the heading change by the blundering aircraft, but it is not critical that the evader aircraft exceed the blunderer's heading change.

Roll Angle and Rate

It is also important that the evader aircraft match or exceed the blunderer's roll rate as well as maximum roll angle. The sensitivity analysis shows that minimal advantage is gained by exceeding the blunderer's roll rate and maximum roll angle; however, significant sensitivity is exhibited if the evader fails to match the roll rate and maximum roll angle.

Delay Time

Delay time, which encompasses the data link update rate, the collision detection and resolution algorithm, the pilot/auto-pilot response time, and the aircraft dynamics, has a major impact on the successful completion of an UCSPA blunder evasion. A detailed discussion on the impact of the delay time is presented in the following section.

Reduced Dimensionality Sensitivity Study

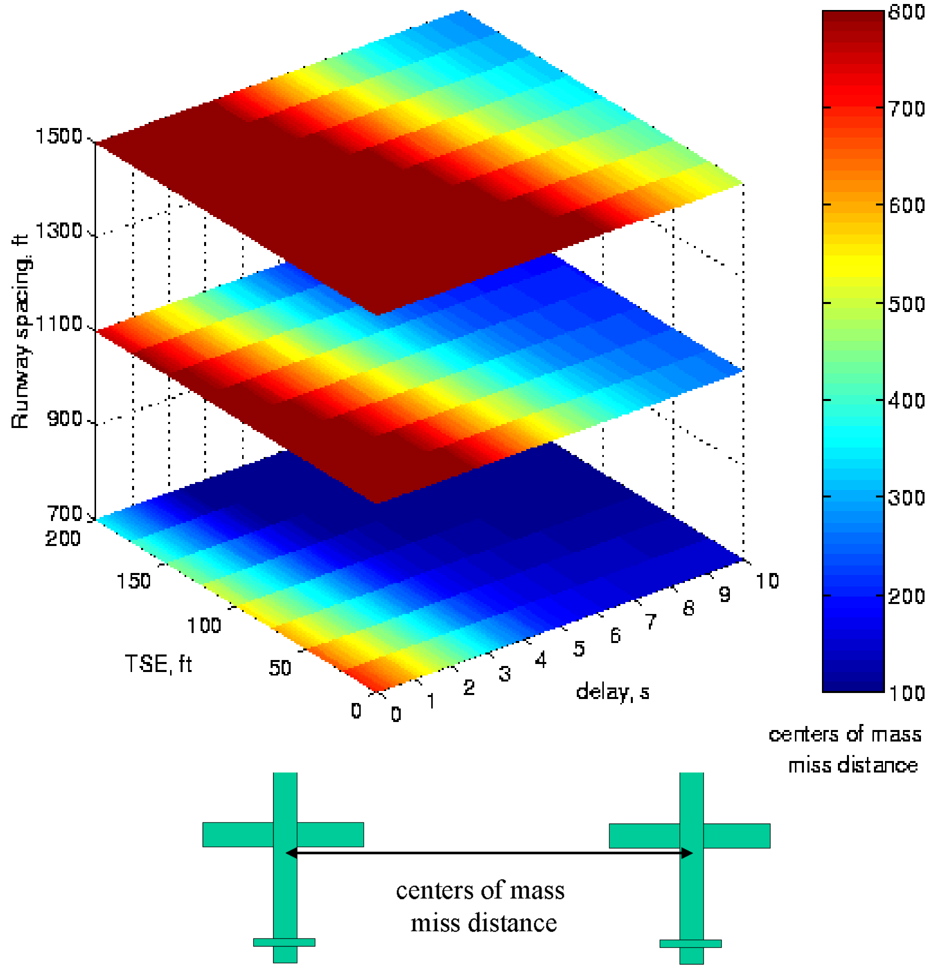
From the previous section, it was shown that three of the critical parameters in UCSPA are the delay time, the TSE of each airplane, and the safety buffer. Varying only these three parameters, a higher resolution simulation was created which highlights the trade-offs in designing UCSPA at various runway spacings. Figure 5 presents a composite view of the critical parameters for runway spacings of 700, 1100, and 1500 ft. The x-axis is delay time in seconds, the y-axis is TSE in feet, and the z-axis is runway spacing, in feet. The colors at each runway spacing corresponds to the safety buffer, with dark blue indicating a collision and dark red indicating a safety buffer of more than 500 feet, wingtip to wingtip.

Note that the safety buffer colors correspond to a distance between two point masses. To determine the safety buffer of an actual airplane, the largest dimension of that airplane must be considered. For example, the fuselage of the B-747-400 is almost 232 ft long, longer than its wingspan. In Figure 5, for two B-747-400s to avoid collision the centers of mass miss distance would need to be at least 232 ft, corresponding to a medium blue. The corresponding critical dimension for a B-737-700 is113 ft.

Impact on Navigation Sensors and Systems

At runway spacings less than 1100 ft, the desired miss distance places very tight constraints on acceptable TSE and delay time. The current "standard" safety buffer used in air traffic control applications is 500 ft. When including the size of the wingspan or fuselage length, this means that only the dark red areas presented in Figure 5 are permissible. Delay time encompasses the on-board collision detection algorithm, the air-to-air data link, airplane roll performance, and the pilot/auto-pilot response time. Data from dual airplane visual formation flying tests showed that a pilot responds to another aircraft rolling towards them in less than 2 seconds when less than 2000 ft apart[14]. The average pilot response from the AILS flight test [5] was 0.6 sec. When adding a possible delay of one second from a one Hz update rate air-to-air data link such as ADS-B and one to two seconds for aircraft roll dynamics, the total delay time can easily become 3 seconds. At 700 ft, this delay means that TSE must be less than 75 ft throughout the approach in order for the two airplanes to just miss each other in the nominal 30 deg blunder scenario.

Figure 5. Detailed parametric trade-off



Conclusions

Future Flight Deck Technology

It has been demonstrated that TSE can be reduced to less than 75 ft by using differential GPS and a recently produced auto-pilot. The other technological hurdle to UCSPA is the delay time between the beginning of the blunder and the initiation of the escape maneuver. Assuming the existence of an air-to-air data link, the fast response times (< 5 sec) required at runway separations less than 1100 ft will require either new displays for pilot-in-the-loop operations or distributed, coupled auto-pilots with high-integrity collision detection algorithms. A combination may be envisioned whereby the auto-pilots of the two aircraft are coupled and the pilots monitor the approach with a different display. Although the ADS-B MASPS [15] specify a 2 Hz update rate with 50% probability of reception, effectively making it a 1 Hz data link, it is probable that UCSPA would require effective update rates of 2 to 4 Hz. In addition, maximum roll angle and roll rate have been shown to be critical parameters in avoiding a blundering aircraft and should be included in the data link message.

Environmental Impacts

The technology to accomplish UCSPA will require new equipment in aircraft and on the ground. It will be such that all aircraft using an airport will need to be equipped with the new technology in order to reap the full capacity benefits. The equipment will probably cost on the order of $100,000 per aircraft. The airframe manufacturers and their airline customers do not easily accept this situation. The easy solution for them is to lobby for no such mandatory re-equipage and to argue for airport expansion with conventional runway spacing. However, a wider view is necessary for the best overall solution for the taxpayers, the airline passengers, and freight shippers who ultimately have to pay for the full system costs, including airport expansions. The wider view also should take into account the welfare of airport neighbors, residents of areas that might become new airports, and the environmental damage brought by expanding airports into areas that are now water. To put this into perspective, the re-equipage of 10,000 aircraft, the approximate size of the US air carrier fleet, would cost approximately $1B whereas the expansion of SFO into the bay for new runways is projected to cost $2B!… and this is just one proposed airport expansion project.

In short, development of technology that allows the use of very closely spaced runways in IMC has *huge* long-term environmental and cost benefits. It should be a high priority for the FAA, NASA, and the avionics manufacturers.

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