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GENERALIZED PHILOSOPHY OF ALERTING WITH APPLICATIONS TO PARALLEL APPROACH COLLISION PREVENTION

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Abstract

Using existing and recently proposed alerting systems for closely-spaced parallel approaches as case studies, three high-level methods or philosophies behind alerting decision-making are introduced. The first philosophy bases an alert decision on whether an aircraft is conforming to expected behavior. The second philosophy extrapolates a situation into the future to determine whether a hazardous incident may occur. Ensuring that a safe escape option always exists is the basis of the third philosophy. These methods apply not only to parallel approach, but to any alerting problem. A better understanding of these philosophies will then facilitate reaching system designs in a more rapid, direct, and repeatable manner than is often the case. An example analysis is presented to show how trajectory predictability impacts the performance of conformance-based and trajectory-based methods. A more detailed study of conformance-based alerting thresholds is also discussed, directly quantifying the benefits to performance (in terms of safety and false alarm rate) that are possible with the use of additional state variables in the decision logic (e.g., lateral position, heading, and turn rate).

Introduction

Typically the alerting logic of a hazard avoidance system begins with an intuitive concept, and evolves as inadequacies become apparent through simulation, the input of experts, and actual use. Each system development process can give rise to a distinct form of logic, sometimes dramatically different from others derived for similar applications. Over 60 variations in modeling methods have been proposed or implemented for air traffic conflict detection and resolution, for instance.[1] It is often unclear which differences between methods are necessary versus which are the result of subjective choices that became fixed early in the design process.

Examination of the underlying properties behind each category of methods may simplify and improve the designs of future hazard avoidance systems. Three examples serve to illustrate these different methods.

First, the Precision Runway Monitor (PRM) is a surveillance and collision avoidance system that enables independent approaches in instrument meteorological conditions (IMC) to parallel runways spaced as closely as 3400 ft.[2] This system employs special air traffic controllers (ATC) to watch approaching traffic on displays with an alerting capability, and intervene to preclude a collision if a deviation or "blunder" occurs. On a PRM controller's display, two adjacent approach paths are shown separated by a strip of forbidden airspace, or No Transgression Zone (NTZ), as shown in Fig. 1. If an aircraft enters the NTZ (or is predicted to do so within several seconds, depending on display settings), PRM controllers receive an alert prompting them to communicate corrective maneuver commands to the affected pilots.

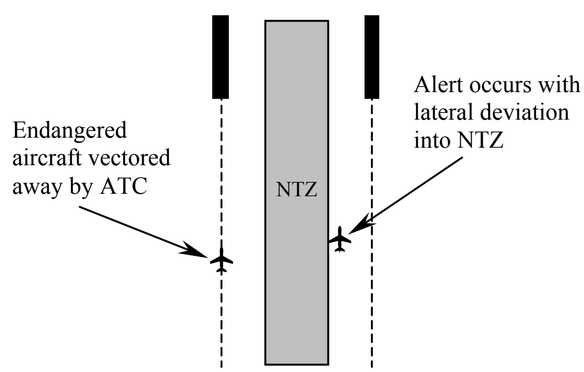

Fig. 1 Precision Runway Monitor

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As a second design method, the Airborne Information for Lateral Spacing (AILS) logic was conceived by NASA Langley with Rockwell-Collins for a proposed cockpit-based parallel approach collision avoidance system.[3,4] It was later modified at Honeywell Technology Center in cooperation with NASA.[5] The purpose of AILS was to enable independent IMC approaches to parallel runways spaced more closely than 3400 ft. This was to be accomplished by reducing delays in the blunder detection and alerting process. Radar surveillance and air traffic controller intervention would be replaced by automatic data link of state data between aircraft, computerized data processing, and alerting aboard each aircraft.

The AILS alerting logic is complex, using a combination of approach conformance and trajectory prediction criteria to make alerting decisions.[5] Of importance to this discussion is that the logic can produce an alert whose basis is that one aircraft is specifically threatening another. For such alerts a near collision must be explicitly predicted as shown in Fig. 2. At brief intervals the future trajectories of all aircraft are projected forward in time. If using the trajectory model a near collision will occur within a limited trajectory projection time, alerts are generated. Depending on the urgency of the situation, the involved pilots receive either attention-getting signals or breakout commands from their respective cockpit alerting systems. The breakout procedure involves a 45° turn away from the adjacent centerline and a simultaneous pull-up to a prescribed final climb rate.

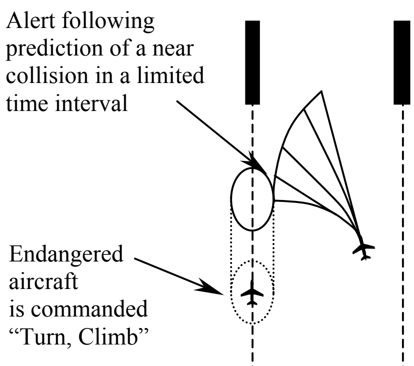


Fig. 2 AILS Predictive Alert Logic

As a third design alternative, a different alerting method was prototyped at MIT.[6] Breakout alerts are again issued directly to the pilots of aircraft, but are based on the estimated safety level of an evasive maneuver (Fig. 3). The metric of safety was the probability of a collision during a procedural turn-with-climb evasion. In an ideal implementation, the probability would be computed in real time via Monte Carlo simulation or analytical methods at brief intervals. The use of an evasive maneuver model to trigger alerts has also been under investigation by Teo & Tomlin for the so-called Paired Approach Concept, and by Zhao & Rock for formation flight.[7,8]

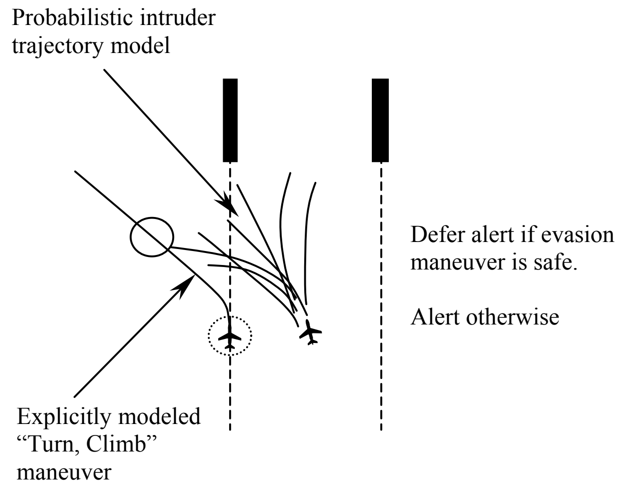


Fig. 3 MIT Parallel Approach Alerting Logic

While the AILS logic involves simulation of the trajectory assuming there is no alert, the MIT model simulates the trajectory occurring after an alert is issued. One aircraft is modeled as performing a prescribed evasion maneuver from its current state, while another is modeled as a potential blunderer, following a variety of trajectories according to its measured initial state and probabilistic weightings. If the probability of a collision reaches a certain threshold, the evasion is deemed necessary under the reasoning that such risk is marginally acceptable and that the probability of a safe evasion might decrease if there is any further delay before alerting. Otherwise, the alert is deferred to minimize the likelihood of a false alarm.

These examples represent three distinct philosophies of decision making that appear to encompass most existing or proposed hazard avoidance algorithms: alerting when the human-controlled system fails to conform to established procedure (PRM); alerting if a hazardous event is explicitly predicted to occur if no intervention takes place (AILS); and alerting based on the risk associated with a planned escape path (MIT). A more detailed discussion of each philosophy follows. But first, some recurrent terms and concepts are discussed.

Alerting Background

An alerting system is designed to prevent occurrence of a catastrophe through timely warnings issued to human operators within a larger system. In this paper, an alert refers to the output of an alerting system, beginning at a particular time and resulting in altered system dynamics. A hazard is represented by a set of system state vectors, any one of which is tantamount to a catastrophe.

The algorithm of an alerting system is described in terms of observable state variables. State variables are measurable quantities that aid in describing the condition of the larger system of which the alerting system, operators, and environment are parts. Examples are continuous variables such as position, speed, acceleration and physical dimensions, and discrete variables that describe different modes or configurations. Some alerting systems employ predictive state trajectory models in decision making. Such a model allows the logic to judge the likelihood or possibility of a future event, such as a hazard. Trajectory models take a number of forms, but can divided into three general groups: single-trajectory prediction, worst case, and probabilistic.[1]

Alerting system performance is often quantified in terms of the rates of hazard and false alarm events. A hazard event occurs any time the system trajectory encounters (ends in) a hazard state. The alerting system may have failed to issue needed alerts, issued a late alert, or even induced the hazard event through unnecessary alerting.

A false alarm occurs if the alerting system issues an alert that is not needed to prevent a hazard event. It may be difficult to say whether an alert that has occurred is a false alarm, because the opportunity to observe the non-alert trajectory of the system is lost as soon as the alert occurs. The frequency or probability of false alarms has sometimes been estimated for a given alerting system by introducing a probabilistic model of the system dynamics in which the behavior of the system before and after alerts is explicitly defined.[9] Note that a false alarm is not mutually exclusive of a hazard event (e.g., in the case of a collision induced by action taken in response to an alert).

A third event type, the "perceived incorrect alert" is also suggested here. An alerting system action (alert or non-alert) is perceived to be incorrect if an operator believes immediately or in retrospect that a better decision should have been made with available information. This can occur when an operator decides that a false alarm has occurred when there was insufficient risk of a hazard occurring nominally, believes that an alert was necessary but finds commanded maneuvers unsafe, is aware of a past alert that induced a hazardous event, or believes that an alert failed to occur when it was necessary. Thus, such events can in principle range from annoying or disruptive false alarms to disasters blamed on the alerting system. It is important to distinguish the other two alerting event types, false alarms and hazard events, from perceived incorrect alerts. While either of the former two events can also fall into the third category, one can imagine cases where a false alarm, perhaps even a hazard event, is not perceived as an alerting system failure. In addition it may be possible for an outcome that is neither of the first two event types to be considered an alerting system failure. For example, an operator could mistakenly consider an alert an unjustified false alarm when it is not a false alarm at all. The key word in this discussion is *perceived*. Assuming that operators initially have high confidence in an alerting system's potential, an accumulation of perceived incorrect alerts can reduce operator confidence in that system.

Three Philosophies of Alerting Logic Design

Three common philosophies of alerting logic design were identified above and related to existing or proposed systems for parallel approach collision prevention. Following is a more detailed description of each philosophy.

Conformance Monitoring

This type of logic uses non-conformance of a system to established procedures as a basis for alerting. For example, Fig. 4 shows a system state with respect to a normal operating region in state space. If the state exits the normal operating region an alert is issued. As shown, the normal region is constructed to be mutually exclusive of the hazard, though the hazard need not be explicitly modeled. In PRM, for example, as long as both aircraft remain outside the NTZ the hazard cannot occur. An aircraft entering the NTZ will trigger an alert whether or not it actually threatens another aircraft.

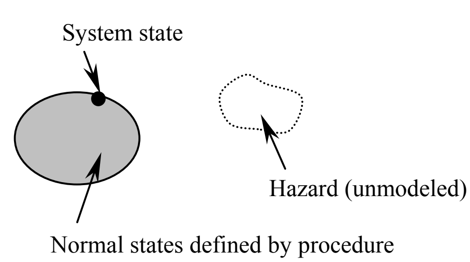


Fig. 4 Conformance Alerting

A deviation ("blunder") from the normal procedure is a necessary precursor to a hazard event, so it can be argued that an observed deviation from normalcy is sufficient reason for an alert and corrective action, provided such a policy does not result in a high rate of alerts occurring without a blunder. Frequent false alarms during normal system operation would be perceived as incorrect by operators, and might in time cause operators to ignore or delay responding to alerts.

In addition to establishing that the non-blunder alert rate is acceptably low, it should be shown that when a blunder does occur there will be an evasive maneuver having an adequate likelihood of success. Decreasing the size of the threshold around the normal operating region can increase the available time to avoid a hazard, but will also increase the false alarm rate. An analysis of this tradeoff typically involves a reference dynamic model of the system and iterative adjustment of the alert threshold until safety and false alarm specifications are met.[10] Because of the dependence of the threshold on the operational procedure, it may be necessary to adjust the procedure itself to achieve performance goals. For example, it was concluded that PRM could be used with parallel runways spaced no less than 3400 feet apart or else the likelihood of safe resolution of a blunder was too low in simulation studies.[2]

Nominal Trajectory Hazard Prediction

This alerting strategy involves checking for a hazard through explicit prediction of the non-alert, or nominal, system trajectory (Fig. 5). A trajectory model, which might be probabilistic, worst case, or a single predicted trajectory, is propagated forward from the current measured location to determine if a hazard will be encountered. For an alert to occur, a hazard event must be specifically predicted. Under this philosophy, the logic avoids alerts that are not clearly justified due to a specific hazard.

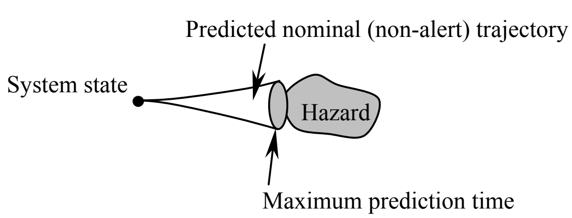


Fig. 5 Nominal Trajectory Prediction Alerting

Due to uncertainty in prediction and the consequent possibility of false alarms, it is insufficient to simply alert when a hazard event is predicted. Typically an additional metric or metrics are required for threshold definition. Possible metrics include the degree of certainty in occurrence of a predicted event (for a probabilistic trajectory model), or the predicted time to collision or miss distance (for worst case or single-trajectory models). The values of threshold parameters must be chosen to satisfy safety and false alarm goals.

Whether a hazard is imminent along the nominal trajectory is not a direct indication of whether an evasion maneuver will be safe. Such safety can be ensured indirectly, in a similar manner as used in the conformance method, through modification in response to observed performance. Too many collision events will suggest increasing the alerting lookahead time; too many false alarms will tend to reduce the desirable lookahead time.

Escape Trajectory Prediction

The third philosophy directly addresses the desire to have an explicit means of checking for the safe resolution of a threat situation. In general there may be specific completion conditions that must be met in order for a potential incident to be considered resolved, and it is possible to defer alerts until such conditions can no longer be ensured. For example, the MIT system issues alerts based on an estimate that a collision may occur with some likelihood assuming that an alert is issued and that an evasive action is taken.

This type of logic is superficially similar to the nominal trajectory hazard method in that it involves a predictive model. As illustrated in Fig. 6, a trajectory model is used to propagate the system state, but this time under the assumption that an alert is issued resulting in escape maneuvers. In general there may be multiple maneuver options (represented by evolving state envelopes—each resembling a horn in Fig. 6), corresponding to different warning inputs that can be issued to operators. Some limit to the trajectory extrapolation is generally needed, and can be defined in terms of completion conditions. As shown, completion conditions may require that the system reach a specific region in state space. In addition, it may be required that the system reach the completion state set within a particular time interval. Finally, the completion state set cannot intersect with the set of hazard states—given that the hazard event is a "catastrophe," it should not be considered as part of a desirable alerting outcome. The escape trajectory model is then examined to determine whether the completion conditions can be met without encountering a hazard event.

According to this philosophy an alert may be deferred as long as available alerting options are safe. An alert can no longer be deferred when safety becomes marginal. In other words, an alert is considered justified when there may be no acceptable option remaining at the next alerting opportunity.

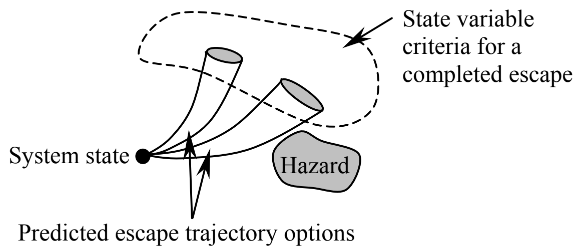


Fig. 6 Ensuring That Evasive Options Exist

With nominal trajectory prediction, there was a loss of direct control over safety. Safety had to be ensured indirectly by tuning the threshold parameters until safe escapes occurred without false alarms. In the escape trajectory method, there is instead a loss of direct control over false alarms. This is because whether an escape maneuver is safe is not a direct indication of whether the nominal system trajectory is safe or whether the alert was a false alarm. For example, it may be possible for an evasion option to become marginally safe, triggering an alert, even when no hazard would be encountered on the nominal trajectory.

For the MIT system a successful alerting outcome was defined as any case where a collision fails to occur within a fixed time after the alert. These conditions do not preclude the occurrence of collisions immediately beyond the prediction time limit, and pilots or air traffic controllers might reasonably object to an alerting system that makes no guarantees about the resolvability of the post-alert situation. More stringent completion conditions could also be used, such as to require a minimum separation, divergence rate, heading difference, etc. between aircraft within the limited time interval for which dynamics are modeled. More stringent completion requirements may translate into a smaller completion set in state space, and thus may cause the alerting system to encounter a marginal safety condition earlier than it would have otherwise. So although increased escape stringency may improve confidence in the safety of an alerting outcome, it can also increase the likelihood of false alarms.

Combined Philosophies

An alerting system must be made to satisfy performance goals that are independent of the preferred philosophy of a particular designer. Depending on the philosophy, satisfying performance goals may ultimately require extensive modification to the initial design. If important issues are not addressed at first, the resulting performance deficiencies can still be eliminated in an *ad hoc* fashion, though this is not efficient.[10] An adequately functioning algorithm may be attained in numerous ways, but there is no guarantee that different methods that are equivalent in performance are also equal in simplicity or understandability.

Each philosophy can be thought of as emphasizing different components of alerting performance. A conformance-based method uses an alert threshold requiring deviation from established normal system dynamics (e.g., operating procedures). It is conceptually simple enough to promote operator belief in the appropriateness of alerts when they occur (though not necessarily in the particular resolution commands chosen), provided it is tuned to minimize normal approach false alarms. It could be said to emphasize minimization of perceived incorrect alerts, but such a logic does not *inherently* ensure that alerts are safe or that they are not false alarms.

A nominal trajectory-based logic provides confidence that an alert is not a false alarm. But based on this trajectory model alone, no direct determination of whether an alert will be safe or how it is perceived can be made.

An escape trajectory-based logic ensures that alerts occur when they are still likely to be successful. But there is no automatic guarantee that such alerts are not false alarms or are perceived as correct.

A strict application of any one of the three discussed philosophies is unlikely to satisfy performance requirements alone — modifications to each basic concept are needed. Rather than produce an initial design according to one philosophy and make later adjustments that amount to the addition of properties of the other two philosophies, it may be simpler and more insightful to begin with an approach that combines philosophies.

Directly combining the nominal and escape methods is an attractive means by which both safety and false alarms can be addressed simultaneously. This combined alerting logic would examine both the likelihood of a hazard event along the nominal trajectory, and the likelihood along the escape trajectory. An alert is issued only when it is necessary (nominal method) and the resulting escape maneuver is clear of hazards (escape method). This concept has been developed and successfully tested in a prototype air traffic conflict detection system, and leads to acceptable performance in a more direct manner than designing a system based on only one trajectory method.[10]

Effect of Trajectory Predictability

Notionally, it would be expected that the quality of decisions made by a trajectory prediction system would decrease as uncertainty in the future trajectory increased. In the limit, a decision based solely on a completely inaccurate trajectory prediction would have no diagnostic benefit. A conformance-based approach might fare better, however, by alerting simply when the state deviated from desired bounds. Conversely, given perfect predictability, a trajectory prediction system would likely outperform a conformance based system because it uses that additional accurate information to better diagnose the need to alert the human.

As an illustration of this concept, the quality of decision-making for a conformance system was compared against a nominal trajectory system as a function of the predictability of the trajectory. To do this, a Monte Carlo simulation of random trajectories was performed. Each trajectory traced the path of a point mass whose lateral velocity was specified by a Markov process. A Markov process has the characteristic that the next state in time depends only on the current state and not on previous states. The predictability of the trajectory can be specified in terms of the autocorrelation of the Markov process.[11] The more highly correlated the process, the more accurately that the future trajectory can be predicted. Two levels of correlation were used here, with characteristic correlation distances (τ) of 100,000 m and 10 m (Fig. 7). The 100,000 m correlation distance resulted in essentially straight-line paths from left to right, while the 10 m correlation distance case resulted in more noisy paths as shown in Fig. 7.

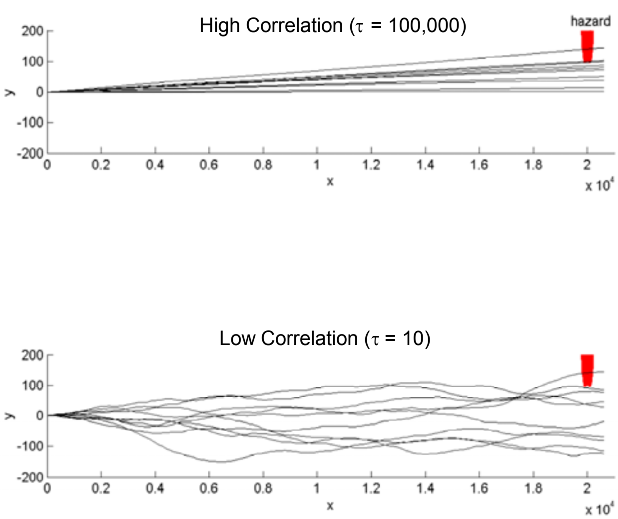


Fig. 7 Example Trajectories

These trajectories were simulated in the presence of a small hazardous region, also shown in Fig. 7. Alerting thresholds were then set using either a conformance method or using a trajectory prediction method (Fig. 8). The conformance threshold was set at a parameter distance *z* laterally from the starting position as shown in Fig. 8a. The location of *z* was then systematically varied to trace out the performance of the system as a function of threshold position. In the trajectory prediction case, a projection from the current state was made using the instantaneous velocity vector. This projection continued for a parameter distance *z* as shown in Fig. 8b; this parameter was also systematically varied to explore its effect on system performance.

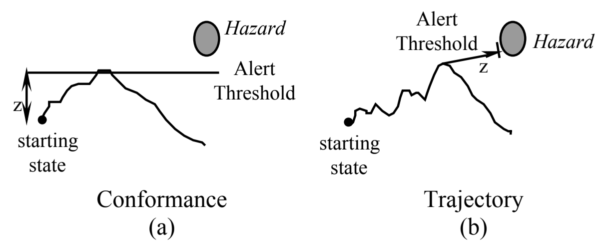


Fig. 8 Alerting Methods

Crossing an alert threshold altered the future trajectory of the process by adding a bias to the lateral velocity, simulating the corrective action taken in response to the alert. Depending on where the alert was issued, the state might still encounter the hazard even after this evasive maneuver had begun. At the moment an alert was issued, a second "ghost" trajectory was also simulated that followed the original Markov process statistics without the escape maneuver bias. This allowed for a check to see if the state would have encountered the hazard had no alerting system been present.

The outcome of each trajectory simulation was categorized as follows. Trajectories that produced an alert that was ultimately successful in avoiding the hazard were called successful alerts. Second, those alerts that were unnecessary were also counted. Unnecessary alerts were those in which the hazard would not have been encountered had the alert not been issued. In other words, after the alert was issued, the second ghost trajectory did not encounter the hazard. For that trajectory, then, the alert was not required according to this strict definition. The number of successful alerts and unnecessary alerts were then counted and divided by the total number of simulation runs to estimate their corresponding probabilities.

When averaged over a large number of simulations, a given alerting threshold setting *z* results in a single observed pair of successful alert probability and unnecessary alert probability. The threshold setting for each method was then systematically varied, from extremely conservative (z was set such that alerts were always generated) to extremely risky (z was set such that alerts were never issued). This then traces out a so-called System Operating Characteristic (SOC) curve.[9] A total of 5000 simulations were performed at each combination of threshold setting, alerting method, and trajectory correlation level.

The results are shown in Fig. 9. In the high-correlation case, it can be seen that the trajectory prediction method performs very well. There is a threshold setting that provides nearly ideal performance, with almost no unnecessary alerts and with almost all alerts being successful (top left corner of the plot). The conformance system is not able to reach the same level of performance, regardless of threshold setting, and incurs a higher rate of unnecessary alerts.

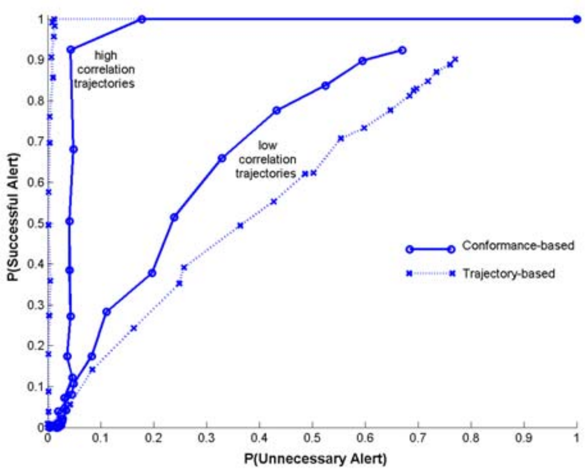


Fig. 9 Alerting Performance Results

In the low-correlation case, the trajectory prediction method performs poorly. Regardless of threshold setting, a high level of successful alert can only be attained while also incurring a high rate of unnecessary alert. The curve for the trajectory prediction case comes close to the diagonal from (0,0) to (1,1) in the SOC plot, indicating that the system is of little diagnostic benefit. The conformance system, however, is able to perform better than the nominal trajectory system in this case. Although both systems' performances are lower than in the high-correlation case, it is seen that a better decision can be made based on the current state (via the conformance boundary) than is possible when relying on inaccurate trajectory information.

Similar analyses can be performed to examine the relative quality of decision-making using each philosophy (or combinations of philosophies) under different conditions. This example serves to demonstrate, however, that a quantitative relationship can be obtained between the characteristics of a problem (e.g., uncertainties) and the performance that is achievable from a given philosophy. This quantitative relationship will be important in targeting design efforts toward the most effective modeling methods.

Conformance Thresholds for Parallel Approach

Summarizing the alerting philosophies described above, there are two main methods to solve parallel approach blunder problems. First, it may be possible to detect that an aircraft is not executing the approach within normal bounds and is blundering. Second, it may be possible to use a trajectory model (either nominal- or escape-based) to determine whether another aircraft is explicitly threatened. If a blunder begins and is not corrected, presumably there is some critical system failure involved. It then becomes increasingly difficult to develop an accurate trajectory model with which to estimate the future position of the aircraft, which in turn makes it more difficult to implement an effective trajectory-based alerting method. Accordingly, parallel approach alerting might best be managed using conformance-based techniques. To examine this potential, a more detailed analysis of conformance-based thresholds was performed.

A PRM-like alerting threshold based on lateral deviation from the approach path is the simplest example of a conformance-based logic for parallel approach alerting. A conformance-based threshold employing state variables in addition to lateral deviation would likely carry some advantages, but would also incur the cost of implementing a data link of these parameters to the alerting system. It is then worthwhile examining the benefits that additional state variables would provide toward decision-making.

Likely parameters to use for conformance-checking are exceeding lateral position, heading angle, or turn rate boundaries. Figure 10 shows an example state space region using two state variables (e.g., lateral position and track angle). The aircraft's location in this space traces out a trajectory as shown. Crossing a threshold boundary can then be used to trigger alerts. The design issue then becomes what variables should be used in the state space, and how should the boundary be shaped.

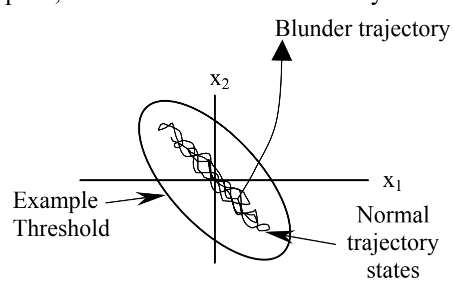


Fig. 10 Conformance Threshold in State Space

The general concept then is to enclose normally-occurring trajectories by a boundary in several dimensions. The boundary must be small enough that a departure from normal operations can be detected rapidly, but not so small that false alarms occur often during normal operation.

Simulation Model

To develop appropriate conformance bounds, it is necessary to understand the behavior of a normally-operating parallel approach system. Trajectory data for an existing system may be difficult to obtain in large quantities. In addition, any future alerting system for parallel approach collision prevention will likely be designed for an approach system operating under approach guidance technology and procedures that have yet to come into standard use. This makes operational data even more difficult, if not impossible, to obtain. As a preliminary step, computer generation of random trajectories of an aircraft operating in a future approach system were used.

Aircraft dynamic models of varying fidelity are commonly available. These range from full nonlinear models to simple models linearized about a particular flight condition. For the current problem it is assumed that an aircraft is established on a straight final approach at constant speed, so that its dynamics are well approximated by a linearized model. The linearized lateral and vertical approach dynamics of an aircraft (a C-47) were selected for initial experimentation in a fast-time simulation.[12] Available state variables included position in three dimensions, velocity, and attitude angles. The control inputs to the aircraft were the aileron, rudder, and elevator angles. A controller was designed using linear quadratic optimal state feedback methods in order to meet approach performance criteria, but normally one would attempt to duplicate as closely as possible the dynamics of the existing or planned aircraft/controller system of concern. Lateral deviation from the approach course was used in the feedback control loop instead of angular deviation, emulating a constant-width approach corridor based on the Global Positioning System (GPS), for example.

Variation of the aircraft state about the nominal approach path was induced through random disturbance inputs to the system. Disturbances included those directly affecting the aircraft state (such as wind gusts), state measurement noise, and controller outputs. Each type of disturbance was approximated as the output of linear filters driven by white noise.

As discussed above, simulation of the normal behavior of an approach system is arguably more reasonable as an analysis technique than random simulation of blunder behavior, as has been attempted in past alerting system analyses.[13,14] When operating normally, the approach system should behave according to well-defined dynamic laws and random inputs that can be observed and modeled. The same generally cannot be said of blunders.

Metrics and Results

To execute the analysis, two performance metrics were computed for an ellipsoidal threshold in a state space incorporating different combinations of state variables. The size of the ellipsoid in each parameter's dimension was set based on the variance of that parameter during normal approach. For example, the ellipsoid could be set to enclose three standard deviations of lateral position error and heading angle. There would then be a 99% probability that the aircraft state would lie within the ellipsoid at any one time.

The first performance metric addressed the frequency with which false alarms were issued during otherwise normal approaches. This metric, T_{FA}, was defined as the mean time before an alert was issued for an aircraft trajectory beginning at the nominal approach state and following the normal dynamic control model. T_{FA} is a function of the specified alerting ellipsoid size: a larger ellipsoid increases T_{FA} and reduces the false alarm frequency.

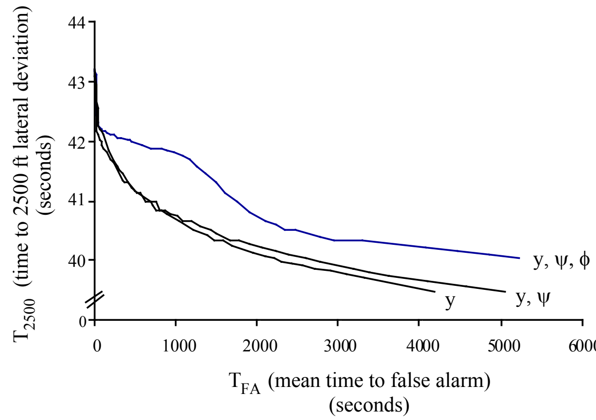
The second performance metric was based on the risk posed to neighboring aircraft when a blunder occurred. This metric, T_{2500}, was defined as the time that transpired starting when the ellipsoid was crossed (and an alert was issued) and ending when the blundering aircraft had deviated 2500 ft from its centerline. T_{2500} provides a first-order indication of the amount of time a pilot may have to begin an evasive action. The blunder maneuver that was used to compute T_{2500} was idealized in that it began at the nominal approach state (centerline), and occurred without random state variations about the blunder trajectory. T_{2500} also depends on the size of the ellipsoid and on the specific blunder that was flown. Several representative blunder maneuvers were simulated, including a 5° constant-bank coordinated turn, and a heading change with roll-out at 30° from the runway centerline. All were at a constant speed of 145 knots.

Alerting threshold variations included the number of state variables on which the threshold was based and the size of the alerting threshold ellipsoid in terms of standard deviations. Three state variables were available as bases for the ellipsoid: lateral position, y, heading angle, ψ, and bank angle, ϕ. Three conditions were examined: alerts based on y only; based on y and ψ; and alerts based on all three variables. As an initial design point, the threshold ellipsoid was sized to enclose the same number of standard deviations in each dimension. In each test condition, the ellipsoid was systematically scaled to a different size, again equally in each dimension. Simulating over these conditions resulted in the performance curves shown in Fig. 11.

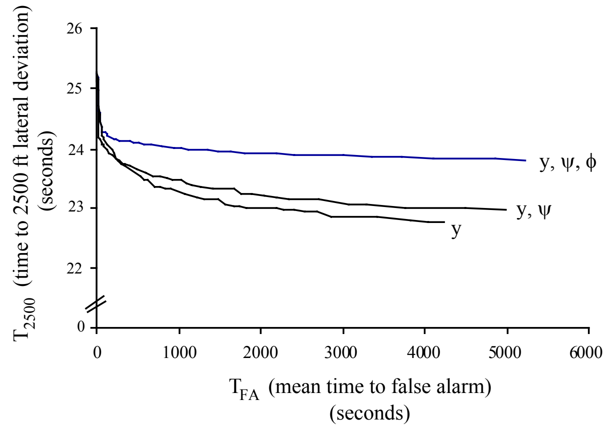
In the plots of Fig. 11 the horizontal axis shows T_{FA}, and the vertical axis shows T_{2500}, providing a measure of the time available to initiate an evasive maneuver. For example, consider a 5° constant-bank-angle blunder and a threshold based on lateral deviation, heading, and roll angle (Fig. 11a, upper curve). A threshold sized such that there would be a 1,000 s mean time to false alarm then results in an alert being issued approximately 42 seconds before that type of blunderer reaches a 2500 ft lateral deviation. As the ellipsoid is expanded, T_{FA} would increase (moving right in the diagrams) and the available escape time (T_{2500}, vertical axis) would decrease. This illustrates the classical design tradeoff in alerting decisions.

For a given value of T_{FA}, more escape time is possible when additional state variables are included in the threshold definition, as shown in Fig. 11. Roll angle is particularly useful in the cases that were studied, resulting in up to a second of saved time for the values of T_{FA} shown. Note, however, that 1 second is still a relatively minor gain when compared to the total time it may take the blunderer to reach an adjacent approach centerline. Heading angle appears to be a relatively ineffective addition to the system compared to roll angle, though even heading angle results in some minor improvement over lateral deviation alone for most conditions.

An issue to point out is that a desired value for T_{FA} is likely to be much larger than the 6000 second maximum shown here. Assuming that a single approach takes 300 seconds, a value of T_{FA} of 6000 seconds means that one alert would occur for every 6000/300 = 20 approaches (or 5% of approaches). This would be operationally unacceptable. Generating data for larger values of T_{FA} as is necessary for a more complete analysis would require extending this method to longer simulation runs, or changing to an analytical model as opposed to fast-time simulation.



(a) 5° Constant Bank Blunder



(b) 30° Heading Change Blunder

Fig. 11 Conformance-Based Threshold Performance

Concluding Remarks

Early design choices for alerting algorithms can ultimately place significant constraints on the potential performance those systems may provide. It is therefore beneficial to understand what general form of design philosophy may be best suited to a given problem's characteristics. To address this need, three general categories or philosophies of alerting decisions were defined: conformance within predefined operating limits; trajectory prediction assuming no additional intervention; and trajectory prediction assuming an evasive action is taken. These philosophies have been distilled through examination of a number of existing and proposed alerting systems over a variety of application problems. Which philosophy or philosophies to apply to a given problem depends on that problem's general characteristics, and are affected in large part by the accuracy with which trajectories can be predicted.

To demonstrate how a given philosophy is connected to system performance, an abstracted alerting simulation was performed. The results quantitatively show (using metrics of successful and unnecessary alert rates) that highly-predictable trajectories lend themselves to the use of a trajectory-prediction type of philosophy, while poorly-predictable trajectories can be better managed through a conformance-based approach. A given problem should therefore first be examined to determine which general approach should be taken when developing alerting algorithms. For example, given the unpredictability of a blundering aircraft's trajectory during an approach, a conformance-based alerting logic may provide an opportunity for higher decision performance than a trajectory-based method.

Finally, an illustrative example of multidimensional conformance-based alerting threshold analysis was described. This example quantified the performance benefits that are possible when new state variables are added to the decision-making process. This is an important consideration when determining whether the costs associated with obtaining additional state information are offset by decision performance benefits. These general concepts will be of use in future enhancements to existing or proposed alerting systems, whether for parallel approach or other applications.

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