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MODELING AND ANALYSIS OF CONFLICTS BETWEEN ALERTING SYSTEMS

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Abstract

The potential for conflicting information to be transmitted by different alerting systems is growing as these systems become more pervasive in operations. Newly-introduced alerting systems must be carefully designed to minimize the potential for and impact of alerting conflicts (or dissonance), but there is little formal understanding to aid this process. One example of alert proliferation is the recently-proposed Airborne Conflict Management (ACM) system which must operate in conjunction with the existing Traffic Alert and Collision Avoidance System (TCAS). Alerts from ACM should be harmonized with alerts from TCAS and vice-versa. A model of alert dissonance is developed to provide a foundation for understanding dissonance and as a tool to identify and resolve dissonance between systems such as TCAS and ACM. Several different types of alerting dissonance are identified using a state-space representation. As a case study, dissonant operating regions for TCAS and ACM are articulated, and it is shown that TCAS advisories cannot be avoided without aggressive maneuvering following ACM alerts in some geometries. This type of analysis should be continued with higher fidelity to further refine ACM specifications.

Introduction

Automated alerting systems are becoming increasingly pervasive in time- and safety-critical operations, with applications spanning aerospace vehicles, automobiles, chemical and power control stations, air traffic control, and medical monitoring systems. As these applications are pushed toward higher safety and capability, new alerting systems have been introduced to provide additional protection from hazards. This has led to an evolutionary, incremental growth in alerting functions to these applications over time. Because it is costly to completely redesign and recertify automation, these new alerting systems are typically required to be independent enhancements that do not directly affect the operation of existing systems.

The addition of new alerting systems to an already complex operation carries several liabilities.[1] First, there may be an increase in the amount of information processing required by the human operator, who now must be trained and able to respond rapidly to new signals. There is also a potential for simultaneous alerts from the different systems, possibly overloading or confusing the human.[2,3] This is a classic human factors challenge found in many work environments. These alerts could also be conflicting (or dissonant) in the sense that the information they provide suggests different actions be taken to resolve problems. Figure 1, for instance, shows an example of dissonance between two alerting systems: one system commands the operator to climb while the other commands a descent. This is an extreme example of dissonance, but other more subtle conflicts are possible and need to be examined to prevent them from reducing safety and increasing workload. It also should be noted that this very type of dissonance has already been observed between human air traffic controllers and automated collision alerting systems – the problem already exists and is likely to become worse if efforts are not directed at predicting and then mitigating dissonance.

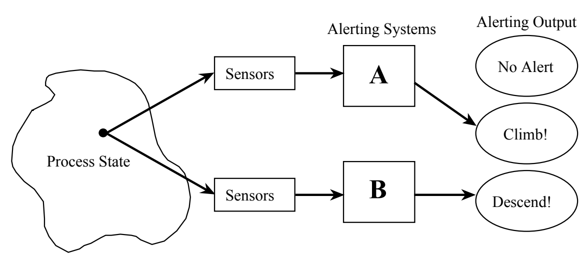

Fig. 1 Example of Alerting Dissonance

This paper provides an overview of alerting dissonance and presents a method by which two or more systems can be examined to determine their potential for dissonance. A specific case study is used to demonstrate the concepts, relating to two air traffic alerting systems that may soon be operating together.

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Air Traffic Alerting Systems

One area where dissonance is becoming an identified issue involves air traffic management safety. Several different traffic alerting system concepts are in use or under development, and they must be carefully matched to prevent dissonance. Time-critical collision alerting is the function of an Airborne Collision Avoidance System (ACAS), and more strategic maintenance of separation between aircraft is the function of a different Airborne Separation Assurance System (ASAS). Each type of system has distinct requirements due to different timescales, consequences, and information quality with which to base decisions. Combining ASAS and ACAS components within a single aircraft and between different aircraft will be a challenging problem to overcome to ensure that these systems convey consistent information to decision-makers.

One form of ACAS already in operation is the Traffic Alert and Collision Avoidance System (TCAS), which has been mandated on U. S. transport aircraft since the early 1990s.[4] TCAS uses range, range rate, altitude, and altitude rate between two aircraft via transponder messages. The quality of this information limits the ability to make accurate collision predictions beyond approximately 45 seconds. Based on this information, TCAS has two alerting functions: Traffic Advisories (TA), which direct the crew's attention to a potential threat, and Resolution Advisories (RA), which provide vertical collision avoidance commands to the crew. As mentioned earlier, climb/descend dissonance has already been noted between TCAS and air traffic controller instructions in actual operations. Dissonance between two different automation systems may exacerbate this type of human factors dilemma.

Recently, an ASAS concept termed Airborne Conflict Management (ACM) is being developed, and initial concepts and specifications have been drafted by an RTCA subcommittee.[5,6] ACM uses an Automatic Dependent Surveillance-Broadcast (ADS-B) data link to enable longer look-ahead than is possible with TCAS. ADS-B periodically broadcasts aircraft information such as identification, horizontal position, velocity, altitude, and the next trajectory change point. This information may enable accurate prediction of traffic conflicts on timescales on the order of minutes. In the initial concept, ACM includes three alert levels built around two separation zones called the Protected Airspace Zone (PAZ), and a smaller Collision Avoidance Zone (CAZ). A Low Level Alert is issued well before the violation of the PAZ with the intent to allow the crew time to resolve the conflict efficiently. If implemented and used properly, Low Level Alerts should be the only alerts issued from ACM. However, if the conflict remains unresolved, a PAZ Alert will be issued. A maneuvering response should then be initiated with a minimum of delay. If the conflict is still not resolved, a CAZ Alert is ultimately issued when immediate action is required to avoid a near-miss.

Several issues relate to the interoperability between TCAS and ACM. One set of issues relates to cases where TCAS and ACM are both installed on the same aircraft. TCAS measures relative range and bearing, while ACM receives the broadcast state vector and intent. The different surveillance sources may result in two targets that need to be merged or fused on displays.[7] The different surveillance methods used by TCAS and ACM may also produce different threat projections between the same targets. While ACM PAZ alerts will protect a much larger minimum separation than TCAS, the enhanced accuracy of ADS-B may allow ACM to determine that no threat exists while TCAS still predicts a threat (in some geometries). As such, TCAS may issue alerts when ACM sees no conflict at all. This may cause a problem if pilots have become accustomed to receiving ACM alerts prior to TCAS alerts. An additional source of concern would be transitioning from a lateral maneuver, which might be preferable during the resolution of a PAZ alert, to a vertical maneuver commanded by TCAS. The ability of pilots to make this transition or the degree to which they may continue the lateral maneuver needs to be studied. Finally, it would be preferable to not experience TCAS alerts at all if an ACM advisory is being followed. It is unlikely, however, due to certification requirements, that TCAS thresholds could be modified to reduce this type of dissonance. So, adjustments may need to be made to ACM instead.

A second group of issues relates to cases where TCAS is installed on one aircraft but ACM is installed on another. In this case, both aircraft can detect each other, but the two systems may issue different resolution advisories at different times. A problem exists if these resolutions are not coordinated or compatible.

Finally, a third group of issues revolves around the integration of both ACM and TCAS with yet other automated traffic alerting systems. Examples include existing or proposed ground-based conflict detection and resolution systems or specialized collision alerting systems for closely-spaced parallel approach.[8-10] Ensuring that these systems all operate harmoniously is going to be an increasingly challenging problem given these systems' complexity.

Aircraft Encounter Kinematics

To simplify the case study, the analysis of TCAS and ACM is limited here to only horizontal-plane motion where the two aircraft are coaltitude and converging.

Diverging and three-dimensional problems have been examined in a similar manner, but are omitted here for brevity.

Several kinematic parameters are required for the mathematical description of TCAS and ACM later in this paper. Figure 2 shows two aircraft (0 and 1) in the horizontal plane using Cartesian coordinates oriented along and perpendicular to aircraft 0's velocity vector. This choice of frame is arbitrary but simplifies the kinematic equations somewhat. The aircraft are a distance x and y apart in this frame, and have velocity vectors $\mathbf{v}_0 = [v_{0x}, 0]^T$ and $\mathbf{v}_1 = [v_{1x}, v_{1y}]^T$. The relative position of the aircraft can also be expressed in terms of their range r and bearing χ:

$$r = \sqrt{x^2 + y^2} \tag{1}$$

$$\chi = \tan^{-1}(y / x) \tag{2}$$

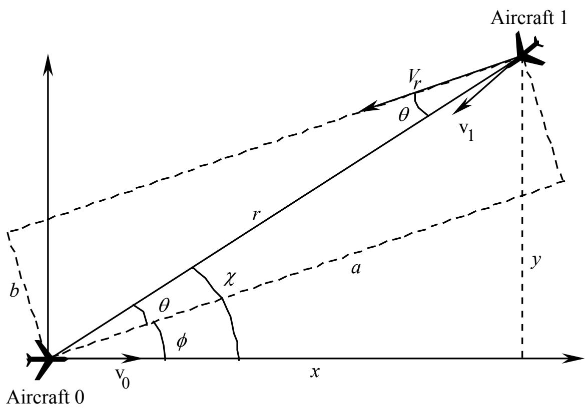

Fig. 2 Horizontal Plane Kinematics

The relative velocity between aircraft is

$$V_r = \sqrt{(v_{1x} - v_{0x})^2 + v_{1y}^2} \tag{3}$$

which can be expressed in terms of the range rate

$$\dot{r} = -V_r \cos\theta \tag{4}$$

where

$$\theta = \chi - \phi \tag{5}$$

and

$$\phi = \tan^{-1}\left(\frac{v_{1y}}{v_{1x} - v_{0x}}\right) \tag{6}$$

Finally, the distance until the closest point of approach, a, and the miss distance, b, are given by:

$$a = r\cos\theta \tag{7}$$

$$b = r\sin\theta \tag{8}$$

Model of Multiple Alerting System Dissonance

To date, management of potential dissonance between systems has occurred without a structured understanding of the specific issues involved. The identification of the potential for dissonance and the development of mitigation methods would be greatly facilitated through the application of a coherent, formal model. Such a model would have three benefits. First, it would aid in understanding the different types of dissonance that may occur. Second, the model would help in identifying when or where the different types of dissonance could occur in a given operation. Third, the model may be used to design and evaluate mitigation contingencies to prevent or preclude dissonance from occurring.

This paper presents an initial model of multiple alerting system interactions that can be used to identify and describe dissonance. Several different types of dissonance are defined, each of which may require a different mitigation approach. A mathematical method for analyzing dissonant situations is then presented and applied toward the integration of TCAS and ACM in a case study.

Management of Dissonance

Dissonance between automation in existing systems has traditionally been resolved using prioritization. Each alerting system can be prioritized, and if more than one alerting system is triggered, the lower priority alerts may be inhibited or only displayed passively (without separate attention-getting signals). Prioritization can help reduce sensory and cognitive overload of the human during a time of high stress. Complex prioritization schemes have been developed for the various alerting systems on board an aircraft.[2,3] Terrain, for instance, is placed at a higher priority than other air traffic, with the rationale that all else being equal, it is less likely that an aircraft would collide with another aircraft than it would hit terrain.

To address one aspect of the TCAS / ACM compatibility issue, a Conflict Resolution System Priority Matrix has been developed.[6] This matrix proposes suppressing any ACM advisories that are dissonant with TCAS RAs. The main issue here is that the dissonant TCAS RA may occur *after* the ACM alert. ACM may need to be designed with some means for predicting that a TCAS alert will be occurring, and ACM advisories may need to be modified to ensure that they remain in consonance with that future TCAS alert.

An alternate way to mitigate the effect of alerting system conflicts is through operator training. Pilots will be trained, for example, that ACM and TCAS use different decision-making logic, and that alerts from the two systems may not (and in fact probably will not) occur in concert. In extreme situations, however, training should not be relied upon too greatly.

Additionally, it may be possible to modify air traffic operations themselves so that dissonance is less likely. A request to pilots to reduce their vertical speed as the aircraft nears a target altitude, for example, is one operational change that has already been made to help reduce the likelihood of dissonance between TCAS false alarms and air traffic controllers.

Finally, it may be necessary to modify the design of the logic in the new (or existing) alerting system to reduce the potential for dissonance as much as possible. It was suggested by the RTCA subcommittee, for instance, that ACM conflict resolution advisories should allow the conflict to be resolved without triggering any TCAS advisories.[6] One means of trying to ensure this is to modify ACM-induced maneuvers so that the likelihood of triggering a TCAS alert is small. This issue is examined in more detail later in this paper.

Alerting System Operation

All alerting systems generally perform four functions, shown in Fig. 3: monitoring, situation assessment, attention-getting, and problem resolution. First, information about the process under control and relevant hazard states must be monitored through a set of sensors. Each alerting system may use a different set of sensors, and thus may form a different view of what is truly occurring in the process and environment. Based on this observable information, the alerting system assesses and categorizes the situation into one of several threat levels or alert stages. If the alert stage is sufficiently high, the human operator is alerted to the problem. This attention-getting function can range from a simple aural or visual cue (e.g., a tone or illuminated light), to displays that indicate the cause for the alert (e.g., a textual or verbal readout such as "Generator Failure"), to displays that also indicate how to correct the problem. The attention-getting signal also provides an indication of the urgency of the problem. This urgency may be conveyed implicitly through the general type of hazard that is being encountered, or it may be more explicitly conveyed by the alarm signal. For example, a chime sound is often used for low-urgency alerts, whereas a buzzer or wailing alarm may be used in more threatening situations.[2,3]

Problem resolution may also be performed either explicitly or implicitly by the alerting system. In explicit systems, additional command or guidance information is presented to the operator. This may be a verbal message (e.g., "Climb!") and/or may include a visual display indicating the type of action to be taken and the aggressiveness with which that action should be taken. In advanced systems like TCAS, continuous guidance may be provided to aid in the resolution action. In implicit systems, the human operator may

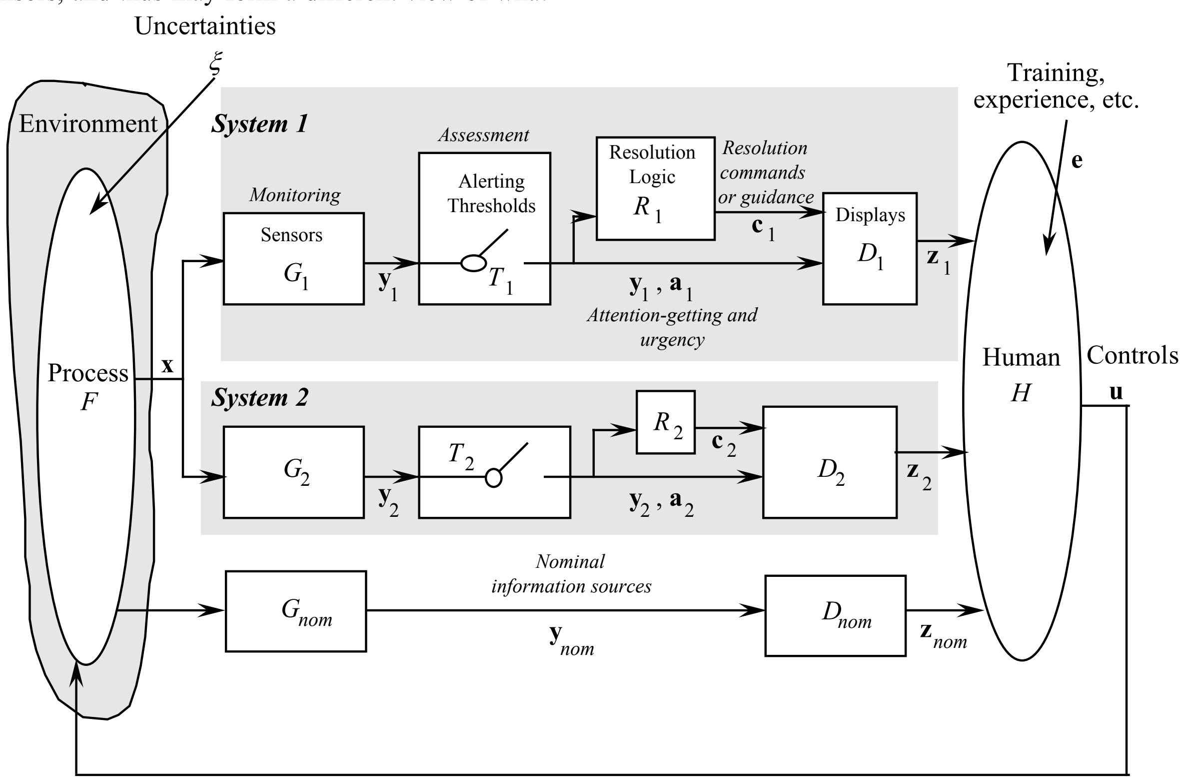

Fig. 3 Block Diagram of Alerting System Elements

have a trained response to a particular alert stage, or may just decide at that time what action is most appropriate.

Also shown in Fig. 3 is the nominal information path by which the human operator obtains information about the controlled process and the environment. This information builds the human's internal model of the situation that may conflict with the conditions implied by one or both alerting systems.

From a more precise mathematical standpoint, we denote **x** as the state vector representing the complete set of physical parameters that describe the dynamics of a hazard situation. In the case of TCAS and ACM, **x** represents the three-dimensional position and velocity vectors of each aircraft involved. As mentioned above, we will focus on the horizontal plane motion of two aircraft, though the examples can be extended to three dimensions.

Consider a situation in which both ACM and TCAS are implemented on aircraft 0 in Fig. 2. In general, the complete state vector is not available to the alerting system logic, but is observed through a set of sensors. The resulting information that is observable to each alerting system is included in the vector **y**. The alerting systems use different sets of observable states defined by different functions G_i operating on **x**. For the i^{th} alerting system,

$$\mathbf{y}_i = G_i(\mathbf{x}) \tag{9}$$

For TCAS (system 1), **y** is a vector including the range and range rate between two aircraft (again, considering the horizontal plane only):

$$\begin{aligned}\mathbf{y}_1 &= [r, \dot{r}]^{\mathrm{T}} \\ &= \left[\sqrt{x^2 + y^2}, -V_r \cos\theta\right]^{\mathrm{T}} \\ &= G_1(\mathbf{x})\end{aligned} \tag{10}$$

In contrast, ACM (system 2) uses the basic state vector components:

$$\mathbf{y}_2 = [x, y, \mathrm{v}_{0x}, \mathrm{v}_{1x}, \mathrm{v}_{1y}]^{\mathrm{T}} = G_2(\mathbf{x}) \tag{11}$$

So, ACM is able to observe the complete kinematic relationship in Fig. 2. TCAS only has access to range and range rate, which significantly limits the degree to which it can predict the evolution of the encounter between aircraft.

Alert Stages and Resolution Commands

Using the information in **y**, each alerting system applies a set of threshold functions or other logic, *T*, to map the situation into an alert stage. The alert stage is represented by the vector **a**, and specifies the level of threat according to that alerting system:

$$\mathbf{a}_i = T_i(\mathbf{y}_i) \tag{12}$$

The logic used by the alerting system to determine the appropriate alert stage and to provide guidance may vary from simple thresholds based on exceeding some fixed value to more complex algorithms involving a number of states. Many alerting systems work with two stages: non-hazardous and hazardous. More complex systems use a series of stages, each corresponding to a higher level of danger and urgency.

With TCAS, there are three alert stages:

Stage 0 = No threat. Traffic is shown on a map display using a white diamond symbol that also indicates its altitude and whether it is climbing or descending. No additional information is provided. $\mathbf{a}_1 = 0$.

Stage 1 = Traffic Advisory (TA). A Master Caution light is illuminated in amber, the traffic icon changes to a yellow circle on the traffic display, and an aural "Traffic, Traffic" alert is issued in the cockpit. $\mathbf{a}_1 = 1$.

Stage 2 = Resolution Advisory (RA). A Master Warning light is illuminated in red, the traffic icon changes to a red square on the traffic display, and an aural resolution command is issued (such as "Climb! Climb!") and the required climb angle or climb rate is shown on a cockpit display. $\mathbf{a}_1 = 2$.

We will focus on the higher two ACM alert stages: the PAZ alert ($\mathbf{a}_2 = 1$), and the CAZ alert ($\mathbf{a}_2 = 2$). It should be remembered, however, that the TCAS alert stages carry different meanings than the ACM stages. For example, $\mathbf{a}_1 = 2$ means that an RA is issued from TCAS, while $\mathbf{a}_2 = 2$ means that a CAZ alert is issued from ACM. The actions the pilot should take in each case may be significantly different. The symbolic notation, though, provides a means for articulating the different alert stages within each system.

Based on the alert stage and on the other information on the situation, the alerting system may produce resolution information, **c**:

$$\mathbf{c}_i = R_i(\mathbf{y}_i, \mathbf{a}_i) \tag{13}$$

The vector **c** includes the type of resolution action to be performed (e.g., turn or climb) and the magnitude of that maneuver.

Referring back to Fig. 3, the vector **z** combines all the information that is displayed to the human operator by the alerting system. In general, **z** includes signals designed to attract the operator's attention, the alert stage, and information to resolve the situation. The function *D* describes the display mapping from the state estimates available to the alerting system (**y**) to the information provided to the human operator (**z**) based on the alert stage (**a**) and resolution information (**c**):

$$\mathbf{z}_i = D_i(\mathbf{y}_i, \mathbf{a}_i, \mathbf{c}_i) \tag{14}$$

For TCAS and ACM, the information in **z** includes a traffic display in the cockpit, aural messages, lights, and any resolution command and guidance information.

In addition to the alerting systems, there are other nominal information sources that provide information to the pilot. This information is included in the vector $\mathbf{y}_{nom}$, which is then modified by the nominal displays D_{nom} as shown in Fig. 3. Cockpit instruments, air traffic control communications, views through the windscreen, and aeronautical charts are examples of nominal information sources for a pilot. The operator is also affected by other factors such as the pilot's internal model of the situation, knowledge of the alerting system's role, prior training, fatigue, and previous experience. Past exposure to false alarms, for instance, has been observed to be a factor in delaying responses to alerts.[8] This modifying information is included in the vector **e**. The function H then maps the observable states (via all the alerting systems and nominal information sources) to the control inputs **u**. That is,

$$\mathbf{u} = H(\mathbf{z}_{nom}, \mathbf{e}, \mathbf{z}_1, \mathbf{z}_2) \tag{15}$$

Ultimately, it is how the inputs to the pilot (as contained in $\mathbf{z}_{nom}$, $\mathbf{z}_1$, $\mathbf{z}_2$, and **e**) are used to develop a control strategy that determines whether there is dissonance between the information elements being used.

To complete the control block diagram, the process' state derivatives are determined from a generalized function, F, of the current state, operator's inputs, and modeling or system dynamics uncertainties, ξ:

$$\dot{\mathbf{x}} = F(\mathbf{x},\mathbf{u},\xi) \tag{16}$$

Having introduced a general state-space model for multiple alerting systems, it is now possible to more formally state the types of dissonance that may occur. At a high level, all alerting systems can be thought of as mapping a set of measured or estimated states of a controlled process into discrete alert stages and discrete or continuous hazard resolution commands. Dissonance may occur whenever a given state maps into two different alert stages or two different resolution commands, or when the time-derivatives of these mappings differ. A brief overview of different forms of dissonance is given here; a more complete description is available in Ref. 11.

Static Dissonance

When $\mathbf{z}_1 \neq \mathbf{z}_2$ at a given time for two alerting systems, static dissonance may exist. Breaking **z** into its components, first consider alert stage conflicts. Differences in alert stage can be present without causing dissonance if the two alerting systems have different roles. For example, ACM is designed to provide an earlier warning of traffic than TCAS. Should this happen, there is probably no dissonance from the pilot's point of view, even though the alert stage from ACM is at a higher level than that from TCAS. If the opposite occurred, however, there may be dissonance because the pilot may not understand why ACM does not rate the traffic as a threat while TCAS does. Another form of dissonance can occur if TCAS rates one aircraft as a threat while ACM rates a different aircraft as a threat, possibly due to differences in sensor information.

Dissonance can also occur due to the resolution information contained in **z**. Generally, the resolution information can be represented by a multi-dimensional vector that is intended to direct the human operator to a safe target state. If two commands are in different dimensions, then there may be dissonance (e.g., a case where system 1 commands a change in altitude but system 2 commands a change in heading).

If two commands are in the same dimension, then dissonance may still be present due to different polarities or magnitudes of the commands. If two systems are both commanding a change in altitude, but system 1 commands a climb and system 2 commands a descent, there is clearly dissonance. Or, if system 1 commands a much stronger climb than system 2, there may be dissonance. Note that these commands need not be explicitly displayed by the alerting system for dissonance to occur. Simply implying some resolution action (through the alert stage and trained procedures) may be enough to cause dissonance.

Dynamic Dissonance

The previous types of dissonance are static: they exist at a given point in time. Since the situation is constantly changing, however, dynamic dissonance may also occur. In dynamic dissonance, it is the *change* in alert stage or *change* in resolution information over time that produces a conflict; that is, when $\dot{\mathbf{z}}_1 \neq \dot{\mathbf{z}}_2$. Consider an example where one system initially indicates no threat while a second system indicates a high degree of danger and a warning is issued. This is static dissonance. However, if the first system upgrades the alert stage to a caution while the second system downgrades the alert stage, also to a caution, dynamic dissonance exists. Even though the two systems now agree about the proper alert stage, the human may be uncertain as to whether the situation is improving or getting worse due to the dynamic dissonance. Dynamic dissonance may also occur when the magnitude or direction of a resolution command changes. A critical case here might be obtaining a turn resolution command from ACM, followed by a climb resolution from TCAS. There may be important changes in safety margin should the pilot attempt to continue the turn or to combine a climb with the turn instead of stopping the turn and climbing straight ahead.

Mathematical Analysis of Dissonance

The preceding section developed the concepts of static and dynamic dissonance by examining the similarities and differences between the information passed to the human operator in **z**. The next step is to formulate a means of identifying how this dissonance originates. By exposing those situations that lead to dissonance, the system design can be modified, operations can be changed, or the operators can be trained to work around the dissonance.

To expose those conditions where static dissonance may occur, we begin by examining the state space of the alerting system and observing when alerts are issued. The threshold functions for each alerting system, T_1 and T_2, map a given state of the process into a corresponding alert stage. These threshold functions are typically defined by a set of predicates (or inequality statements) based on certain parameter values. Each predicate evaluates to either true or false. One example predicate for collision alerting might be: if the time to impact is less than p seconds, then use alert stage 1, where p is some parameter value. In general, there may be a set of such comparisons made between the states in **x** and a set of threshold parameters.

Let the i^{th} alerting system have a number of such predicates where the j^{th} predicate is denoted f_{ij}. Each predicate represents a boundary that divides the state space into a subset. Inside the subset, the predicate is true; outside, the predicate is false. Combinations of these subsets then form the alert stage space within the entire state space. Each resulting subset is denoted A_{ik} for the k^{th} alert stage of system i (Fig. 4). It is then possible to map out what states in the space of **x** lead to different alert stages. Here, TCAS is defined as system 1 and ACM is defined as system 2. Then, A_{11} is the region in state space where a TA is active. Similarly, A_{12} is the region for an RA, A_{21} is the region for a PAZ alert, and A_{22} is the region for a CAZ alert.

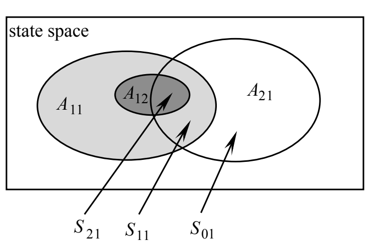

Fig. 4 Example Alert Stage and Intersection Sets

When the two systems operate simultaneously, the combinations of alert stages lead to behavior that may result in dissonance. The combinations of alert stages of the two systems are given by the intersections of the A_{ik} sets. These intersection sets are denoted S_{mn} where m is the alert stage from system 1 and n is the alert stage from system 2 (Fig. 4):

$$S_{mn} = A_{1m} \cap A_{2n} \tag{17}$$

S_{20}, for example, represents the region in state space where a TCAS RA is active but no ACM alert is active. With this mathematical basis, different forms of alert dissonance can now be identified.

Analysis of TCAS and ACM Thresholds

The converging, horizontal-plane TCAS thresholds are based on four parameters: $DMOD$, $DMODTA$, τ, and τ_{TA}. In this case, the RA threshold can be defined as:[4]

$$r < (DMOD - \tau\dot{r}) \iff \text{RA Alert} \tag{18}$$

if an RA is not issued, a TA occurs when the following is satisfied:

$$r^2 < DMODTA^2 - r\dot{r}\tau_{TA} \iff \text{TA Alert} \tag{19}$$

Even though TCAS operates with only r and $\dot{r}$ as states, its thresholds can be rewritten in terms of the more general state parameters from Fig. 2. From Eq. 19, the TA threshold then lies in state space according to the following equation:

$$a^2 + b^2 < DMODTA^2 + V_r \tau_{TA} a \tag{20}$$

Or equivalently,

$$(a - \frac{V_r \tau_{TA}}{2})^2 + b^2 < DMODTA^2 + (\frac{V_r \tau_{TA}}{2})^2 \tag{21}$$

So, aligned in a new (a, b) Cartesian coordinate frame in Fig. 2 (along and perpendicular to the relative velocity vector), the TA threshold is a circle centered on $(\frac{V_r \tau_{TA}}{2}, 0)$ with radius $\sqrt{DMODTA^2 + (\frac{V_r \tau_{TA}}{2})^2}$.

In a similar manner and coordinate system, the criterion for an RA (Eq. 18) can be rewritten as:

$$(a - \frac{V_r \tau}{2})^2 + b^2 < DMOD\sqrt{a^2 + b^2} + (\frac{V_r \tau}{2})^2 \tag{22}$$

The alert stage sets for TCAS are then formally defined by the threshold function T_1 using predicates:

$$T_1 = \begin{cases} f_{11} : (a - \frac{V_r \tau_{TA}}{2})^2 + b^2 < DMODTA^2 + (\frac{V_r \tau_{TA}}{2})^2 \\ f_{12} : (a - \frac{V_r \tau}{2})^2 + b^2 < DMOD\sqrt{a^2 + b^2} + (\frac{V_r \tau}{2})^2 \\ A_{10} = \bar{f}_{11} \cap \bar{f}_{12} \\ A_{11} = f_{11} \cap \bar{f}_{12} \\ A_{12} = f_{12} \end{cases} \quad (23)$$

So, for example, if predicate f_{11} is true but f_{12} is false, then the state lies in the region A_{11} and a TA is issued.

The thresholds for ACM are based on four parameters, PAZ, CAZ, τ_{PAZ}, and τ_{CAZ}:[6]

$$\frac{a - \sqrt{CAZ^2 - b^2}}{V_r} < \tau_{CAZ} \Leftrightarrow \text{CAZ Alert} \quad (24)$$

if there is no CAZ alert, then a PAZ alert is issued according to:

$$\frac{a - \sqrt{PAZ^2 - b^2}}{V_r} < \tau_{PAZ} \Leftrightarrow \text{PAZ Alert} \quad (25)$$

With ACM, A_{20} corresponds to a no-alert or low level alert condition, A_{21} corresponds to a PAZ alert, and A_{22} represents the space where a CAZ alert is issued. These regions are formally defined by the threshold function T_2:

$$T_2 = \begin{cases} f_{21} : \frac{a - \sqrt{PAZ^2 - b^2}}{V_r} < \tau_{PAZ} \\ f_{22} : \frac{a - \sqrt{CAZ^2 - b^2}}{V_r} < \tau_{CAZ} \\ A_{20} = \bar{f}_{21} \cap \bar{f}_{22} \\ A_{21} = f_{21} \cap \bar{f}_{22} \\ A_{22} = f_{22} \end{cases} \quad (26)$$

Equations 23 and 26 then give a formal basis by which a given state can be translated into an alert stage for each system. By then comparing combinations of alert stages between the two systems, conditions leading to static or dynamic dissonance can be identified.

As discussed earlier, a TCAS RA without any prior ACM alert conditions may be dissonant if pilots become accustomed to ACM advisories occurring before TCAS alerts. This condition is represented by the set $S_{20} = A_{12} \cap A_{20}$, or equivalently in terms of predicates:

$$S_{20} = f_{12} \cap \bar{f}_{21} \cap \bar{f}_{22} \quad (27)$$

In terms of the specific state values involved, and because the CAZ threshold is always within the PAZ threshold, Eq. 27 can be rewritten as:

$$\left\{ (a - \frac{V_r \tau}{2})^2 + b^2 < DMOD\sqrt{a^2 + b^2} + (\frac{V_r \tau}{2})^2 \right\} \cap \left\{ \frac{a - \sqrt{PAZ^2 - b^2}}{V_r} > \tau_{PAZ} \right\} \quad (28)$$

A more convenient way of visualizing this region is to plot the four alert stages for the two systems (TA, RA, PAZ, CAZ) for a given aircraft encounter situation. Figure 5 shows one example case for two aircraft heading in opposite directions, each at 500 kt. The four alert threshold regions are then shown to scale in the relative frame of one aircraft, with threshold parameter values set assuming the encounter occurs at an altitude of 20,000 ft.[4,6] A given type of alert will occur if the intruder aircraft enters into the regions shown.

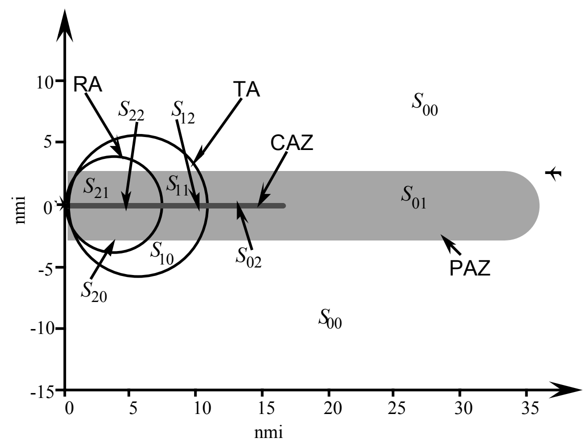

Fig. 5 TCAS and ACM Thresholds (500 kt each aircraft, opposite direction)

As Fig. 5 shows, the PAZ region extends well in front of the CAZ, TA, and RA regions. This is intentional, to provide the pilots ample time to respond to a potential conflict well before severe maneuvering is required. The CAZ is a significantly thinner region, also extending farther forward than the TA or RA. In this situation, however, note that the TA and RA thresholds do extend laterally beyond the CAZ and PAZ regions. If an intruder were to enter the S_{10} or S_{20} regions, dissonance could be present if the pilot was concerned why a PAZ alert did not accompany or precede the TCAS alert. Although regions S_{10} and S_{20} appear to be relatively small in Fig. 5, they do extend between 3 to 6 nmi laterally and cover an area over 16 nmi^2.

One difficulty in visualizing alerting behavior is that the problem is complex and multidimensional. A change in speed or heading, for example, would change the sizes and orientations of all of the alerting regions in Fig. 5. Still, such a diagram can be useful for examining specific encounter situations.

Dynamic Analysis

In addition to examining the alerting regions to expose areas where static alert stage dissonance could be present, it is also necessary to examine the process dynamics to see how dissonance may evolve over time. One of the major issues with the integration of ACM and TCAS is how to manage ACM alerts that are later upgraded to TCAS alerts. If action is taken in response to an ACM alert, it is preferable that no TCAS alert occur.[6] Accordingly, one issue to examine is what types of ACM resolution maneuvers are required to avert TCAS alerts from occurring.

As a somewhat extreme example, consider a situation in which a CAZ alert is issued against one aircraft directly in front of another and heading in the opposite direction, with both aircraft at 500 kt. In response to the CAZ alert, assume that one aircraft begins a turning maneuver with a certain response delay, a roll-in to a certain bank angle, and a roll-out at a certain new heading angle.

Figure 6 shows four snapshots (spaced every 10 seconds) of the two aircraft and the alert thresholds assuming one aircraft follows a turning avoidance action with a 10 second time delay, 10^o bank angle, and 20^o final heading change. Figure 6(a) shows the situation immediately following the 10 second time delay. Approximately 10 seconds later (Fig. 6[b]), the CAZ region is exited but the aircraft crosses the boundary of the TCAS TA region. Within the next 10 seconds (Fig. 6[c]), a TA is issued. Finally (Fig. 6[d]), an RA is issued from TCAS, commanding the pilot to climb or descend. So, in this extreme situation there is a progression from taking action in response to an ACM alert that ultimately ends in a TCAS RA. The RA command itself may also cause some confusion as the pilot must determine whether to continue the turn that has already been initiated, or to execute the climb or descent command.

The same thresholds in Fig. 6 could also be placed on the second aircraft, which might then also receive and react to alerts. In particular, it may be relatively

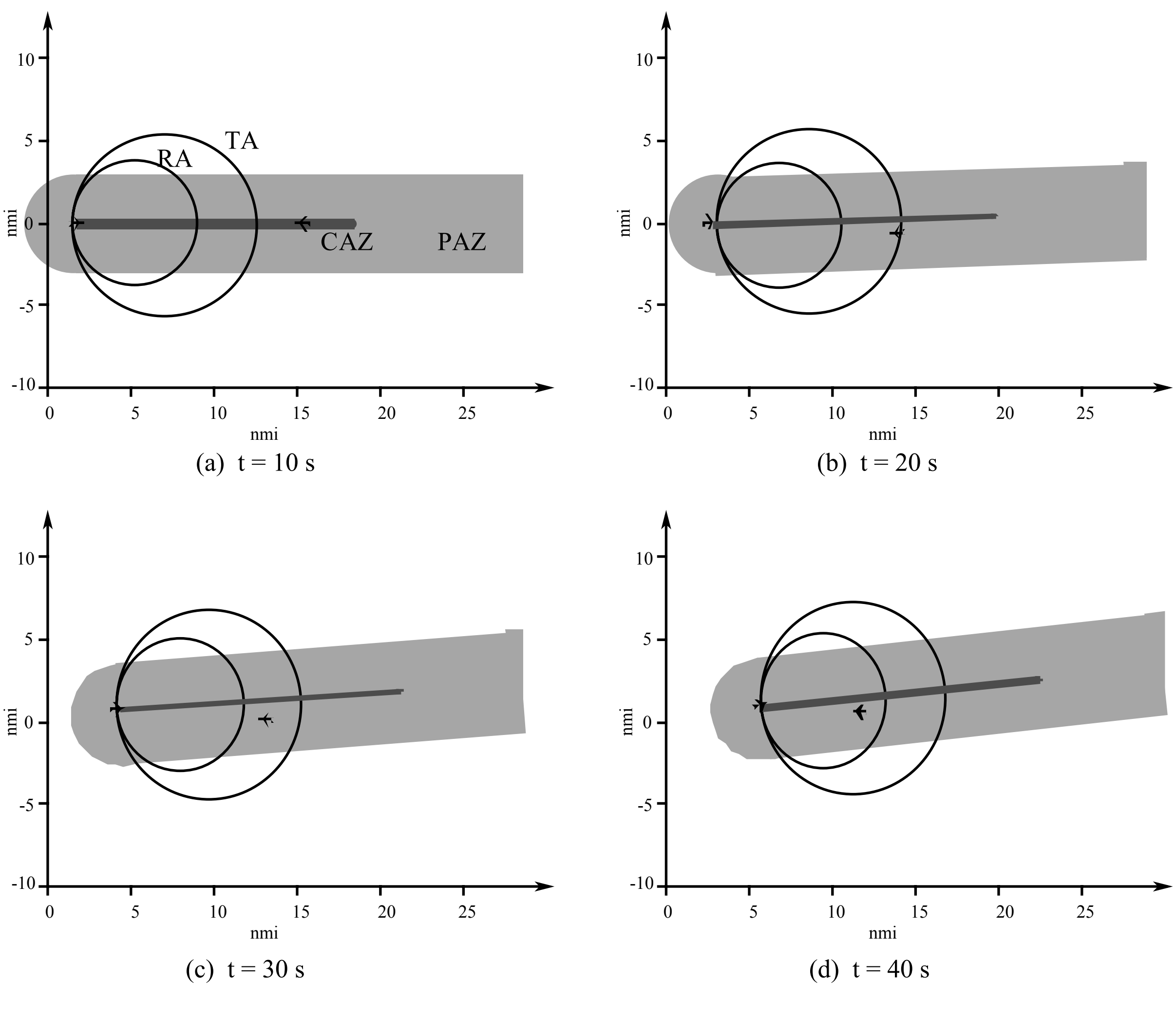

Fig. 6 TCAS and ACM Thresholds During Avoidance Maneuver

common for ACM to be installed on one aircraft while TCAS is installed on the other. In that situation, the ACM aircraft would begin maneuvering in response to the PAZ or CAZ alert. Unless that aircraft performed a sufficiently aggressive maneuver, a TCAS TA or RA could still be issued on the second aircraft. If not designed properly, ACM might not able to prevent the second aircraft from having to maneuver in response to TCAS.

To address these issues, a point-mass simulation was executed to examine the interaction between aircraft trajectories and the alert stages of ACM and TCAS. To run the simulation, an intruder aircraft was placed directly in front of a host aircraft, traveling in the opposite direction, with each aircraft at 500 kt. Upon crossing the PAZ alert threshold, a given time delay was implemented, and then the host aircraft performed a roll-in to a certain bank angle and rolled out at a given heading angle. Time delay, bank angle, and heading change parameters were systematically varied. Depending on the combination of response latency, bank angle, and turn angle, either no TCAS alert would be issued, a TA would be issued during the maneuver, or both a TA and RA would be issued.

Figure 7 shows the interactions between delay, bank angle, turn heading, and TCAS alert status. The curves that are shown represent boundaries between different TCAS alert behaviors. Two groups of curves are shown. The solid lines represent the boundary between RA and TA (lower solid line) or between TA and no alert (upper solid line) when there is no time delay following the PAZ alert. The dashed lines show similar boundaries when there is a 10 second response delay after the PAZ alert. A combination of bank angle and turn angle toward the lower-left of the plot will result in an RA. Performing a maneuver between sets of curves will result in a TA. Making a large enough turn with a large enough bank angle (upper-right part of the diagram) will avoid any TCAS alert from occurring.

For example, with no time delay and a 15 degree bank angle, the host aircraft must turn beyond 20 degrees to avoid triggering a TCAS TA. The host would have to turn at least 12 degrees to avoid triggering a TCAS RA. A 10 second response delay would add several degrees to these turn minima. Thus, relatively significant avoidance maneuvers must be performed following an ACM PAZ alert in order to prevent triggering TCAS TAs or RAs.

It is even more difficult to prevent TAs and RAs following a CAZ alert. In fact, in this 500 kt opposite-direction example, a TCAS TA cannot be avoided without exceeding an extreme maneuver (at least 30 degree bank angle and 60 degree heading change). Figure 8 shows the TCAS alerting behavior following a response maneuver to a CAZ alert. Avoiding an RA after a CAZ alert also requires an extreme maneuver. With a 30 degree bank angle, a 32 degree heading change is required without time delay, and 40 degree heading change is required if there is a five second delay.

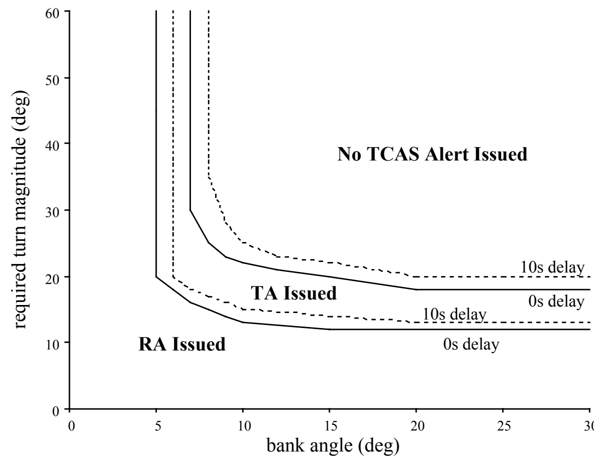

Fig. 7 Effect of PAZ Avoidance Maneuver on TCAS Alert Status (500 kt opposite direction)

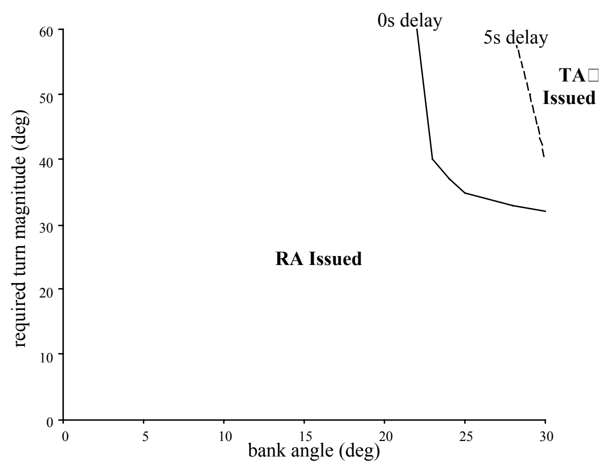

Fig. 8 Effect of CAZ Avoidance Maneuver on TCAS Alert Status (500 kt opposite direction)

Simulations were also performed for vertical maneuvers following ACM PAZ and CAZ alerts. It was assumed that the aircraft performed a pull-up maneuver at a load factor of 1.2 g to a given vertical rate. Table 1 shows the minimum climb rates that are required under these conditions to avoid receiving a TCAS TA or RA alert. Climbs or descents at approximately 400 ft/min are required to avoid a TA if action is started immediately after a PAZ alert is issued. RAs are more easily avoided, with rates less than 100 ft/min required. After a CAZ alert, TAs cannot be avoided without a significantly more extreme maneuver (a load factor of approximately 2.4 g is required). RAs after a CAZ alert could be avoided with vertical rates between approximately 600 and 900 ft/min depending on the response delay of the pilot and aircraft.

Table 1
Vertical Maneuver Requirements (ft/min) to Avoid TCAS Alerts (1.2 g pull-up load factor)

ACM Alert	0 second delay		10 second delay	
	TA	RA	TA	RA
PAZ	380	70	450	80
CAZ	—	600	—	900

Concluding Remarks

Alert system dissonance has not been a major concern in the past beyond the desire to minimize simultaneous alerts and prevent information overload. Conflicting alert information is likely to become more prevalent as alerting systems continue to be injected into complex system operations. Several areas in aerospace have already been identified where dissonance is likely to become a more critical issue in the near future, and certainly there are other regimes where similar problems are of concern.

An analysis of the initial specifications for the Airborne Conflict Management (ACM) system in connection with the current Traffic Alert and Collision Avoidance System (TCAS) suggest that there may be operating conditions in which TCAS alerts could occur without having first received ACM advisories. The simulations also show that it may be difficult to avoid receiving a TCAS alert even after taking action in response to an ACM alert in certain geometries. These may not be dissonance problems, but need to be investigated further to determine the scope of encounters that may lead to this type of behavior and to examine other human factors issues relating to this problem. Potential solutions include modifying the ACM threshold parameters or ACM resolution maneuvers (or both), or accepting that TCAS alerts may occur in certain geometries and training pilots to understand why that dissonance exists and how it can be resolved.

Finally, some simplification of TCAS and ACM was used to perform this initial analysis. A more detailed study that includes factors such as communication and filtering delays should be performed if higher-fidelity results are desired.

Acknowledgment

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