Dissonance Between Multiple Alerting Systems Part II: Avoidance and Mitigation

Lixia Song and James K. Kuchar

***Abstract*—The potential for conflicting information to be transmitted by different automated alerting systems is growing as these systems become more pervasive in process operations. Newly introduced alerting systems must be carefully designed to minimize the potential for and impact of alerting conflicts. A model of alert dissonance, developed in a companion paper (Part I), provides both a theoretical foundation for understanding conflicts and a practical basis from which specific problems can be addressed. Alerting systems are hybrid processes, involving continuous process dynamics and discrete alert level changes in state space. This paper presents a hybrid model to facilitate analysis of dissonance. Using backward reachability analysis, regions of dangerous dissonance space are identified. Then, modifications can be made to the control strategy of the process or to the alerting thresholds to avoid dangerous consequences of dissonance. An example problem is presented to demonstrate the application of the hybrid model to identify dangerous dissonance space and to identify proper actions to avoid dangerous consequences of dissonance.**

***Index Terms*—Alerting systems, avoidance, dissonance, hybrid analysis.**

I. 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. The addition of alerting systems to an already complex operation carries several liabilities [1]. First, there is an increase in the amount of information processing required by the human operator, who now must be trained and able to respond rapidly to more information. There is also a potential for simultaneous alerts from the different systems, possibly overloading or confusing the human. These alerts could also be conflicting in the sense that the information they provide suggests different actions be taken to resolve problems.

To date, management of potential dissonance between systems has occurred without a structured understanding of the specific issues involved. A coherent, formal model that articulates the design issues is developed in a companion paper (Part I). This model helps in understanding the different types of dissonance that may occur, and identifying when or where the different types of dissonance could occur in a given operation. In brief, our approach involves the following steps.

1) Each alerting system is formally described in terms of how a given state vector is mapped into an alerting system output called an alert set. Alert sets include a categorization of the level of threat posed by a hazard as well as command or guidance information to the operator. Example alert sets might be: no alert; an informational traffic advisory; or an explicit climb command to a pilot to avoid a collision. Accordingly, in this step, mathematical mapping functions are defined for each alerting system.
2) Sensor and dynamic modeling errors can be introduced to make the mapping of state vectors into alert sets probabilistic rather than deterministic. This step involves modeling uncertainties using probability density functions (PDF) and carrying those PDFs through the mapping functions defined in step 1.
3) Visualization of the alert set mapping for each alerting system can then be created. This is simply a view of state space in which the different alert sets are demarcated by their boundaries defined by the mapping functions of steps 1 and 2. When uncertainties are present, the view can show contours of probability of a state being in a given alert set.
4) Two alerting systems are then overlayed to examine potential regions where dissonant alert sets occur simultaneously. This can be done both formally through mathematics and informally through a visual depiction of state space. This new depiction of state space shows regions of intersection between the various alert sets of each alerting system. Thus, one can see how a given state maps into a combination of the alert sets of each system.
5) Each intersection of alert sets must then be examined to determine whether dissonance may exist. This is an area requiring significant human factors research beyond the scope of this paper. It is critical that designers are able to predict whether a given combination of alerting system information might or might not produce dissonance. To better focus on the portion of the problem that is more readily described through formal mathematics, we assume that such a human factors study can be performed. We therefore, assume that we know which combinations of alert sets are dissonant and which are not. This is, however, a significant assumption that points to a definite need for more human factors studies into the effects of dissonance.

Manuscript received October 31, 2002. This paper was recommended by Associate Editor E. J. Bass.

The authors are with the Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, Cambridge, MA 02139 USA (e-mail: jkkuchar@mit.edu).

Digital Object Identifier 10.1109/TSMCA.2003.817046

The identification of dissonance space enables more advanced mitigation contingencies to prevent or impede dissonance from occurring. For instance, the logic or algorithms of alerting systems can be modified to eliminate dissonance space, or operational procedures can be modified so that the process does not enter regions of dissonance.

A hybrid process is one in which continuous and discrete dynamics coexist and interact with each other. An alerting system is one example of a hybrid process because it includes continuous dynamics from the controlled process and discrete state changes when alerting threshold boundaries are crossed. Crossing an alerting threshold can result in a discrete change in the dynamics of the process as the human operator adopts a new control strategy. For analysis, we extend a unified hybrid systems model introduced in [2] that captures discrete phenomena arising in hybrid systems. These phenomena include autonomous switching where the continuous dynamics change automatically when the state hits certain boundaries and controlled switching when the vector field changes abruptly in response to a human control command.

This paper presents a hybrid model to describe the dynamic behavior of a process incorporating two or more alerting systems. Using the hybrid model and based on the analysis theory developed in Part I, regions of dangerous dissonance space are identified using backward reachability analysis. This involves starting at a given hazardous region and reversing the system dynamics to determine how that hazardous state could be reached. Then, mitigation methods to avoid dangerous dissonance space are described and applied in an illustrative example.

II. Hybrid System Analysis of Dissonance

We take a state space view of the controlled process, alerting systems, and the human operator. By observing how the process' state moves through state space, we can determine whether the system will operate safely or whether certain hazards may be encountered. More formally, we define hazard space as that region in state-space where an undesirable event would occur. Depending on the application, hazard space could involve, for example, the region in space where two aircraft are colocated or a region in which excessive temperature or pressure would harm a chemical process. The alerting systems have been implemented with the goal of aiding the operator in avoiding regions of hazard space.

In our analysis, we require several assumptions about the behavior of the human and controlled process in state space. In general, we assume that the operator applies one of a set of possible control actions, where this set of actions is determined by the current combination of alert sets. That is, we might expect one type of behavior from the operator if no alerts have been issued (such as continuing in a relatively straight line), and a different type of behavior if an alerting system is issuing avoidance commands to miss a threat (making a turn, for example).

A second assumption is that each alerting system alone has been designed such that hazard space will be avoided. We assume that false alarms or missed detections are rare or that they have minimal impact on the safety of the process. This assumption facilitates the initial analysis and may be relaxed later if a more detailed and accurate analysis is needed.

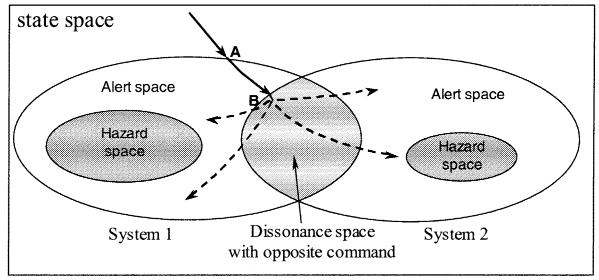

Fig. 1. State trajectory evolution.

An example history of a process is shown in Fig. 1. In Fig. 1, two regions of hazard space are shown, each with a corresponding alerting system. The process begins near the top center of the figure outside of the alert space regions. No alerts are issued by the systems, and the process follows a straight line path. When the process reaches point A in Fig. 1, system 1 is triggered and issues an alert. This causes a discrete change in the operator's control strategy to avoid the embedded region of hazard space. As the process evolves, it reaches point B in Fig. 1. Here, system 2 also issues an alert. The shaded region shown is assumed to be one in which the two alerts are dissonant. For example, avoidance commands from the two systems might be inconsistent in this dissonant region (e.g., simultaneous turn left and turn right commands). Due to the dissonance, the operator switches to a new control strategy which might be significantly more uncertain than that chosen with each alerting system alone, as shown with the dashed lines in Fig. 1. Ultimately the process might reach hazard space due to the dissonance that was encountered.

Using the method in Part I and through the results of human factors studies, regions of dissonance space need to be identified. This can then be further refined by breaking the dissonant region into two subsets: dangerous and nondangerous. We define a *dangerous dissonance state* as a state in dissonance space from which hazard space can be reached. As shown, state B in Fig. 1 is a dangerous dissonance state because some of the possible trajectories leaving point B enter hazard space. *Dangerous dissonance space* is then simply the union of dangerous dissonance states. Although the rest of the dissonance space is not called dangerous from this formal view, in the long-term the human operator may still distrust the system. Accordingly, the system designer should at least eliminate dangerous dissonance space and, if possible, all dissonance space.

A. Hybrid Model of Multiple Alerting Systems

To model the hybrid behavior of a process with multiple alerting systems, transition functions are introduced to represent the human operator's responses to alerting system commands. The transition functions are activated when the process state hits alerting threshold boundaries. Transition functions randomly select one trajectory from a set of trajectories determined by the current alert set combination of the two alerting systems. The sets of possible dynamics are probabilistically distributed and bounded by worst case or physical performance limits of the process, or possibly by some other limits determined through human factors studies, for instance.

More formally, given the ith alerting system, at any time t we can separate the whole state space $\mathbf{U}$ into several subsets A_{ik} based on the system alert sets

$$\mathbf{U} = \cup_k A_{ik} \tag{1}$$

where each A_{ik} is a connected, open set of $\mathbf{R}^n$. $\mathbf{R}^n$ is the continuous state space of the process. A_{ik} is the kth system alert set of the ith alerting system, as defined in Part I. There are two alert sets for each system shown in Fig. 1: the system does not alert (outside alert space), or the system does alert (inside alert space).

For the ith alerting system, the continuous dynamics in each region A_{ik} is given by a set of vector fields $\mathbf{F}_{ik} : A_{ik} \rightarrow \mathbf{R}^n$. The vector field describes the process dynamics governed by the following:

$$\dot{\mathbf{x}}(t) = \mathbf{f}_{ik}(\mathbf{x}(t), \mathbf{u}(t), \mathbf{d}(t), t) \in \mathbf{F}_{ik} \tag{2}$$

where $\mathbf{u}(t)$ is the continuous control applied to the process at time t while the alerting system is in alert stage k, and $\mathbf{d}(t)$ is the disturbance at time t. We define the set of vector fields $\mathbf{F}_{ik}$ as the *allowed action space* of the ith alerting system in region A_{ik}. For example, $\mathbf{F}_{ik}$ for a region where alerting system 1 alerts alone might include varying degrees of left turns. $\mathbf{F}_{ik}$ for a region where alerting system 2 alerts alone might include varying degrees of right turns.

As discussed in Part I, the intersections of the alert sets of two alerting systems are denoted by the sets S_{mn} where m is the alert set from system 1 and n is the alert set from system 2. The whole state space then can be separated into subsets S_{mn}, that is

$$\mathbf{U} = \cup_{m,n} S_{mn} = \cup_{m,n}(A_{im} \cap A_{jn}). \tag{3}$$

Next, human factors issues have to be considered by examining each set S_{mn} to determine if there is dissonance in that situation. This human factors analysis is beyond the scope of this paper; we assume here that we are able to determine which regions S_{mn} are in fact perceived to be dissonant. The subset of space where perceived dissonance exists is then called dissonance space.

If S_{mn} is not dissonance space, then the continuous dynamics of the process is governed by

$$\mathbf{F}_{mn} = \mathbf{F}_{im} \cap \mathbf{F}_{jn}. \tag{4}$$

which is defined by the intersection of the two alerting systems' allowed action space. But if S_{mn} is dissonance space, the intersection of two alerting systems' allowed action space may be empty. That is, $\mathbf{F}_{mn} = \mathbf{F}_{im} \cap \mathbf{F}_{jn} = \phi$. In this case, $\mathbf{F}_{mn}$ is not well defined in the dissonance space. Exposed to this situation, an operator might take any of a large range of actions, and the continuous dynamics would be given by a different set $\mathbf{F}$ of differential operators. $\mathbf{F}$ could be uniformly distributed and bounded by the physical performance of the process, or could be a probabilistic distributed set and bounded by the worst case describing the human operator's response in dissonance space. This set could be determined more precisely through running a focused human-in-the-loop experiment or simulation.

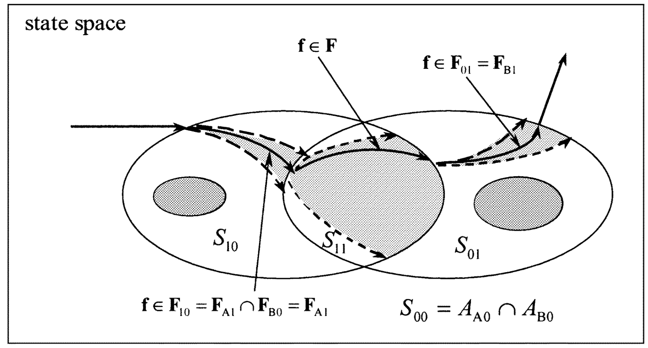

Fig. 2. Example transition functions.

For example, consider Fig. 2, which again shows two alerting systems, A and B, each of which has two alert sets 0 (no alert) or 1 (alert). There are four subsets in state space: $S_{00} = A_{\mathrm{A0}} \cap A_{\mathrm{B0}}, S_{01} = A_{\mathrm{A0}} \cap A_{\mathrm{B1}}, S_{10} = A_{\mathrm{A1}} \cap A_{\mathrm{B0}}$, and $S_{11} = A_{\mathrm{A1}} \cap A_{\mathrm{B1}}$. When system A is in alert stage 1 (A_{A1}), it commands a right turn within some set of heading changes; in alert stage 0 (A_{A0}), there is no restriction for action. When system B is in alert stage 1, it commands a left turn within some set of required heading changes; there is no action restriction in alert stage 0. The state begins in region S_{00} in Fig. 2 where there are no restrictions on what the operator does, in this example. The state eventually hits the boundary of subset S_{10} and a right turn is commanded from system A. The transition function selects a specific amount of right turn from a set of possible values, shown in Fig. 2 as a solid curve within a shaded region of possible turns. The process then hits the boundary of region S_{11} where system B begins to command a left turn. Here, there is no satisfactory response that satisfies both the command to turn left and to turn right, and the operator selects a new control action from a larger set of possibilities. This represents, in this example, more uncertainty on what the operator will do when faced with dissonance. The state then reaches region S_{01} where alerting system A stops its command. The operator then selects a new action consistent with system B's command to turn left. Finally, the state exits the alerting region altogether.

Formally, the dynamics describing the evolution of the state are generated each time a discrete transition occurs at the alerting threshold boundaries. In region S_{10} this is described by $\mathbf{F}_{10} = \mathbf{F}_{\mathrm{A1}} \cap \mathbf{F}_{\mathrm{B0}} = \mathbf{F}_{\mathrm{A1}}$. The intersection between the action space of system A in set 1 (F_{A1}, right turn) and the action space of system B in set 0 ($\mathbf{F}_{\mathrm{B0}}$, no restriction) is nonempty and involves some form of right turn. When the continuous state hits the boundary of S_{11}, the intersection of action spaces is empty. The operator takes on a new control strategy defined by a different set $\mathbf{F}$, which would need to be determined from human factors modeling of how the operator would behave in the face of dissonance. At the boundary of subset S_{01}, the transition function randomly chooses a governing differential equation within set $\mathbf{F}_{01} = \mathbf{F}_{\mathrm{A0}} \cap \mathbf{F}_{\mathrm{B1}} = \mathbf{F}_{\mathrm{B1}}$ which would be a left turn. It is assumed here that the effect of dissonance

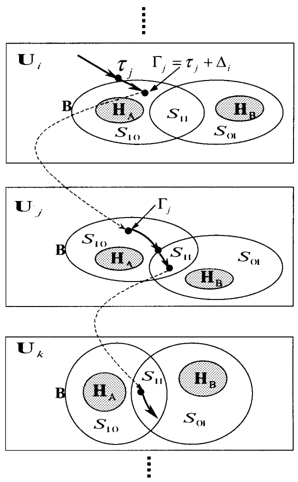

Fig. 3. Example dynamics of the hybrid model.

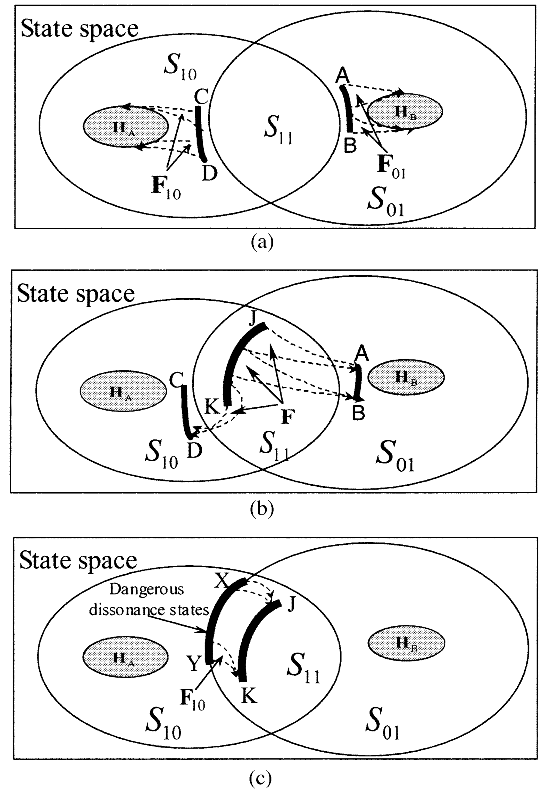

Fig. 4. Identification of dangerous dissonance space.

on the operator's choice of control does not continue into the nondissonance region S_{01}.

Now we can define the hybrid model of the process incorporating multiple alerting systems. The model consists of a state space

$$\mathbf{U} = \cup_{q \in Q} \mathbf{U}_q, \quad Q \equiv \{1, \ldots, N\} \tag{5}$$

where each $\mathbf{U}_q$ is a connected, open set of $\mathbf{R}^n$. $\mathbf{R}^n$ is the continuous state space of the hybrid process, and $Q \equiv \{1, \ldots, N\}$ is the set of discrete states of the hybrid process (i.e., the different combinations of alert sets S_{mn}). A state of the process is a pair $(q, \mathbf{x}) \in Q \times \mathbf{U}$. $\mathbf{B}$ is the boundary associated with each discrete state, meaning that the state $(q, \mathbf{x})$may flow within q only if $\mathbf{x} \notin \mathbf{B}$, and when $\mathbf{x} \in \mathbf{B}$, transition function $\mathbf{T}$ is activated to define the continuous dynamics in the following discrete state q'. In each discrete state q, the continuous state $\mathbf{x} \in S_{mn}$. The continuous dynamics are given by vector fields $\mathbf{f} : \mathbf{U}_q \to \mathbf{R}^n$ as determined by transition functions. The model also includes $\mathbf{H}_i$, the hazard space monitored by the ith alerting system. The state of the process $(q, \mathbf{x})$ is required to stay outside the hazard space $\mathbf{H}_i$.

We use Δ_q to represent a response delay to changes in the alert set. The dynamics of the hybrid process can now be described as follows. There is a sequence of *pre-switch times* $\{\tau_i\}$ and another sequence of *post-switch times* $\{\Gamma_i\}$ satisfying $0 = \Gamma_0 \leq \tau_1 < \Gamma_1 < \tau_2 < \Gamma_2 < \cdots \leq \infty$, such that on each interval $[\Gamma_{j-1}, \tau_j)$ with a nonempty interior, $\mathbf{x}(\cdot)$ evolves according to the differential equations $\dot{\mathbf{x}}(t) = \mathbf{f}$ determined by transition function $\mathbf{T}$ in some $\mathbf{U}_i$. At the next pre-switch time (say, τ_j), $\mathbf{x}(\cdot)$ hits the boundary $\mathbf{B}$, and the vector field switches according to transition functions at time $\Gamma_j = \tau_j + \Delta_i$.

Part of the dynamics of the example introduced above (in Fig. 2) is shown in Fig. 3. The state $(q_i, \mathbf{x})$ flows within q_i before τ_j; at time τ_j, the state hits the boundary of S_{10}, and the activated transition function chooses a governing differential equation from $\mathbf{F}_{10} = \mathbf{F}_{\text{A1}}$ within time delay Δ_i. During the time delay Δ_i, the state $(q_i, \mathbf{x})$ still flows within q_i governed by differential equation $\dot{\mathbf{x}}(t) = \mathbf{f} \in \mathbf{F}_{00}$ as before τ_j. At time $\Gamma_j = \tau_j + \Delta_i$, the process is in discrete state q_j, on interval $[\Gamma_j, \tau_k)$, and $\mathbf{x}(\cdot)$ evolves according to the differential equations $\dot{\mathbf{x}}(t) = \mathbf{f}$ determined by transition function $\mathbf{T}$ in $\mathbf{U}_j$; and the process dynamics continue.

B. Identification of Dangerous Dissonance Space

As mentioned above, some subset of the trajectories following dissonance may encounter hazards. Using backward reachability analysis we can identify those regions of dangerous dissonance space. In essence, we begin at the edge of hazard space and work backward by reversing dynamics to determine what states could lead to that hazard. Two further assumptions at this point are that the hazard regions are metric spaces, and the set of functions $\mathbf{F}_{mn}$ and $\mathbf{F}$ are monotonic.

Continuing the example given previously, the process to identify dangerous dissonance space can be described with Fig. 4. We begin in Fig. 4(a) which shows reversing dynamics from the two hazard spaces to the edge of dissonance space S_{11} (displaced due to the response delay time). With hazard space $\mathbf{H}_\text{B}$ as target state space, the states between points A and B in Fig. 4 can be identified by solving the set of differential equations $\dot{\mathbf{x}}(t) = \mathbf{F}_{01}(\mathbf{x}(t), \mathbf{u}(t), \mathbf{d}(t), t)$ at time Γ_q. Any state between A and B could then encounter $\mathbf{H}_\text{B}$. With the hazard space $\mathbf{H}_\text{A}$ as target state space, the states between C and D can be identified by solving the set of differential equations $\dot{\mathbf{x}}(t) = \mathbf{F}_{10}(\mathbf{x}(t), \mathbf{u}(t), \mathbf{d}(t), t)$ at time Γ_q. Next, dangerous dissonance states between J and K [Fig. 4(b)] in dissonance space can be identified by solving the set of differential equations $\dot{\mathbf{x}}(t) = \mathbf{F}(\mathbf{x}(t), \mathbf{u}(t), \mathbf{d}(t), t)$ at time Γ_{q-1}, with those states between A and B, and C and D as target states. The dangerous dissonance space on the dissonance space boundary (between X and Y) can then be identified with one more backward step, solving the set of differential equations $\dot{\mathbf{x}}(t) = \mathbf{F}_{10}(\mathbf{x}(t), \mathbf{u}(t), \mathbf{d}(t), t)$ at time τ_{q-1} with the states between J and K as target states [Fig. 4(c)]. The dangerous dissonance space is then that dissonant space that could be reached from the dangerous dissonance states between X and Y.

III. Avoiding and Mitigating Dissonance

To date, dissonance has been largely managed through 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 (i.e., without separate attention-getting signals). Several complex prioritization schemes have been investigated for the various alerting systems on board an aircraft [3], [4]. 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. Prioritization can run into trouble, however, if two alerts are both valid but the operator is only receiving or responding to one. Still, prioritization can help reduce sensory and cognitive overload of the human during a time of high stress.

An alternate way of managing conflicts between systems is to modify operation so that dissonance is unlikely. In the area of air traffic collision alerting, the Traffic Alert and Collision Avoidance System (TCAS) has been mandated on U.S. transport aircraft since the early 1990s. TCAS warns the pilots to an immediate collision threat and provides escape commands and guidance. Recently, other collision alerting systems have been under development to enhance safety and capability for closely-spaced approaches to parallel runways [5], [6]. Specialized systems are required for parallel approach capability since TCAS was not developed with this type of operation in mind and would require major modifications to work in that environment. One means of trying to ensure compatibility of parallel approach alerting systems with TCAS is to modify air traffic control procedures so that the likelihood of a simultaneous TCAS alert and parallel traffic alert is very small. Yet another option would be to modify the design of the logic in the new (or existing) alerting system to reduce the potential for dissonance as much as possible.

A third way to mitigate the effect of alerting system conflicts is through operator training. The Ground Proximity Warning System (GPWS), for example, was mandated on U.S. transport aircraft in the mid-1970s [7]. GPWS uses measurements of the height of the aircraft above terrain to predict whether there is a threat of an accident, and is susceptible to occasional false alarms or late alerts. In the late 1990s the Enhanced Ground Proximity Warning System (EGPWS) was introduced to provide earlier and more accurate warnings of terrain threats. EGPWS uses an on-board terrain database and includes a graphical display of the terrain field around the aircraft. Due to cost and certification issues, GPWS has been retained on aircraft and EGPWS has been added as a separate, independent system that does not change the operation of GPWS. Pilots are trained that EGPWS and GPWS use different decision-making logic, and that alerts from the two systems may not (and in fact probably will not) occur in concert. In more severe cases, however, training may fall short.

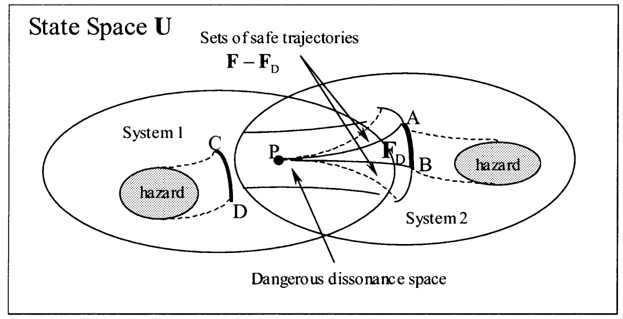

Fig. 5. Restricted trajectories in dangerous dissonance space to avoid hazards.

A final method to manage dissonance is to redesign the alerting thresholds so that regions of dissonance space are minimized or otherwise become inconsequential. Additionally, the alerting system logic may be modified such that the commanded actions the operator should take do not lead to hazards. This may involve additional guidance information or other cues to aid the operator in resolving dissonance. A formal model of such a modification is provided in the next section.

A. Modifying the Control Strategy

After identifying dangerous dissonance space using the hybrid model developed in the last section, the dangerous effect of dissonance might be avoided by modifying the control strategy of the process. That is, we may be able to identify a subset of the differential operators of set $\mathbf{F}$ in dissonance space with which the hazard space can still be avoided. This is equivalent to determining the proper alerting system command that would avoid entering the dangerous dissonance space.

With the dangerous dissonance states as initial conditions, and the states between A and B, and C and D (Fig. 5) as the target states, a subset of $\mathbf{F}_{\mathrm{D}}$ the differential operator set $\mathbf{F}$ in dissonance space can be identified with which the hazard space cannot be avoided. Then the subset $\mathbf{F} - \mathbf{F}_{\mathrm{D}}$ includes differential operators in dangerous dissonance space that will avoid the hazard spaces. Thus, if the dangerous dissonance space cannot be eliminated by adjusting the alerting system thresholds, then possibly the human operator can be given certain operating commands in dangerous dissonance space such that the continuous dynamics would be given by the differential operators in set $\mathbf{F} - \mathbf{F}_{\mathrm{D}}$.

Fig. 5 shows an example of restricted trajectories in dangerous dissonance space to avoid hazards. Given a dangerous dissonance state P, part of the original restricted set of trajectories intersects the states between A and B, which could lead the process to hazard space. After identifying the dangerous subset $\mathbf{F}_{\mathrm{D}}$ of the original differential operators set $\mathbf{F}$ in dissonance space, the trajectories governed by those differential operators in subset $\mathbf{F} - \mathbf{F}_{\mathrm{D}}$ (e.g., turn right at least 30 ° or turn left at least 25°) would be able to avoid both hazards monitored by both alerting systems.

Another way to avoid the dangerous effect of dissonance is to modify the alerting system command (the allowed action space) such that the continuous dynamics in the alert space of each alerting system alone would not enter dangerous dissonance space. With the alert space boundary of each alerting system as initial conditions, and the dangerous dissonance states as target

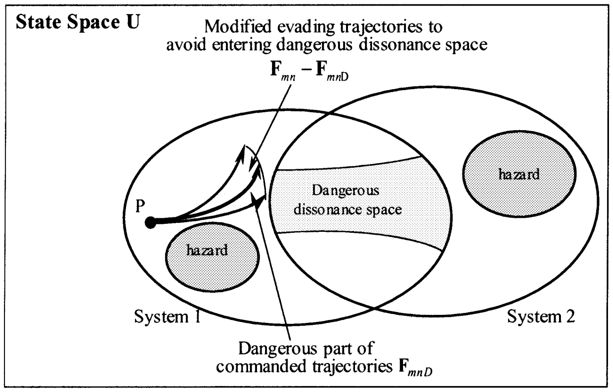

Fig. 6. Modifying evading trajectories to avoid unsafe effect of dissonance.

states, the subset of differential operators in alert space $\mathbf{F}_{mn\mathrm{D}}$ can be identified from which the continuous dynamics would hit the dangerous dissonance space. Then the continuous dynamics given by any differential operator in set $\mathbf{F}_{mn} - \mathbf{F}_{mn\mathrm{D}}$ can avoid the dangerous dissonance space, and thus the dangerous effect of dissonance space.

Fig. 6 shows an example of modified evading trajectories. Given an alert state P in alert space of system 1, the original set of evading trajectories according to the alerting system's resolution advisories (e.g., turn left at least 10°) may enter dangerous dissonance space. After modifying the resolution advisories (e.g., turn left at least 30°), the corresponding evading trajectories governed by any differential operator in set $\mathbf{F}_{mn} - \mathbf{F}_{mn\mathrm{D}}$ would be able to avoid both hazards monitored by both alerting systems since it does not enter dangerous dissonance space.

IV. In-Trail Spacing Example

In this section, we use an in-trail spacing case study to demonstrate the hybrid modeling method of identifying dangerous dissonance space. Consider a simplified one-dimensional problem in which the in-trail separation of two vehicles is monitored by two independent alerting systems placed in the trailing vehicle. As a baseline, assume that system 1 is set up to issue an alert if the two vehicles get too far apart. An alert from system 1 would command the trailing operator to accelerate to reduce the separation between vehicles, to satisfy a requirement of spacing. System 2 is set up to alert if the vehicles are projected to be too close within some amount of time, or if the vehicles are very close together and not diverging fast enough. An alert from system 2 would command the trailing operator to decelerate and increase separation, to satisfy a safety requirement. The leading vehicle (vehicle 1) follows some path open-loop, while the trailing vehicle (vehicle 0) may receive alerts to speed up or slow down to maintain spacing.

A. Possible Dissonance Space

This example has a simple, binary alert set for each system: 0 or 1. System 1 alerts $(\mathbf{a}_1 = 1)$ when the range between vehicles (r) is greater than a threshold distance R_1. Predicates (or inequalities) denoted f_{ij} are defined to divide the state space into subsets (see Part I, Section IV.A, where a method is presented to formally describe alerting systems in terms of how a given state vector is mapped into an alerting system output called an alert set). When the state is inside the subset, the predicate is true; when outside, the predicate is false. Combinations of these subsets then form the alert sets within the universe of the state space, $\mathbf{U}$. Each resulting subset is denoted A_{ik} for the kth alert set of system i. So, for system 1 in this example, an alert occurs when the state is in region A_{11}. The threshold function is then formally defined as

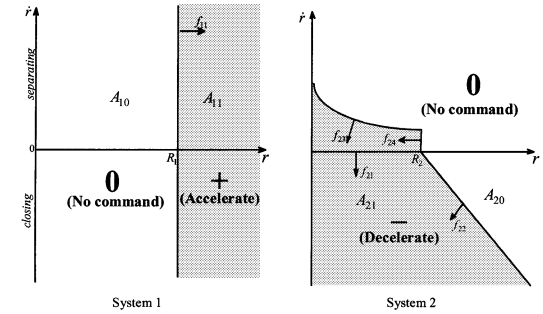

Fig. 7. Example in-trail separation alert set mapping.

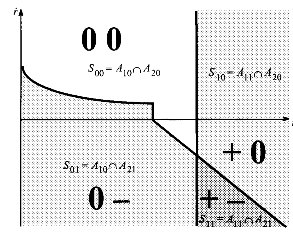

Fig. 8. Combined in-trail alert sets.

$$T_1 = \begin{cases} f_{11}, r > R_1 \\ A_{11} = f_{11} \\ A_{10} = \mathbf{U} - A_{11} \end{cases}. \tag{6}$$

System 2 alerts $(\mathbf{a}_2 = 1)$ when the vehicles are converging and projected to be less than a range R_2 apart within τ seconds, or if they are close together and diverging but at a slow rate $(r\dot{r} < H$, where H is some constant). The threshold function of system 2 can be formally defined as

$$T_2 = \begin{cases} f_{21},\ \dot{r} < 0 \\ f_{22}.\frac{r - R_2}{-\dot{r}} < \tau \\ f_{23},\ r\,\dot{r} < H \\ f_{24},\ r < R_2 \\ A_{21} = (f_{21} \cap f_{22}) \cup (f_{23} \cap f_{24}) \\ A_{20} = \mathbf{U} - A_{21} \end{cases} \tag{7}$$

Fig. 7 shows the two alerting systems' alert spaces in the two-dimensional $\mathbf{y}$ space of r and $\dot{r}$. A "+" has been added to the active alert set in the diagram for system 1 to emphasize that an alert from that system commands the trailing operator to increase speed. A "0" implies that no command or guidance information is displayed by the alerting system. A "−" is used to show where a command to reduce speed would be given by system 2.

Having set up the basic alert stage regions in state space, we can analyze the two systems together as shown in Fig. 8. We assume that the range threshold for efficient operation would be larger than the range threshold for the safety requirement, that is, $R_1 > R_2$. When the two systems are combined, the intersections of their alert sets are denoted by the sets S_{mn} where m is the alert set from system 1 and n is the alert set from system 2

$$S_{mn} = A_{1m} \cap A_{2n}. \tag{8}$$

Assume there is some limit on the potential acceleration of the vehicle, $a_{\max}$. If system 1 is not alerting, then the operator is conceivably allowed to apply any acceleration he or she may desire within that acceleration limit. Thus, set A_{10} can be thought of mapping to the action space $[-a_{\max}\ a_{\max}]$. If system 1 does alert, then the operator should accelerate the trailing vehicle above $a_{\min}$. This corresponds to action space $[a_{\min}\ a_{\max}]$. Similar mappings can be made for system 2: system 2 has the same action space as system 1 if there is no alert. However, an alert from system 2 commands the trailing vehicle to decelerate corresponding to action space $[-a_{\max}\ -a_{\min}]$. Then region S_{11} in Fig. 8 could be quite problematic because the intersection of the two systems' action spaces $\{[a_{\min}\ a_{\max}]$ and $[-a_{\max}\ -a_{\min}]\}$ is empty. That is, the two systems are issuing contradictory resolution commands (one to accelerate, the other to decelerate). Thus, S_{11} is dissonance space, and the formal condition for this dissonance space is

$$\begin{aligned} S_{11} &= f_{11} \cap f_{21} \cap f_{22} \\ &= \left\{ (r, \dot{r}) \,|\, \dot{r} < 0, r > R_2, \frac{r - R_2}{-\dot{r}} < \tau \right\}. \end{aligned} \tag{9}$$

B. Dangerous Consequence of Dissonance

Now, we want to identify those dangerous dissonance states in S_{11} by establishing a hybrid model of the process. Then in the next section, we can avoid the dangerous consequence of dissonance by imposing restrictions on process control.

Here, we assume two vehicles are moving on the same straight line, so thrust T_0 of the trailing vehicle is the only control input. To simplify the case study, we assume that the front vehicle does not change its velocity, and the trailing vehicle changes velocity constantly according to each system's alert set. A point-mass equation of motion is adequate to analyze dissonance in this case.

Thus, the dynamics of process for this one-dimensional (1-D) case can be described as

$$\begin{aligned} \dot{x}_0 &= v_0 \\ \dot{x}_1 &= v_1 \\ \dot{v}_0 &= T_0/m_0 \\ \dot{v}_1 &= 0 \end{aligned} \tag{10}$$

where m_0 is the mass of the trailing vehicle.

In observable state space $(r, \dot{r})$, the trajectory of the process is given by

$$r(t) = r_0 + \dot{r}_0 t + \frac{1}{2}(a_1 - a_0)t^2 \tag{11}$$

$$\dot{r}(t) = \dot{r}_0 + (a_1 - a_0)t \tag{12}$$

where $r_0 = x_1(0) - x_0(0), \dot{r}_0 = v_1(0) - v_0(0), a_0 = T_0/m_0, a_1 = 0$, and the initial state $[x_0(0), v_0(0)]^T$ for the trailing vehicle and $[x_1(0), v_1(0)]^T$ for the front vehicle.

In this example, we will not consider any uncertainty. We also assume that the human operator would respond to the alerting system command without any delay on each alert space boundary. That is, $\Delta_q = 0$ for each $q \in Q \equiv \{1, \ldots, N\}$.

Given alerting system 1 in this example, the whole state space $\mathbf{U}$ can be separated into two subsets A_{10} and A_{11} (Fig. 7), that is, $\mathbf{U} = A_{10} \cup A_{11}$ and $A_{10} \cap A_{11} = \phi$. In state space A_{10}, the continuous dynamics of the process are given by the vector field $\mathbf{F}_{10} : A_{10} \to \mathbf{R}^2$. As explained earlier, in state space A_{10} the operator is conceivably allowed to apply any acceleration he or she may desire within an acceleration limit. To simplify the study case, we assume the operator would not change the velocity if there were no alerting system command. So, in state space A_{10}, the process dynamics is governed by the differential equation (10) with $T_0 = 0$, and both vehicles move with constant velocities. That is, the trajectory is given by (11) and (12) with $a = a_1 - a_0 = 0$. In state space A_{11}, the continuous dynamics of the process are given by the vector field $\mathbf{F}_{11}$. The alerting system commands the operator of the trailing vehicle to accelerate with $a_0 \geq a_{\min}$, and the trajectory is given by (11) and (12) with $a = a_1 - a_0 \in [-a_{\max}\ -a_{\min}]$ (the trailing vehicle accelerates and the front vehicle does not change speed).

Similar to alerting system 1, state space $\mathbf{U}$ can be separated into two subsets A_{20} and A_{21} for alerting system 2. In state space A_{20}, the vector field is $\mathbf{F}_{20}$, and we assume the trajectory is given by (11) and (12) with $a = a_1 - a_0 = 0$. In state space A_{21}, the vector field is $\mathbf{F}_{21}$. Alerting system 2 commands the operator of the trailing vehicle to decelerate with $a_0 \leq -a_{\min}$, and the trajectory is given by (11) and (12) with $a = a_1 - a_0 \in [a_{\min}\ a_{\max}]$ (the trailing vehicle decelerates and the front vehicle remains at the initial speed).

When $\mathbf{x} \in S_{11}$, there is dissonance since the two systems are issuing contradictory resolution commands (one to accelerate, the other to decelerate), and the vector field is not well defined. We assume here that the operator would apply any acceleration or deceleration within the performance limits in this dissonance space. That is, the trajectory is given by (11) and (12) with $a = a_1 - a_0 \in [-a_{\max}\ a_{\max}]$.

In this example, alerting system 1 is attempting to maintain efficient spacing between vehicles. Alerting system 2 is monitoring hazard space, where two vehicles will crash when $r = 0$. Since the region with negative range rate and $r = 0$ is not reachable, we define the hazard space for this example as

$$\mathbf{H}_2 = \{(r, \dot{r}) \,|\, r = 0, \dot{r} < 0\}. \tag{13}$$

We also assume that the threshold functions are designed such that the required deceleration $-a_{\min}$ of alerting system 2 would avoid the hazard space.

Thus, the hybrid model of this process consists of a state space $\mathbf{U} = \cup_{q \in Q} \mathbf{U}_q$, where $q \in Q \equiv \{1, \ldots, N\}$. Q could be an infinite set if two vehicles will not crash and the process dynamics carry on indefinitely. The state $(q, \mathbf{x})$ of the process may flow within q only if the continuous state is within any of the following sets: $S_{00} = A_{10} \cap A_{20}, S_{01} = A_{10} \cap A_{21}, S_{10} = A_{11} \cap A_{20}$, and $S_{11} = A_{11} \cap A_{21}$. The dynamics of the process within each subset do not change unless the state reaches the boundaries of these subsets. That is, the acceleration a does not change within each subset once it is chosen.

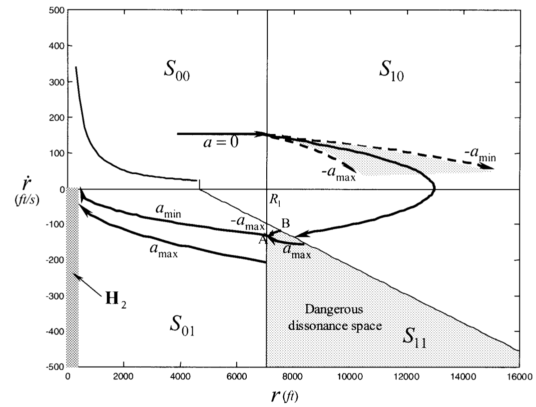

Fig. 9. Dangerous dissonance space.

Given the hazard space $\mathbf{H}_2 = \{(r, \dot{r}) | r = 0, \dot{r} < 0\}$ monitored by alerting system 2, we can use backward reachability analysis to identify dangerous dissonance space within the dissonance space S_{11}.

Fig. 9 shows the process of identifying dangerous dissonance space with threshold parameters of two alerting systems given in Table I as an example. If the trajectory with $a = a_{\min}$ can reach the hazard space $\mathbf{H}_2 = \{(r, \dot{r}) | r = 0, \dot{r} < 0\}$, then there must be trajectories with some $a \in [a_{\min}\ a_{\max}]$ that could also reach the hazard space. So, in state space S_{01}, using (11) and (12) with $a = a_{\min}$ and destination state $r(t) = 0$ and $\dot{r}(t) = 0$

$$0 = r_{\mathrm{A}} + \dot{r}_{\mathrm{A}} t + \frac{1}{2} a_{\min} t^2 \tag{14}$$

$$0 = \dot{r}_{\mathrm{A}} + a_{\min} t. \tag{15}$$

We can identify point A (Fig. 9) on the boundary of alerting system 1 $\{(r, \dot{r}) | r = R_1\}$. Solving (14) and (15) with $r_{\mathrm{A}} = R_1$, we can get $\dot{r}_{\mathrm{A}} = -\sqrt{2 a_{\min} R_1}$. From any point below A on the boundary of alerting system 1 $\{(r, \dot{r}) | r = R_1, \dot{r} \leq -\sqrt{2 a_{\min} R_1}\}$, it is possible to reach the hazard space following the trajectory given by (11) and (12) with $a \in [a_{\min}\ a_{\max}]$ in state space S_{01}.

Now, with points $\{(r, \dot{r}) | r = R_1, \dot{r} \leq -\sqrt{2 a_{\min} R_1}\}$ as the target states, with system dynamics given by (11) and (12) with $a \in [-a_{\max}\ a_{\max}]$, we want to identify those initial states on the boundary of alerting system 2 $\{(r, \dot{r}) | (r - R_2 / -\dot{r}) = \tau\}$. As we can see from Fig. 9, we only need to identify point B, since if the trajectory with $a = -a_{\max}$ can reach point A from point B, then any state below B on $\{(r, \dot{r}) | (r - R_2 / -\dot{r}) = \tau\}$ could reach points $\{(r, \dot{r}) | r = R_1, \dot{r} \leq -\sqrt{2 a_{\min} R_1}\}$ following the trajectories given by (11) and (12) with some $a \in [-a_{\max}\ a_{\max}]$.

In state space S_{11}, solving (11) and (12) with $a = -a_{\max}$ and destination state $r(t) = R_1$ and $\dot{r}(t) = -\sqrt{2 a_{\min} R_1}$ (state A)

$$R_1 = r_{\mathrm{B}} + \dot{r}_{\mathrm{B}} t - \frac{1}{2} a_{\max} t^2 \tag{16}$$

$$-\sqrt{2 a_{\min} R_1} = \dot{r}_{\mathrm{B}} - a_{\max} t \tag{17}$$

and an additional condition

$$\frac{r_{\mathrm{B}} - R_2}{-\dot{r}_{\mathrm{B}}} = \tau \tag{18}$$

TABLE I
THRESHOLD PARAMETERS FOR THE EXAMPLE PROCESS DYNAMICS

	System 1	System 2
Threshold Functions	$r = R_1$	$r + \dot{r}\tau = R_2$ $r\dot{r} = H$
Parameter values	$R_1 = 7050$ ft	$R_2 = 4650$ ft $\tau = 25$ s $H = 102631\ \mathrm{ft}^2/\mathrm{s}$

we can identify point B with

$$\dot{r}_{\mathrm{B}} = a_{\max}\tau - \sqrt{2(a_{\min} + a_{\max}) R_1 - 2 a_{\max} R_2 + a_{\max}^2 \tau^2} \tag{19}$$

and (17). So the dangerous dissonance space boundary is the set

$$\left\{ (r, \dot{r}) \middle| \frac{r - R_2}{-\dot{r}} = \tau, \dot{r} \leq a_{\max}\tau - \sqrt{2(a_{\min} + a_{\max}) R_1 - 2 a_{\max} R_2 + a_{\max}^2 \tau^2} \right\}. \tag{20}$$

As shown in Fig. 9, the dangerous dissonance space is the space below the curve AB in the dissonance space S_{11}. Entering S_{11} above the curve will be safe as long as $a \in [-a_{\max}\ a_{\max}]$.

C. Modifying the Control Strategy to Mitigate Dissonance

Given an initial condition, we can identify the acceleration requirement for the trailing vehicle in the alert space of system 1 to avoid entering the dangerous dissonance space in S_{11}. With point B in Fig. 9 as a target state, (11) and (12) can be used to identify the relation between initial range rate $\dot{r}_0$ when $r = R_1$ and the required acceleration of the trailing vehicle that would prevent entering S_{11}. That is, solving

$$R_2 - a_{\max}\tau^2 - \tau\sqrt{2 a_{\min} R_1 - 2 a_{\max} R_2 + a_{\max}^2 \tau^2} = R_1 + \dot{r}_0 t + \frac{1}{2} a t^2 \tag{21}$$

$$a_{\max}\tau - \sqrt{2 a_{\min} R_1 - 2 a_{\max} R_2 + a_{\max}^2 \tau^2} = \dot{r}_0 + \mathrm{at} \tag{22}$$

we obtain a relationship between the required acceleration a and $\dot{r}_0$

$$a = \frac{\dot{r}_B^2 - \dot{r}_0^2}{2(r_B - R_1)} \tag{23}$$

where

$$r_B = R_2 - a_{\max}\tau^2 - \tau\sqrt{2 a_{\min} R_1 - 2 a_{\max} R_2 + a_{\max}^2 \tau^2} \tag{24}$$

$$\dot{r}_B = a_{\max}\tau - \sqrt{2 a_{\min} R_1 - 2 a_{\max} R_2 + a_{\max}^2 \tau^2}. \tag{25}$$

As we mentioned earlier, in state space S_{10}, alerting system 1 commands the operator of the trailing vehicle to accelerate with $a_0 \geq a_{\min}$, and the trajectory is given by (11) and (12) with $a = a_1 - a_0 \in [-a_{\max}\ -a_{\min}]$ (the trailing vehicle accelerates and the front vehicle does not change speed). So, if we then let $a = a_1 - a_0 = -a_{\min}$ (the trailing vehicle accelerates with minimum acceleration) in (23), then the initial range rate must be $\dot{r}_0 = \sqrt{\dot{r}_B^2 + 2 a_{\min}(r_B - R_1)}$. That is, given an initial state $(R_1, \dot{r}_0)$,

TABLE II
SUMMARY OF REQUIRED ACCELERATION TO AVOID DANGEROUS DISSONANCE SPACE

Initial range rate $\dot{r}_0$ on the boundary $r = R_1$ (r = 7050 ft)		Required acceleration in region S_{10} to avoid dissonance	
general form	with parameter values from Table 1	general form	with parameter values from Table 1
$0 < \dot{r}_0 < \sqrt{\dot{r}_B^2 + 2a_{\min}(r_B - R_1)}$	$0 < \dot{r}_0 < 137$ ft/s	$a_0 \in [a_{\min} \quad a_{\max}]$	1.5 ft/s $< a_0 <$ 3 ft/s
$\dot{r}_0 > \sqrt{\dot{r}_B^2 + 2a_{\min}(r_B - R_1)}$ & $\dot{r}_0 < \sqrt{\dot{r}_B^2 + 2a_{\max}(r_B - R_1)}$	137 ft/s $< \dot{r}_0 <$ 145 ft/s	$a_0 > \dfrac{\dot{r}_0^2 - \dot{r}_B^2}{2(r_B - R_1)}$	$a_0 > \dfrac{\dot{r}_0^2 - 16384}{1596}$
$\dot{r}_0 > \sqrt{\dot{r}_B^2 + 2a_{\max}(r_B - R_1)}$	$\dot{r}_0 >$ 145 ft/s	No solution	No solution

to prevent the two vehicles from entering the dangerous dissonance space in S_{11}, the acceleration of the trailing vehicle a_0 in state space S_{10} must be larger than $(\dot{r}_0^2 - \dot{r}_B^2)/(2(r_B - R_1))$ when $\dot{r}_0 > \sqrt{\dot{r}_B^2 + 2a_{\min}(r_B - R_1)}$ since $a = a_1 - a_0 = -a_0$. Also, if we let $a = a_1 - a_0 = -a_{\max}$ (the trailing vehicle accelerates with maximum acceleration) in (23), then the initial range rate must be $\dot{r}_0 = \sqrt{\dot{r}_B^2 + 2a_{\max}(r_B - R_1)}$. That is, with any initial range rate $\dot{r}_0 > \sqrt{\dot{r}_B^2 + 2a_{\max}(r_B - R_1)}$ on $r = R_1$, it is impossible (with $a \in [-a_{\max} \; -a_{\min}]$) to prevent the two vehicles from entering the dangerous dissonance space in S_{11}.

As a summary and example illustration of the prior calculations, assume that we have two alerting systems with the threshold parameters shown in Table I where the maximum acceleration of the vehicles cannot exceed 3 ft/s^2, and the commanded minimum acceleration from alerting system 1 is 1.5 ft/s^2. Now consider the case where the vehicles begin in region S_{00} where no alerts are issued and they are diverging with some positive range rate $\dot{r}_0$. At the moment the state crosses into region S_{10}, system 1 will begin alerting the operator to speed up so as to reduce the separation between vehicles. Based on the magnitude of $\dot{r}_0$ at that moment (when $r = R_1$), several possibilities exist regarding whether dangerous dissonance can be avoided. Three distinct cases exist, as summarized in Table II. If $\dot{r}_0 < 137$ ft/s on the boundary of region S_{10}, then any trajectory with an acceleration between 1.5 and 3 ft/s^2 can avoid entering the dangerous dissonance space. If instead $\dot{r}_0 = 140$ ft/s, for example, then the trailing vehicle should accelerate at more than 2.0 ft/s^2 or else dangerous dissonance space will be entered. Should $\dot{r}_0$ be greater than 145 ft/s, then no acceleration within the limits of this example would be able to avoid dangerous dissonance space.

The implications of this simplified example are that first, efforts should be made to minimize the possibility of having two vehicles diverging at greater than 145 ft/s. This might be facilitated by providing additional range-rate cues to the operator. If divergence rates are kept small, then the potential for dissonance is reduced. Secondly, if divergence rates between 137 and 145 ft/s do occur, a more aggressive alert could be issued from system 1 to guide the operator to maintain an acceleration of at least $(\dot{r}_0^2 - \dot{r}_B^2)/(2(r_B - R_1))$. The best case would be to prevent the vehicles from diverging at a rate greater than 137 ft/s. In such a case, any acceleration between the assumed bounds of 1.5–3 ft/s^2 would avoid dangerous dissonance. A focused human-in-the-loop simulation study would certainly be warranted to examine these issues in more detail. Still, the analysis presented here can help guide designers toward those situations that may be most important to study.

V. 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, however, as alerting systems continue to be injected into complex system operations. Several areas in aerospace have already been identified where dissonance is likely to occur if this issue is ignored, and certainly there are other regimes where similar problems are of concern.

To date, management of dissonance between systems has mainly involved inhibition of alerts, and has typically occurred without a structured understanding of the specific issues involved. Based on the model and analysis of dissonance in a companion paper (Part I), this paper developed a hybrid model to describe the interactions between the discrete state of alerting systems and the continuous dynamics of the process incorporating multiple alerting systems. Certainly, more human factor studies are needed to effectively identify dangerous dissonance regions by more accurately modeling human behavior when exposed to dissonance.

In some cases, unsafe consequences of dissonance may be avoided by (1) changing the alerting threshold design to eliminate dangerous dissonance space altogether, (2) by restricting operational procedures or alerting system commands to keep the process from entering dangerous dissonance space, or (3) by restricting or modifying the human operator's control to avoid hazard space if dissonance is experienced. Which of these methods may be the most effective for a given problem certainly depends on many specific issues and on focused human factors studies beyond the scope of this paper. The example in this paper showed how, for a well-structured problem one can determine specific acceleration limits to avoid dissonance from occurring.

A critical aspect of alerting dissonance is the impact of conflicting information on the human's situation awareness and decision-making processes. This impact depends on the specific application, situation, and human operator characteristics, and so it is difficult to develop a general model of human behavior at this time. It will ultimately be critical to examine how a conflict in information translates into human performance problems.

REFERENCES

[1] A. Pritchett, B. Vandor, and K. Edwards, "Testing and implementing cockpit alerting systems," *Reliab. Eng. Syst. Safety*, vol. 75, no. 2, pp. 193–206, Feb. 2002.

[2] M. S. Branicky, "Studies in Hybrid Systems: Modeling, Analysis, and Control," Doctor of Science dissertation, Dept. Elect. Eng. Computer Sci., Mass. Inst. Technol., Cambridge, MA, June 1995.

[3] B. Berson, D. Po-Chedley, G. Boucek, D. Hanson, M. Leffler, and H. Wasson, "Aircraft Alerting Systems Standardization Study, Vol. 2: Aircraft Alerting System Design Guidelines," Nat. Tech. Inform. Service, Springfield, VA, DOT/FAA/RD-81/38/II, Jan. 1981.

[4] G. Boucek, D. Po-Chedley, B. Berson, D. Hanson, M. Leffler, and R. White, "Aircraft Alerting Systems Standardization Study, Vol. 1: Candidate System Validation and Time-Critical Display Evaluation," Nat. Tech. Inform. Service, Springfield, VA, DOT/FAA/RD-81/38/I, Jan. 1981.

[5] M. Waller and C. Scanlon, Eds., *Proc. NASA Workshop Flight Deck Centered Parallel Runway Approaches Instrument Meteorological Conditions*. Hampton, VA: NASA Conf. Pub. 10 191, Dec. 1996.

[6] J. K. Kuchar and B. D. Carpenter, "Airborne collision alerting logic for closely-spaced parallel approach," *Air Traffic Cont. Quart.*, vol. 5, no. 2, pp. 111–127, 1997.

[7] D. Bateman, "Development of ground proximity warning systems (GPWS)," presented at the Royal Aeronautical Society Controlled Flight Into Terrain One Day Conf., London, UK, Nov. 8, 1994.

Lixia Song received the S.B. and S.M. degrees from the Department of Engineering Mechanics, Hunan University, Changsha, China, in 1994 and 1997, repectively. She received the S.M. degree from the Department of Aerospace Engineering and Mechanics, University of Minnesota, Minneapolis, in 1999, and the Ph.D. degree from the Department of Aeronautics and Astronautics, Massachusetts Institute of Technology (MIT), Cambridge, in 2002.

She is currently a Postdoctoral Researcher at MIT. Her research includes modeling and simulation, system dynamics, estimation and control, optimization, hybrid system analysis, system integration, system requirements analysis.

James K. Kuchar received the S.B., S.M., and Ph.D. degrees from the Department of Aeronautics and Astronautics, Massachusetts Institute of Technology (MIT), Cambridge, in 1990, 1991, and 1995, respectively.

He has been on the faculty at MIT since 1995, where he is currently Associate Professor. His research interests focus on information management, including decision aiding and alerting system design, air traffic conflict detection and resolution, safety assessment, modeling of humans and automation, advanced display concepts, and flight simulation. At MIT, he teaches courses on flight simulation, decision aiding and alerting systems, computational tools, and estimation.

Dr. Kuchar was awarded the William E. Jackson Award from RTCA and the Charley Wootan Award from the Council of University Transportation Centers for his work on alerting system performance modeling, in 1995. He has been active on several committees with the Society of Automotive Engineers and RTCA to develop industry standards for aircraft automation, and recently served on a National Research Council committee to evaluate space launch range safety. He is a member of Sigma Xi and the American Institute of Aeronautics and Astronautics.