Integrated Human Centered Systems Approach to the Development of Advanced Air Traffic Management Systems

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ABSTRACT

Human performance considerations are expected to be central to the performance of advanced Air Traffic Management (ATM) systems. The development of information systems and decision aids in these advanced systems will be simultaneously driven by technical and human capabilities coupled with operational requirements. An Integrated Human Centered Systems Approach is suggested which considers the human controller as a functional component of the closed loop information system. Recent research activities which illustrate different aspects of human performance issues are discussed.

INTRODUCTION

The development of new information systems within Air Traffic Control (ATC) architectures has historically been driven by increasing traffic and operational constraints taking advantage of improvements in surveillance and communications technologies. The human controller has always been recognized as the key component in the Air Traffic Management (ATM) system, historically compensating for limitations in technology. The outstanding performance of modern Air Traffic Management Systems is a testament to the skill, training, and adaptability of Air Traffic Controllers.

The increase in information and communication technologies has changed the process and requirements for the development of human−automation interfaces. Historically, automation advances in the aerospace industry have evolved from technical capability. However, technology has advanced to a point where system designs can, and indeed must, include the human as a functional element in the system design. In future information intensive environments such as advanced ATM and Flight Management Systems (FMS) it is likely that the capabilities of the operator will become a limiting factor. While the bandwidth of the information technologies will increase significantly, the "bandwidth" of the human operator will remain relatively constant.

Careful consideration must be given to the human operator in the development of decision aiding systems and automation to ensure that overall system performance does not actually degrade. Degradation could be caused by factors such as information saturation, divided attention, and task load association with management of the decision aids. This paper discusses an Integrated Human Centered Systems development process where the human is considered as a functional component of the closed loop ATM system.

HUMAN ISSUES IN ATM AUTOMATION

The evolution of automated ATM systems from simple alerting systems to more complex decision aids such as schedulers and descent advisors has paralleled the evolution of automation in other supervisory control systems such as aircraft flight management systems. Many of the generic human−automation issues which emerged in the aircraft domain are also applicable in the ATM domain.[1−3] In addition there are issues specific to ATM operations. A few of these are discussed briefly below.

System Performance

One basic tenet of automation systems is that the automation must improve the performance of the coupled human/system. While this seems obvious it implies that the test for applicability of any automation system is to compare it against the performance of a non−automated alternative. These comparisons must span the full range of potential operating conditions including non−normal situations as well as partial and complete automation system failure.

Situational Awareness

One of the critical factors in ATM operations is for the controller to have a sufficient understanding (i.e. picture) of all relevant factors to allow well informed control decisions and actions. Currently the term Situational Awareness is used to describe this meta−level understanding.[4,5] As the control environment becomes more complex, crowded, unstructured (i.e. "Free Flight") and constrained, it will be more difficult to maintain controller Situational Awareness. In addition, as multiple humans share responsibility (i.e., Controller, Pilot, Dispatcher), shared Situational Awareness will become more important.

Attention Limitations

It is well known that humans are poor monitoring agents and that operator monitoring performance will degrade with boredom and loss of attention.[6,7] If automation is poorly applied, it is possible for the human to be allocated a monitoring task which is out of the primary control loop. This can result in degraded performance. In addition, the controller may be expected to suddenly resolve situations beyond the capabilities of the automation. If the controller is not actively involved in the decision loop, he or she will require a finite time to orient and develop sufficient Situational Awareness to provide appropriate control actions.

Information and Task Overload

One of the key human performance issues in advanced information systems is to determine the appropriate quantity, format, and pre−processing of information to provide to the operator to prevent loss of situational awareness due to information overload. Essentially, if the bandwidth of the important and available information is greater than the human's capacity, then information will be missed. For multi−tasking environments such as ATM, this problem is exacerbated by a loss of multi−tasking capability as information saturation is approached. Unskilled controllers will tend to focus on single information elements while more skilled operators can prioritize information to effectively reduce the incoming bandwidth. Understanding of controller prioritization strategy is important in predicting traffic complexity (sometimes known as dynamic density) related performance limits.

Understanding of the Automation Criteria

In an effort to minimize information overload, automation is often used to pre−filter and condition the information which is presented to the controller. In addition, the decision aids may make recommendations based on some optimization criteria. These decision aids and displays can improve performance if the information is presented in an intuitive format and the optimization criteria is clear to the controller. This has been observed in the close parallel approach investigations discussed in the paragraph below. However, performance can be degraded if the controller does not clearly understand the roles and criteria of the automation. This has been a problem in some complex aircraft Flight Management Systems where the underlying automation structure is not clear to the user.[3]

Changes in Authority

Current ATC operations exist with an ambiguous, but functional, definition of authority between pilots and controllers. Controllers have responsibility for traffic separation while pilots have responsibility for safety of flight. In practice, authority derives from information. Pilots will typically defer to controllers in matters of traffic where the controllers have more information. Conversely, controllers will often defer to pilots in matters of weather where pilots often have superior information. The incorporation of high bandwidth datalink with more shared information may actually destabilize the authority structure if not carefully considered. This has already been observed in some cases during the introduction of the Traffic Alert and Collision Avoidance System (TCAS).

Changes in Communications Modes

One impact of datalink technologies is the potential change in the communication of control instructions. Many of the existing flight procedures and route structures have been developed and named in order to allow efficient voice communication over low bandwidth VHF and HF links. With the ability to digitally communicate a complex series of 4D waypoints (Latitude, Longitude, Altitude, Time) the potential exists for the use of unnamed procedures which cannot be communicated by voice in the event of a datalink failure.

Loss of "Party Line" Information

One of the major concerns of the extensive use of datalink communications is the loss of "Party Line" information and the Situational Awareness which is achieved by monitoring secondary voice conversations on VHF and HF channels.[8−11] Based on survey and simulator studies, the important areas appear to be traffic and weather information. Potential "Party Line" compensation mechanisms are under study including TCAS and datalink distribution of weather information.

Unexpected Compensatory Behavior

In some cases, technology can have unexpected and undesirable side effects. For example, the presence of TCAS in some cases reduced terminal area capacity because some controllers added additional "in trail" separation to TCAS aircraft to avoid inadvertent violation of in−trail wake vortex criteria which could be observed and reported by pilots.

Human Acceptance and Trust of Automation

There are many social and psychological factors which influence how automation will be accepted. In systems like ATM where the human is ultimately responsible, the controller must develop "trust" in the automation.[7] While there are many factors which influence "trust", it is clear that the automation must be reliable and the controller must have a clear understanding of the operation and limitations of the automation. A second factor in the acceptance of automation is any perception of "threat" that the automation poses for the controller. This "threat" can be minimized if the automation is seen as a vehicle to enhance the controller capabilities rather than to supplement them. One mechanism for improving the acceptability of automation is to include current controllers early in the development process.

Human Reliance on Automation

As automation is used to improve the performance of the human/automation system, issues of human reliance and reliability must be considered. If the potential exists for automation failure, procedures and policies must exist to maintain controller base skill levels for adequate operation in the non−automated state. If automation is critical to the task then issues of fault tolerance and system redundancy must be addressed.

INTEGRATED HUMAN CENTERED SYSTEMS APPROACH

The Integrated Human Centered Systems Approach is well suited to the development of advanced ATM information systems.[12] This approach applies known techniques of human centered design but maintains a Systems Engineering methodology in the development process. Within this context, the human is considered as a functional component of the closed loop information system. System level trades are considered to evaluate the allocation of capability and responsibility between the human and other components of the information systems such as the sensors, displays, or automation systems.

A key element of the integrated approach is practical consideration for the actual operating environment. Many proposed information system elements which look good on paper, in theory and in static models fail in dynamic operation. A simple example would be a decision aid which did not consider real world behavior such as the variability in pilot response time to controller instructions or the possibility of a blocked communication.

The key steps in the Integrated Human Centered Systems Approach are described below.

Model the System and Operator (or Operators) as a Closed Loop Feedback Process

The first step in the process is to create a model of the system with the operators represented as single elements, or as more complicated subsystems if necessary. These elements will have inputs in the form of sensory data, and outputs in the form of control actions on various other system elements. Fig. 1 shows an example of a closed loop model of a portion of the current aerospace system. In this model, Air Traffic Control, the Pilot and the Airline Operations Center (AOC) are all considered functional elements.

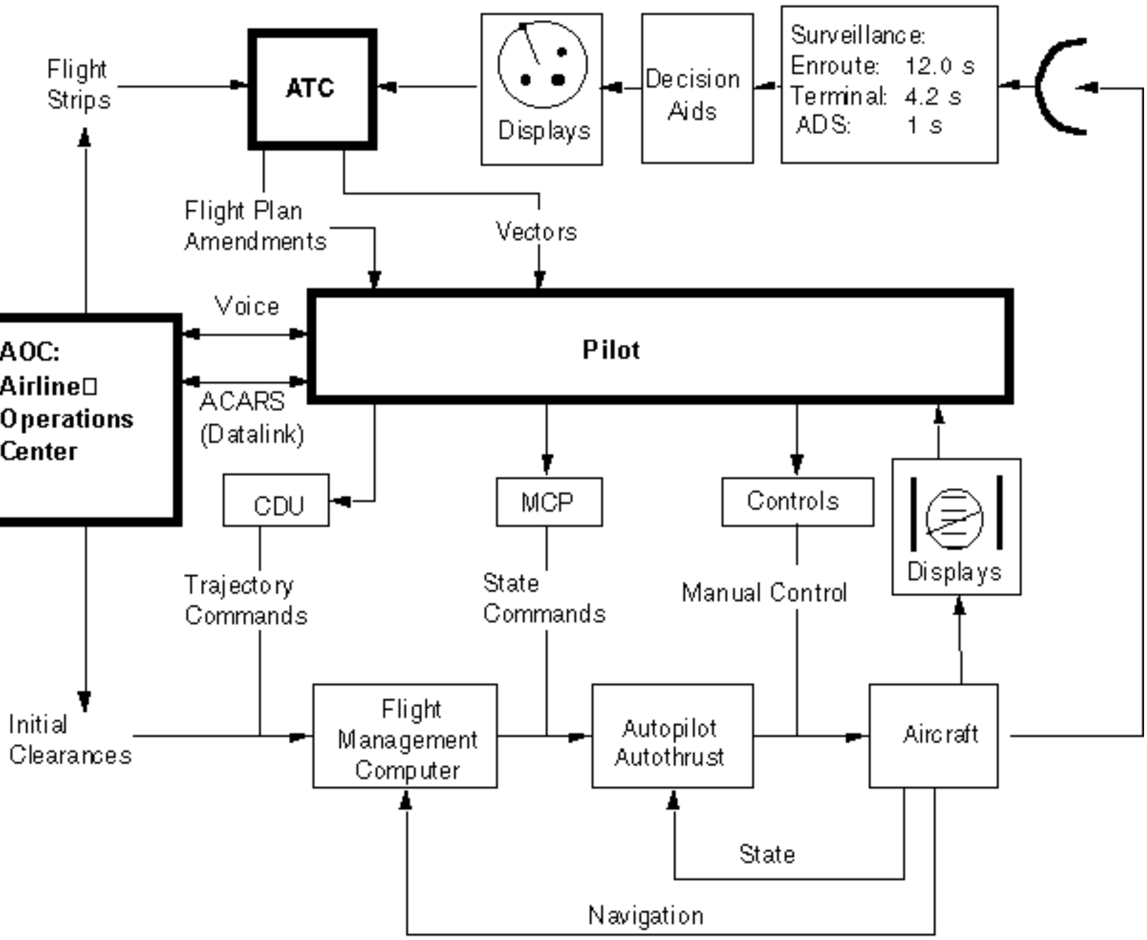

Figure 1. Simple Closed Loop Model of the ATM System.

Determine the Information That the Operator Requires to Perform the Task

Information requirements are defined by the inputs necessary for the operator to perform and manage the necessary tasks. Typically a functional analysis and time line analysis of the operation are conducted to determine a base set of information requirements. For evolutionary systems it is more applicable to identify key issues and obtain operational insight by conducting focused interviews and surveys of operators currently using similar systems.

Use the Information Requirements to Determine the Display/Automation Requirements

Once the information requirements have been identified, the functional requirements for the display can be derived. These requirements often highlight issues that will need to be dealt with before continuing. It is useful at this stage to identify information which may be unobservable or difficult to display, and perhaps re−examine its impact on task requirements.

Develop Prototype Systems

Based on the results of the information requirements analysis and an assessment of technological capability, prototype information systems are developed to explore various system options and to address issues. The systems are typically developed on rapid prototyping part−task simulators based on graphical workstations which allow easy exploration of different system options at the cognitive level. In many cases, fundamental issues are identified and resolved in the prototyping process when the degree of fidelity is matched to the functional requirements of the task.

Perform Simulation Evaluations

Iterative simulation evaluations of prototype information system options are conducted using controller subject populations. Both performance metrics and subjective metrics are used for evaluation purposes.

Integrated Simulation Testing

For some development systems, it is necessary to run more complex simulation studies to investigate the interaction dynamics between multiple agents (controllers and pilots). This can be conducted in distributed simulation facilities with combinations of real and simulated systems.[12]

System Evaluation

Based on the result of the simulation evaluations, system level assessments are conducted with regard to the potential benefits and impact of the information system. This would include development requirements, system effectiveness, safety implications and cost−benefit analysis.

Field Development Phase

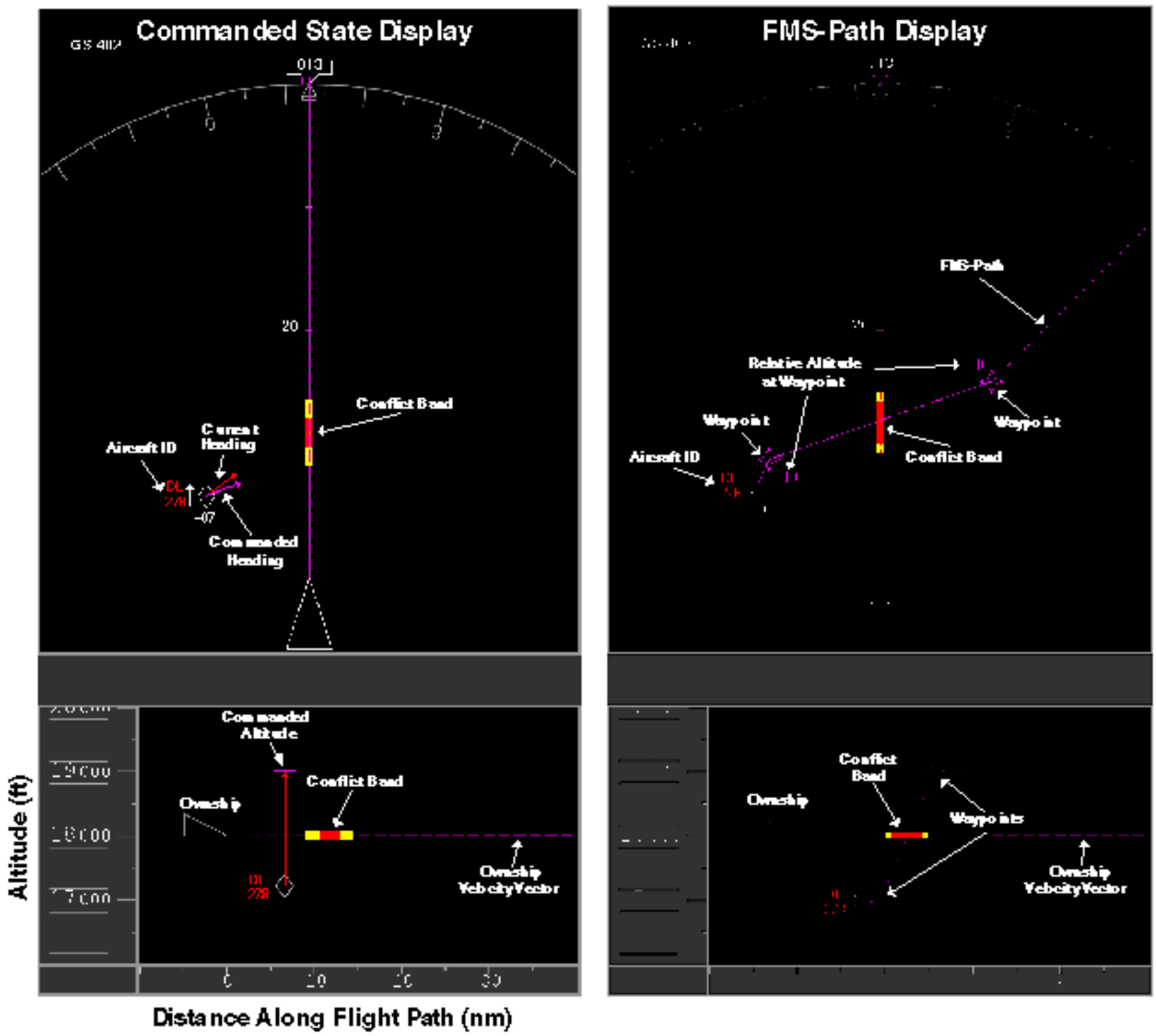

Figure 2. Commanded State and DMS−Path Displays.

For those systems which have favorable cost−benefit profiles, preliminary systems are developed for field studies with live controllers and ultimately live aircraft. The results of these field studies are used to develop system specifications which are used to procure operational systems. In some cases it has been found beneficial to transition the technology into the field in incremental stages. The technology is first introduced to operating central facilities in a non−interfering "shadow mode". Once operational issues have been resolved and controller acceptance has been obtained in this manner, the technology is more easily incorporated into operational facilities. This method has been used in initial TCAS implementation.

EXAMPLES

The integrated human centered systems approach has been applied in many programs within the MIT International Center for Air Transportation. Several examples of ATM relevant programs are discussed briefly below. Further details are available in noted references.

Experimental Studies of Intent Information on Cockpit Traffic Displays[13]

This investigation studied the utility of various levels of intent information to aid in detecting and resolving traffic conflicts. From a system model similar to Fig. 1, various levels of intent information (available in the Flight Management System) were identified. Displays were prototyped at four different levels of intent including: TCAS (baseline), a Rate Display which supplemented the TCAS display with horizontal and vertical velocities, a Commanded State Display, and a FMS−Path display. Examples of the latter are shown in Fig 2. The effect of a conflict probe was also studied. Pilots flew a series of conflict scenarios in a "Free Flight" environment and maneuvered to resolve conflicts.

An example of the results is presented in Fig. 3, which shows the separation violation (1 mile, 500 ft) percentages for the baseline TCAS and the Commanded State display. The results indicate that the addition of either conflict bands or intent information to the baseline TCAS display resulted in fewer separation violations.

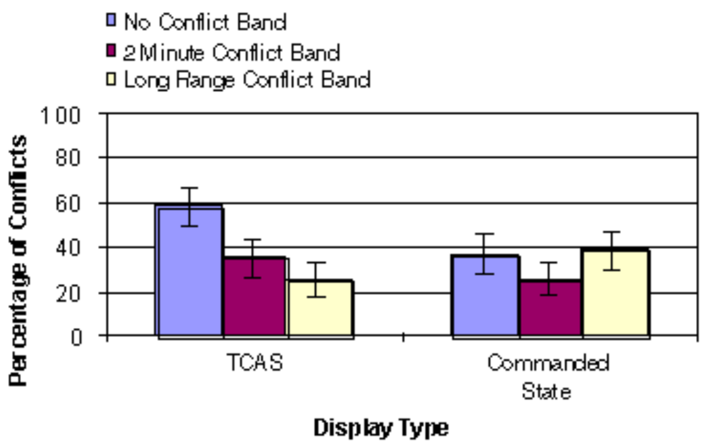

Figure 3. Separation Violation Percentage vs. Display Option.

Hazard Alerting and Conflict Probe Design Issues[14−17]

Hazard alerting systems monitor potential threats and issue warnings to human operators when undesirable incidents are projected to occur. Typically, alerting systems are developed through an ad hoc, evolutionary process, although many design issues are common across applications. Due to uncertainties in sensors and in the human response, these issues are not clear, and evaluating system performance can be difficult. To meet this need, a generalized methodology for modeling and evaluating alerting systems takes the integrated systems approach and has been developed and used to examine several approaches to hazard alerting. The methodology includes models of sensor accuracy, decision logic, and human performance (e.g., response time or maneuver selection). As part of the methodology, the alerting decision is recast as a signal detection problem, and System Operating Characteristic (SOC) curves are introduced to describe the tradeoffs between alerting threshold placement and system performance. Fig. 4 is an example SOC curve showing how the probability of Successful Alert and the probability of Unnecessary Alert change as the alerting threshold is moved. As sensor accuracy improves or human response time decreases, the SOC curve shifts toward the ideal operating point in the upper−left corner. Thus, the SOC approach provides a graphical indication of how system performance changes in response to design modifications. It also allows for direct comparison of hardware or software changes and human performance considerations.

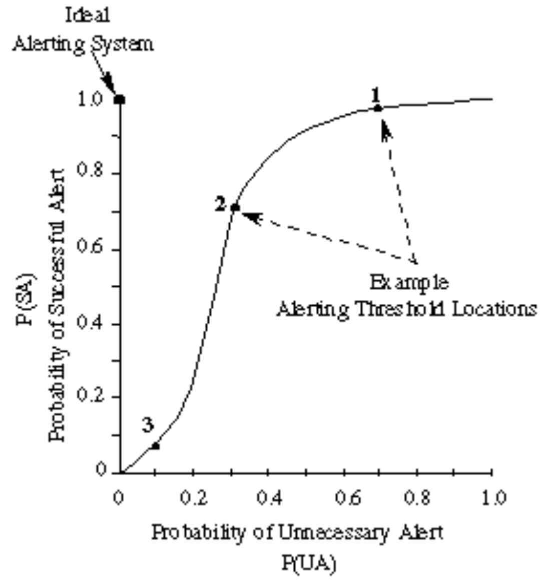

Figure 4. Example System Operating Characteristic Curve.

The methodology has been used with a simplified model of human performance to evaluate the Ground Proximity Warning System (GPWS), recent modifications of TCAS, and ground vehicle headway alerting. The approach has also been applied to develop a conflict probe that has been used in several piloted flight simulation studies at the NASA Ames Research Center. The conflict probe has models of sensor accuracy, pilot response time, and the potential for traffic to maneuver under free flight, and outputs an estimate of the probability of a conflict. Fig. 5 shows an example plot of contours of conflict probability for a situation in which traffic is crossing at a 30º angle.

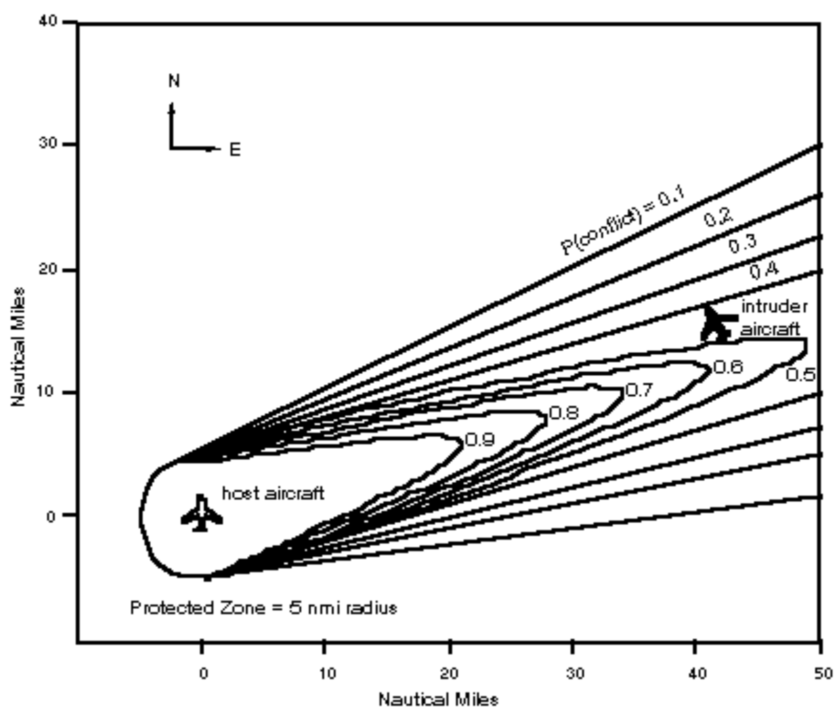

Fig. 5. Example Conflict Probability Contours (30º crossing angle).

Minimal Noise Approach and Departure Procedures[18]

Advanced flight guidance technologies such as Area Navigation (RNAV) utilizing the Global Positioning System (GPS) offer the potential to reduce the impact of aircraft noise in communities surrounding airports by enabling more flexible approach and departure procedures that reduce noise exposure to the most sensitive areas. A system analysis methodology that incorporates the impact of aircraft noise as a consideration in the design of approach and departure procedures has been developed.

The primary tool used in the systems analysis is NOISIM. This tool combines a Flight Simulator, a Noise Model, and a Geographic Information System (GIS) to create a unique rapid prototyping environment in which the user can simulate an aircraft's operation in existing and potential guidance and navigation environments, while simultaneously evaluating the aircraft's noise impact. NOISIM provides a user interface that accurately simulates the interaction between the flight crew and the aircraft and the response of the aircraft to these inputs. The NOISIM GIS, created with United States Geographical Survey (USGS) Land Use and Land Cover data, and United States Census Bureau (USCB) Population Density data, is used to calculate the residential area and population impacted by aircraft noise at specific levels. The combined features of NOISIM provide an environment in which the factors that determine whether a noise abatement procedure is possible, practical and effective may be considered simultaneously.

NOISIM was used for parametric and case studies of several approach and departure procedure options. These analyzes illustrate the unique simulation capability provided by NOISIM, and provide useful insight into appropriate implementation strategies. Studies of approach procedures using the "human in the loop" capability of NOISIM indicate that a 3° decelerating approach provides significant noise reductions compared to the baseline Instrument Landing System (ILS) Approach, and is preferred by pilots to other more complex noise abatement approaches. Studies of departure procedures indicate that the appropriate noise abatement procedure is heavily dependent on the population distribution, and must be developed on a case by case basis.

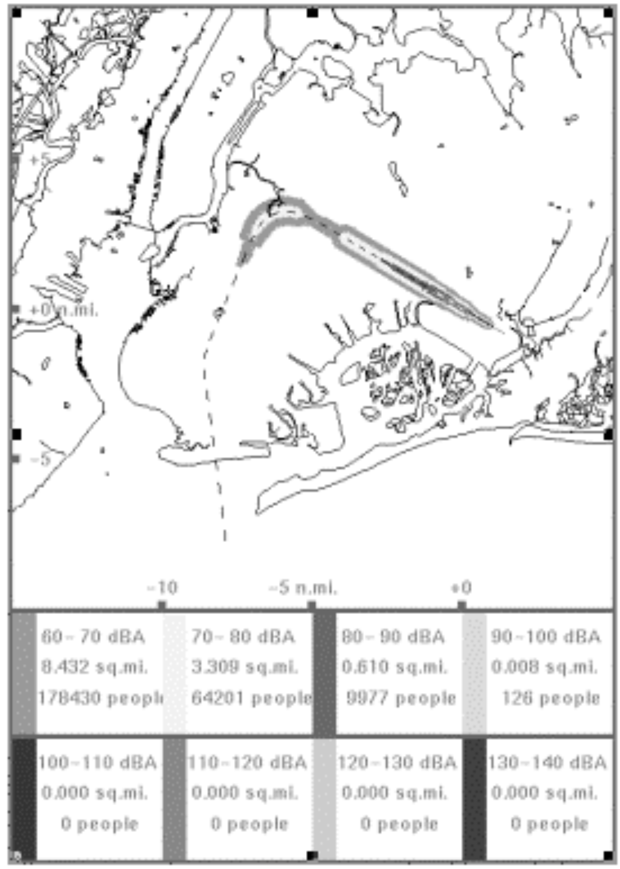

Figure 6. Footprint and Impact of ILS Approach to JFK Runway 13L.

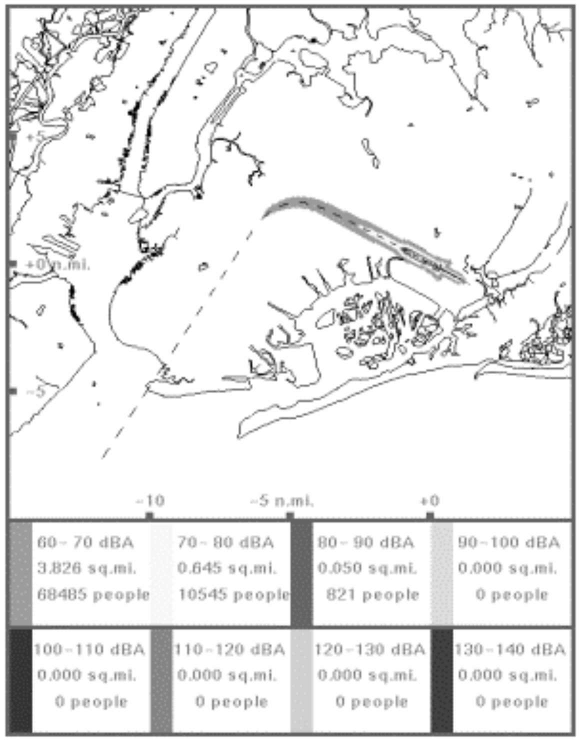

Figure 7. Footprint and Impact of 3° Decelerating Approach to JFK Runway 13L.

An extreme example of the method is shown for JFK runway 13L. The baseline ILS approach is shown in Fig. 6. It can be seen that the 70−80 dBA contour covers 3,309 square miles and impacts 64,201 people. By comparison in Fig. 7, the 70−80 dBA contour of the 3° decelerating approach covers only 0.645 square miles and impacts 10,545 people.

Mode Awareness in Advanced Flight Management Systems[19]

Automation mode awareness problems have been experienced on many air transport aircraft and have been reported to the Aviation Safety Reporting System (ASRS) database. An examination of current generation AutoFlight Systems and a review of the ASRS database highlighted a lack of feedback in the vertical channel of aircraft automation. It was hypothesized that many of the incidents involving mode awareness problems could be mitigated by increased feedback in the vertical channel through an Electronic Vertical Situation Display (EVSD).

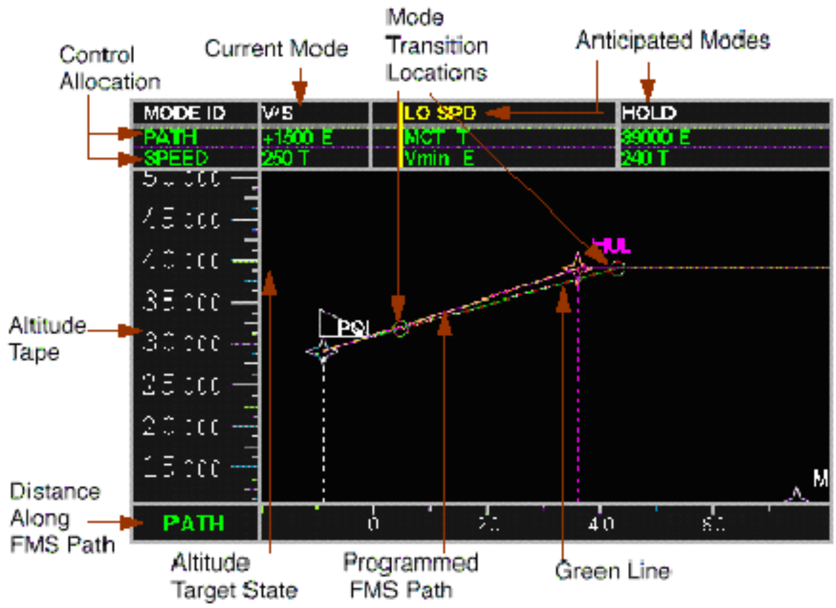

Figure 8. Electronic Vertical Situation Display (EVSD).

Functional requirements for an EVSD were developed and the implementation of the display shown in Fig. 8 was prototyped on a part task simulator. An experimental set of test scenarios were developed based on a representative set of known mode awareness problems.

Certain types of scenarios showed a statistically significant improvement when the EVSD was available. In scenarios where another display explicitly showed the relevant information, availability of the EVSD was not correlated with improved performance. The EVSD was not observed to hamper pilot performance on any of the scenarios. A rating of the subjects' understanding of the scenarios showed a statistical improvement when the EVSD was available. Subjective surveys of the subjects rated elements of the EVSD as useful and helpful.

Collision Avoidance Alerting System Conformance During Closely Spaced Parallel Approaches[20,21]

In simulator tests of close parallel approaches, pilots have been observed to not conform to alerting system commands by delaying their response or by not following the automatic commands exactly. Non−conformance to the automatic alerting system can reduce its benefit. Therefore, a need exists to understand the causes and effects of operator non−conformance in order to develop automatic alerting systems whose commands pilots (or other operators such as controllers) are more likely to follow.

These considerations were examined through flight simulator evaluations of the collision avoidance task during closely spaced parallel approaches. This task provided a useful case−study because the effects of non−conformance can be significant, given the time−critical nature of the task, and because closely spaced parallel approaches in instrument meteorological conditions (IMC), while useful for increasing airport capacity, is unfamiliar to pilots.

A preliminary evaluation of alerting systems identified non−conformance in over 40% of the cases and a corresponding drop in collision avoidance performance. The rate of non−conformance was increased by cockpit traffic displays which provided the pilots with more information about the other aircraft, but may have displayed information which conflicted with the logic used by TCAS in triggering alerts and commanding an avoidance maneuver. These results were supported by a follow−on experiment which found subjects' alerting and maneuver selection criteria were consistent with different strategies than those used by automatic systems, indicating the pilot may potentially disagree with the alerting system if the pilot attempts to verify automatic alerts and commanded avoidance maneuvers. A final experiment found that supporting automatic alerts by explicit displaying its underlying criteria (*consonance* between the display and the alerting system) resulted in more consistent subject reactions. Conversely, significant variability was found between subjects' reactions to automatic alerts when justification for the alert was not available.

Compensation for "Party Line" Information Loss in the Datalink Environment[8–11]

"Party Line" information is an area of concern in the transition to datalink communications. The perceived importance and utilization of "Party Line" information by air crews was initially studied by surveying air carrier flight crews who rated the importance, availability and accuracy of specific "Party Line" information elements.

The importance, availability, and accuracy of "Party Line" information elements were explored through surveys of pilots of several operational types. The survey identified numerous traffic and weather "Party Line" information elements which were considered important. These elements were scripted into a full−mission flight simulation which examined the utilization of "Party Line" information by studying subject responses to specific information element stimuli. The awareness of the different "Party Line" elements varied, and awareness was also affected by pilot workload. In addition, pilots were aware of some traffic information elements, but were reluctant to act on "Party Line" Information alone. Finally, the results of both the survey and the simulation indicated that the importance of "Party Line" information appeared to be greatest for operations near or on the airport. This indicates that caution should be exercised when implementing datalink communications in tower and close−in terminal control sectors.

CONCLUSIONS

Human performance considerations are expected to be central to the performance of advanced Air Traffic Management Systems. The development of information systems and decision aids in these advanced systems will be simultaneously driven by technical and human capabilities coupled with operational requirements. An Integrated Human Centered Systems Approach is suggested which considers the human operator as a functional component of the closed loop information system. Examples of the application of this approach have been presented.

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