Free Flight and the Context of Control: Experiments and Modeling to Determine the Impact of Distributed Air-Ground Air Traffic Management on Safety and Procedures.[1]

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ABSTRACT

The world community of aviation operations is engaged in vast, system-wide, advancement in the methods by which air traffic management is undertaken. We have conducted an experiment and developed a predictive human performance model that address the impact of distributed self-separation operations on air traffic controllers, and in modeled operation, on the flight crew. We will present the results of this study and model analysis. The experiments were performed in current airspace configuration and provided four modes of control: current operation with positive ground control, current operations with direct routing, twenty percent of the aircraft in the sector free maneuvering and self-separating and then eighty percent free maneuvering and self-separating. The results indicate that as the flight deck becomes increasingly involved in self-separation, the controller task loading increases and performance parameters (communication time, frequency, points of closest approach, and efficiency) vary systematically with the type of control. The model analysis was performed in a multi-sector scenario to investigate the impact of ground and air conflict alerting systems interacting as the simulated aircraft engaged in self-separation. The model results indicate increased load levels and significant interactions between the air and ground performance.

INTRODUCTION

There has been much speculation and some analysis undertaken to describe the impact of distributed air and ground operations on the controller and flight crew engaged in those operations (cf. Endsley, 1997; Hansman and Endsley, 1998; Lozito et al. 1997; Corker, Pisanich and Bunzo, 1997). An international research agenda has been focused on the development of advanced technologies and procedures for air traffic management. The basic form of these technologies is that of cognitive aiding systems for air traffic controller and flight deck operations. The basic change in procedure is a relaxation of constraints in operation wherever and whenever that is possible. In the design and evaluation of such systems, the dynamic interaction between the airborne elements and the ground-based systems forms a critical coupling for control. This evolution in ATM operation challenges human performance in a significant way (Wickens et al., 1997, 1998). The human operators (pilots, air traffic controllers, and airline operations personnel), in addition to there current roles, must monitor and predict any change in the distribution of authority and control that might result as a function of the airspace configuration, aircraft state or equipage, and other operational constraints. The operators are making decisions and sharing decisions not only about the management of the airspace, but also about the operating state (the mode of control) of that airspace. In order to safely and effectively describe the new process and

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procedures for this evolving concept, the human operator's performance must be clearly and consistently included in the design of the new operation and of any automation aiding that is proposed to help the operators in their distributed activities.

In order to provide a baseline of performance data resultant from shifts to decreased constraints on aircraft routing, maneuvering and separation, we performed a full-mission controller-focused experiment using a range of control modes in a current airspace (OCALA Sector, Jacksonville Center) with fully qualified air traffic controllers as participants. In order to extend that baseline to other operational issues and other airspaces, we have developed a human performance model that simulates and predicts the interaction of flight crew and air traffic controllers in a range of "free flight" operations. This paper will document both of those developments.

EXPERIMENT IN FREE MANUEVERING AND SELF-SEPARATION

The experiment was intended to explore the limits in performance as "free flight" operations (in the form of aircraft free maneuvering and self-separating) were undertaken in a complex center airspace. The Jacksonville Center in Florida handles traffic transition from Oceanic operations to the east, over flight aircraft, approach and departure aircraft streaming north/south as well as east/west and local short haul aircraft popping up and descending out of the Center's airspace. The experiment concentrated on the performance of the air traffic controller working the radar and communication position in a sector (OCALA) of the Jacksonville Center.

SCENARIOS

The experiment was designed to measure the performance of fully trained controllers in scenarios containing aircraft that were under their control and aircraft that were self-separating in a "free flight" operation. Four scenarios were presented to the air traffic controllers. These were:

(1) Traditional ground-based control,
(2) Traditional control but with all aircraft flying direct,
(3) All aircraft flying direct with 20% self separating and,
(4) All aircraft flying direct with 80% self separating.

Each traffic scenario was approximately 1 hour in duration. The experimental group consisted of 8 controllers with each subject participating in all 4 scenarios. The four experimental runs for each subject were presented in the same order as described above. In the conditions of self-separation the appropriate aircraft entered the sector as 'self-separating" and so identified themselves to the subject controller at hand-off.

The level of traffic was constant across the traffic samples, so that the total number of aircraft handled by the controllers was the same in each scenario. However, the traffic was ramped up across the duration of the scenarios through 3 traffic levels -- low, medium and high and these levels were presented in an ascending order. There were a number of intentional conflicts introduced within the samples so that some positive intervention was required to resolve them; these scripted conflicts amounted to 3 per scenario.

EQUIPMENT & PROCEDURES

Radar displays were simulated to have the same look and feel as those currently in OCALA sector. (Post session interviews with the participants confirmed this similarity.) Traffic was displayed using conventional track signatures and track block data were available as in normal operation. In order to account for the two conditions of control (positive ground-based control and self-separation), a new color-coding convention was introduced. Self-separating aircraft were identified on the radar display by presenting them and associated track block data in a blue color, although in all other respects self-separating traffic appeared the same as normal traffic. As discussed below, the procedural instruction to the controller participants provided them an opportunity to take separation control from a self-separating aircraft and return to themselves. In order to provide a visual reference that this had been done, the representation of an aircraft that had been self-separating but was now under ground control was a blue aircraft identifier line in the track block data and all other markings as a standard track.

Controllers were advised that self-separating aircraft were to be left on their own as much as possible (a standard set of instruction were read to the controllers at the initiation of each experimental session); however, the controllers were also advised that they had the final responsibility for all traffic in the scenario. Thus, if there was an imminent separation violation, the controllers were obliged to take control of the self-separating aircraft. They could then return control to the self-separating aircraft when they thought this was appropriate.

Pseudo pilots were trained members of the staff of the University and remained the same throughout the exercises.

RESULTS

The results of these experiments span a range of variables (including communication initiation times, maneuver times, ranges, and geometry angles and aircraft performance parameter.) For the purpose of this paper, we have selected variables that are associated with the load and performance of the controller. Output data were analyzed using trend analysis, regression analysis, and analysis of variance. Additionally, individual questionnaire analyses were used to supplement the quantitative analysis.

Workload Overall Trends

A regression analysis was conducted using subjective workload as the dependent variable and the objective measures mentioned in the data section as the independent variables. Equation 1 (below) presents the results of this analysis followed by the individual " t " values and their two tailed significance levels (see Table 1):

Workload = 0.578 + 0.0102 latency + 0.0546 aircraft + 0.441 centime + 0.477 difctABC_D - 0.136 difctABD_C + 0.0951 acslow + 0.0804 hoac.

Equation 1. Workload calculation equation.

Table 1 shows the trends associated with the regression analysis for the different scenarios. The workload estimates were elicited from the controllers by a probe approximately every five minutes. The numbers in this table represent an overall impression of workload, although they are not related to specific quantitative variables.

As can be seen, the exercises would increase in difficulty as a function of the interaction of the changing control modes and increase in traffic density - at least as far as the subjective evaluation was concerned.

Predictor	Coeff	SD	T	P
Constant	0.5783	0.1241	4.66	0.000
Latency	0.010243	0.002578	3.97	0.000
Aircraft	0.05459	0.01674	3.26	0.001
Comtime	0.4413	0.1018	4.33	0.000
DifctABC	0.4771	0.1686	2.83	0.005
DifctABD	-0.13622	0.06810	-2.00	0.046
Acslow	0.09511	0.03596	2.64	0.009
Hoac	0.08045	0.02244	3.58	0.000

$r = 0.698$, $r^2 = 48.8\%$, r^2adj = 47.7%

Table 1. Regression analysis on the subjective workload data.

The variables are defined as follows:

Workload is the subjective evaluation of the controller on a scale of 1-5 with respect to how busy he/she is.
Latency is the amount of time it takes the controller to respond to the on-screen prompt to record the workload level.
Aircraft are the number of aircraft under control or self-separating at the time workload is recorded.
Comtime is the amount of communications time, measured in minutes, between the controller and the aircraft for each 5-minute period.
DifctABC_D is the difference in communications time for each 5-minute period between exercises AB and D.
DifctABD_C is the same measurement between exercises AB and C.
Acslow is the difference between fast moving aircraft and slow-moving aircraft measured by the number of slow-moving aircraft for each 5 minutes. This variable was included as a workload regressor because the controller's indicted in post-run de-briefing that aircraft mix in this sector is an important workload determinant.
Hoac is the number of aircraft waiting for handoff per 5 minutes.

It is important to note that, in the context of the regression, communication time does not measure the absolute value of time spent issuing instructions and control; rather, it measures the incremental addition of the additional communication as it relates to the controller's subjective estimation of workload. The absolute time of communication analysis and discussion is presented below in the section on communications. Therefore, as the air traffic situation changes or separation is eroded, the controller finds it necessary to issue further instructions--this is reflected statistically by the correlation between the extra communication time and greater workload estimation. Thus, communication time acts as a surrogate variable for an increasingly complex air traffic situation. This is demonstrated even more dramatically in the large size of the coefficient both absolutely and relative to the other explanatory variables. For example, a 30-second increase in communication produces almost a quarter of a standard deviation increase in subjective workload.

Communications Load Analysis:

In addition to the incremental analysis above, total communications times were analyzed as a function of control mode and as a function of time and number of aircraft under a controller’s responsibility. The data from analysis show an interesting pattern. As illustrated in Figures 1 and 2.

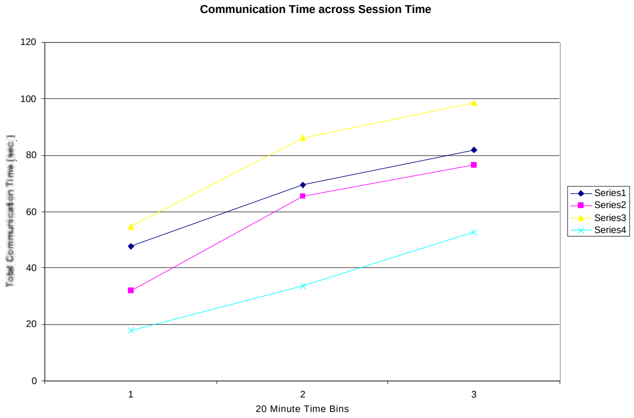

Figure 1. Illustrates total communication time across twenty-minute segments of the scenarios. The different forms of control are plotted as series where Series 1: indicates current control, Series 2: indicates current control with direct routing, Series 3: indicates 20 % “free flight” operation and Series 4: indicates 80 % “free flight” operation.

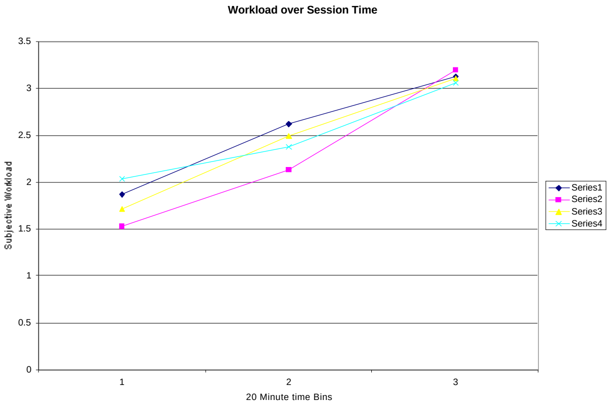

Figure 2. Illustrates the Subjective assessment of workload as a function of control mode and plotted against 20 minute time bins in the session. The different control modes are plotted as a series where Series 1: indicates current control, Series 2: indicates current control with direct routing, Series 3: indicates 20 % “free flight” operation and Series 4: indicates 80 % “free flight” operation.

Standard Operations:

The communication increases with the number of aircraft in the sector. This is to be expected in a near linear manner and this is what is shown.

Direct-to-Routing:

The communications time overall here shows a slight but statistically significant decrease as compared to the standard operations. This to follows from the operation in that the positive control of the aircraft is reduced based on an approved direct to route.

Twenty-Percent “Free Flight”:

The communication here increases significantly in terms of total time. However, when the communication time is compared with an analysis of workload under comparable control (20 % “free flight”) and across all traffic, the workload and the communication time do not co-vary. So while there is an increased communication load, the subjective workload associated with that increase is not significant. The implication (strengthened in subjective reports in subjects debrief) is that the increased communication is for “intent information exchange”. This information does not impose a control burden on the controllers in this operating mode. It does, however, represent a significant increase in the communication channels’ resource use.

Eighty-Percent “Free Flight”:

In the eighty- percent “free flight” operation we see a significant decrease in total communication as compared to the twenty-percent operation, and as compared to the standard operation. However, in this case there is a negative correlation between workload and communication. Despite a reduced communication load the subjective assessment of the participants is that of high workload at the outset and increasing with the number of aircraft in the sector. Our supposition is that the controller workload is associated with constant monitoring of all traffic without knowledge of its future intention.

CONCLUSIONS

These data support a hypothesis that the controller operating in conditions of extensive “free flight” operations finds the task of monitoring that traffic workload intensive, independent of the communication tasks usually associated with positive air traffic control. Further the increase in communications in the condition of moderate traffic indicates that at those levels the controller is seeking to reduce their control burden by gathering intent information on the minority free flying vehicles.

Both of these conclusions suggest that some form of information and or aiding is needed by the controller in “free flight” operations. Presentation of intent information for free flying aircraft was highly desired by the participants. In addition, information (or aiding) for “conformance monitoring” is also required; so that the controller can determine if the intention as specified is being carried out.

HUMAN PERFORMANCE MODELS OF “FREE FLIGHT” OPERATIONS

In order to provide a general framework for the process of shifts in responsibility and control among operators in an evolving and modernizing international airspace, we have expanded on previous work in human performance modeling (Laughery and Corker, 1997; Corker, Pisanich and Bunzo, 1997). In this modeling paradigm, computational representations are developed for the “intelligent agents” in the simulation of interest. This provides for a representation of human performance and for some level of automated-aiding of that performance.

The model of human performance predicts and simulates emergent behavior based on elementary models of human behaviors such as perception, attention, working memory, long-term memory and decision-making. This modeling approach focuses on micro models of human performance that feed-forward and feedback to other constituent models in the human system.

The Man Machine Integrated Design and Analysis System (MIDAS) is composed of models imbedded within its framework that describe the expected human operator’s responses in several areas that are required for the safe and reliable operation of advanced systems (Figure 3). This object-oriented software structure is composed of objects and software entities that maintain and manipulate values representing human, equipment and environmental states.

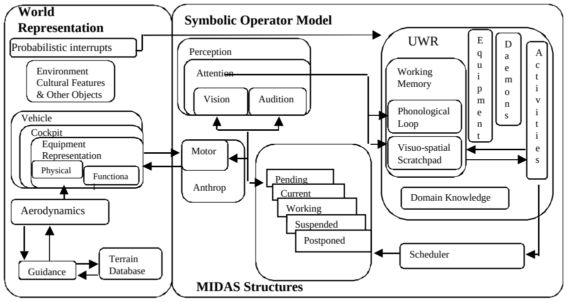

Figure 3. Software components of the MIDAS model representing perceptual, cognitive and motor functions of human operators.

EXPERIMENTAL DESIGN AND ASSUMPTIONS

The human operator’s performance was simulated in the distributed air/ground air traffic management (ATM). This required that multiple controllers, and multiple flight crews to be represented. Two scenarios were created in the current modeling effort. The first scenario was operation under current active positive control. The second scenario was operation consistent with “free flight” rules of operation. Each scenario involved a response to a scripted conflict situation in a number of conditions as set out by the description of independent variables below.

Independent Variables

The independent variables manipulated were locus of control, handoff, and weather. The first LOC simulated the current controlled airspace operations and the second LOC simulated the “free flight” operations. The handoff condition also had two levels. The first level did not involve a handoff. The second level did require a handoff. Two weather conditions will be evaluated, one replicating normal operations with no weather concerns and one replicating an emergency communication operation related to a weather event. Figure 4 outlines the sector organization that was utilized to study the current cross comparison.

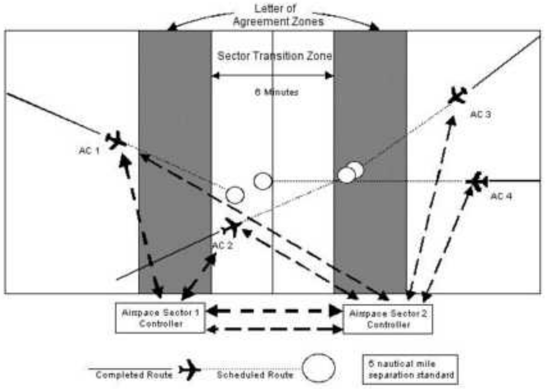

Figure 4: Pictorial representation of the current study. In Figure 4, AC 2 is currently under control of ATC 1. AC 1 is at the beginning of the ATC 2 control due to the letter of agreement. AC 1 is at the entrance of the letter of agreement handoff zone where the handoff can begin. AC 1 can be handed off with the current trajectory, as there will not be a conflict situation occurring in the new airspace sector. AC 2 by contrast is on an airspace collision course with AC 3. This will occur in sector 2. ATC 1 needs to take action to avoid this conflict situation prior to finalizing the handoff.

Dependent Variables

This experiment collected data on four categories of dependent measures. These measures included conflict-related, operational-related, ATC/internal related, and flight crew/internal related measures.

The safety related dependent variables of interest included those aspects related to aircraft conflict. Conflict-related measures included the point of closest approach, and the time of the point of closest approach. Operational measures included efficiency-related information including aircraft positional information, clutter, and time in sector. Operational measures included ATC-related operations and flight crew-related operations. ATC operations included calls to adjoining sectors, clearances to aircraft, calls received by ATC. The flight crew operational measures included calls to the aircraft from the ATC, time of call and action taken by the flight crew.

Experiment Runs and Procedure

Each scenario was run through 50 Monte Carlo runs. There were eight data sets per simulation run made up of the manipulations outlined in the independent variables list. Each scenario was run in an en route flight condition of twenty minutes in duration traveling through a generic airspace. This generic enroute airspace sector replicated an aircraft traveling in the ‘high altitude’ section of Sector 43 towards Sector 33 in the San Francisco Bay area at flight level 350. The human performance-modeling tool made multiple passes through this predefined airspace sector. In all scenarios the aircraft was subject to an airspace conflict with an intruder aircraft approaching from the East going towards the West. The multiple passes through the scenario are analogous to testing multiple subjects. The dependent variables will be taken for each manipulation that has been made.

RESULTS

A series of analyses were performed on both the simulated representation of the aircrews and of the air traffic controllers. A complete review of these data is provided in Gore 1999 and 2000. Controller response times and controller workload estimates are provided those substantiate the human performance data reported above. Workload associated with “free flight” operations shifts as a function of the context under which the control is effected. Emergency conditions (weather related descent) significantly interacted with the type of control and the "position" or role of the operator. These analyses show a high correlation in the workload estimates provided by the human participants in the experimental study and those that were generated by the model.

CONCLUSIONS

We provide an analysis of model behavior as compared with the human operator behavior finding correlations in parameters associated with workload. We conclude that the process by which the controller is moving from active and strategic control in current operations to "opportunistic" and reactive control in the increasing "free flight" operations is consistent with system performance models developed by Hollnagel (1993) and his colleagues. This condition requires that the controllers be provided aiding information through systems that move them back to an information state that is consistent with strategic control. We recognize that this kind of information to enhance conformance monitoring is likely to be of a different type than the information with which they maintain active and positive control. Some suggestions are made as to the type and format of information required.

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BIOGRAPHICAL STATEMENTS:

Kevin Corker is an Associate Professor of Engineering in the Computer Information and Systems Engineering Department of the San Jose State University. He is also the Director of the Graduate Program in Human Factors and Ergonomics there. Prior to that appointment Dr. Corker was Deputy Director of NASA’s Aviation System Capacity program and the Aviation Operations Systems program. His technical interests include computational human performance modeling, cognitive psychology and automation design and integration in complex dynamic systems.

Brian Gore is a Senior Human Factors Research Associate with the San Jose State University (SJSU) Foundation who is currently examining Advanced Air Transport Technologies’ (AATT) impact on human-system performance out of the Human Automation Integration Branch at NASA Ames Research Center. Brian received his Master’s of Science degree in Human Factors/Ergonomics out of the Industrial Engineering Department at SJSU. Brian’s current work includes both software development and experimentation for verification of software prediction. His work will provide a capability that others in the field will be able to take advantage of and expand in the coming years. His technical areas of expertise include computational human performance simulation modeling of complex dynamic systems, cognitive engineering, cognitive psychology, human performance high fidelity simulations of complex human-system interactions.

John Lane is a former British (Royal Air Force) military air traffic officer with over 34 years of experience in operations and data processing. He has performed as a terminal and enroute controller in some of the Royal Air Force's busiest facilities worldwide. In 1994 he joined Embry Riddle Aeronautical University as a Senior ATC Research Associate; since then he has become an expert in the design and implementation of air traffic control system updates and improvements, with an emphasis on automation and human factors. He his also an expert in the simulation and modeling of airport and airspace management systems in the study of delay, demand and system capacity. He is one of the world's leading experts in the use of the Total Airspace and Airport Modeler (TAAM) simulation tool. John has performed numerous studies and evaluations of airspace, airport and air traffic control systems focusing on the evaluation of those systems with regard to delay, demand and capacity issues.

Dr Ken Fleming is the Director of Modeling and Simulation at Embry Riddle Aeronautical University and received his Ph.D. in Economics from the University of California. A former military pilot with over 3,000 hours in nine different aircraft, he holds a FAA Commercial Pilot Airplane Single and Multi-engine Instrument Rating. During the past five years, he has been involved in many programs where modeling and simulation technologies were used to assess and evaluate airspace and airport operations, delay and capacity, efficiencies and processes. These initiatives included funded research programs for Lockheed Martin Corporation, Harris Corporation, NASA Ames Research Center and NASA Langley Research Center, as well as numerous other requirements for operations research-oriented experiments in aviation systems and facilities. Dr Fleming has also led the development of a number of ERAU proprietary airspace and airport modeling and analysis tools used in the study of system efficiency and operational capacity. He is a published and recognized expert in aviation economics as well as the modeling and simulation of airspace and airport operations.