EXPERIMENTAL DESIGN FOR REAL-TIME SIMULATIONS OF AIR TRAFFIC CONTROL CONCEPTS

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ABSTRACT

One of the most effective tools for use in air traffic control experimentation, evaluation, and systems studies is the Digital Simulation Facility (DSF) of the Federal Aviation Administration's National Aviation Facilities Experimental Center located at Atlantic City, New Jersey. The DSF combines computer hardware, software, and personnel for testing and evaluating advanced air traffic control (ATC) concepts and procedures.

DSF simulations, performed principally in the real-time mode, permit the analysis of the man-machine interface of the ATC system. This paper describes the design, experimentation, and analysis activities involved in real-time simulations of air traffic control concepts on the DSF.

INTRODUCTION

The volume of air traffic in the United States has increased steadily since the advent of modern aviation. The Federal Aviation Administration (FAA) has met the challenge of maintaining a safe air traffic control (ATC) system in this dynamic environment with technological and procedural improvements to its ATC system. Proposed advances in ATC travel a long road from the development of an initial concept to their implementation in the field. These new concepts are subjected to many and varied analyses which question their suitability for meeting their intended ATC objective, their reliability, their impact on the existing ATC system, and their operational acceptability.

Controlling air traffic is a complex, multi-faceted, man-machine operation. Seemingly

minor changes may have a profound effect on safety, throughput, and both system and user cost. Quite often these effects, particularly those involving the people in the system (i.e., the controllers and pilots), manifest themselves only in full-scale system level tests. The only practical and cost-effective means of providing that type of testing is simulation. Simulation also provides a means of examining situations which occur only rarely or are difficult to create in the real world. The mission of the Digital Simulation Facility (DSF) at the FAA's National Aviation Facilities Experimental Center (NAFEC) is to provide the FAA with a realistic real-time experimentation capability in which advanced concepts and their related operational procedures can be evaluated and refined.

A unique feature of DSF simulations is the presence of the man-machine interface. The ATC controller is an integral component of the control loop with which new ATC concepts must be compatible. Experiments must be designed which accurately measure the controllers' subjective response, while at the same time, reduce the random variation due to the controller in the system responses.

DSF experiments typically are concerned with the problem of quantitatively and qualitatively comparing alternate system configurations. Since each data collection run is expensive in terms of manpower and laboratory utilization, the smallest number of data runs is a goal of the design. On the other hand, the software and laboratory modifications required to perform experiments on the DSF are costly. Therefore, the primary experimental design criterion is to obtain a sufficient amount of information for valid testing in the minimum number of runs.

The DSF experimenter does have the capability of completely specifying the number of levels of each factor and the number of replications. If the data runs are considered as independent and identically distributed random observations, then classical experimental design methodology can be used to select the design which best meets the previously stated criterion.

DIGITAL SIMULATION FACILITY

An overview of the Digital Simulation Facility is presented in this section. For a complete description of the system, see References 1 and 2.

The primary focus of the DSF is on the controller. Every attempt is made to keep his interfaces with the system as realistic as possible. The DSF is made up of three components; an air traffic controller laboratory, a simulator pilot complex, and a central computer facility.

In the controller laboratory, the controllers view displays and direct traffic movement in accordance with established or proposed ATC procedures. Instructions or clearances to aircraft are issued by voice communications to the simulator pilot complex. Each controller also has voice communications with other controllers to provide for coordination of actions. The controller may also use the keyboard and trackball to communicate with the computer system to control the presentation of data on his display or to perform additional functions required by the concepts being tested.

The central computer facility simulates all the other ATC functions required. It interprets the data entry messages from the simulator pilots and "flies" the aircraft accordingly. Depending upon the sensor systems being simulated, the actual positions are degraded to reflect surveillance and tracking errors, and are updated on the controller scopes at the scan rate of the sensor. The central computer facility also provides controller display information as required by the concept being studied.

The software of the DSF System is composed of on-line, real-time programs written in SYMBOL, the assembler language of the Sigma computers, and off-line programs written in FORTRAN.

The programs which comprise the software can be grouped into three major areas:

1. Data Preparation Programs
2. DSF Operational Programs
3. Data Reduction and Analysis Programs

The Data Reduction and Analysis Programs provide a means of extracting and analyzing the data measures related to the concept under study. The reduction of simulation data is performed off-line.

EXPERIMENT DESIGN AND ANALYSIS ACTIVITIES

Each DSF project can be divided into three phases: planning, experimentation, and data reduction and analysis. A schematic diagram illustrating the interconnection of the activities involved in performing a real-time simulation

on the DSF is presented in Figure 1. The shaded blocks denote the design and analysis activities discussed in this paper.

Planning

Formulate Goals and Objectives

The initial project activity is a statement of the problem to be addressed. This sounds rather obvious, but in practice it often takes a while to reach a general agreement as to the specific project goals and objectives with the simulation sponsor. It is important to bring out all points of view to establish what the experiment is intended to do, and whether it is feasible on the DSF. As an example, in an upcoming collision avoidance system simulation, one of the initially requested objectives was the determination of the seriousness of conflicting commands from the controller and the automatic logic in true collision encounters under normal operations is similar to the real world (extremely low probability), the probability of obtaining a significant number of observations is practically zero within a reasonable period. Special contrived scenarios were recommended to analyze this problem. A careful statement of the objectives goes a long way towards meaningful simulation.

Select Test Environment

The DSF laboratory can be configured to model either an enroute or terminal area. The type of facility is specified in the initial activity. The specific geometry selected, whether it is existing or generalized, can bias the experimental results. If very complicated sector geometries are selected, the run to run variation with respect to the controller may mask the system response. Or, local advantage may inflate the effectiveness of the proposed system.

The experimenter must make every effort to determine "a priori" whether the test environment is responsive to the experiment's objectives. For DSF projects, air traffic control specialists have proven to be the best source of "a priori" evaluation of the test environment.

Develop Experimental Design

The goals and objectives of the experiment are used to formulate hypotheses which can be tested through real-time simulation. This is a crucial step in experimental design.

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Sometimes it is tempting not to form specific hypotheses so that the results of an experiment will not be restricted. This is done under the assumption that any significant results will become evident during the course of experimentation. Unfortunately, the results of different data measures are often mixed in a complex, real-time simulation environment. Since multiple performance measures are collected on the DSF, the probability is high that at least one of the measured results will be "statistically significant" purely because of randomness. This "hit or miss" method of experimentation is comparable to searching for a street in the suburbs without a road map. If the experimenter cannot formulate specific hypotheses, then the project should not yet be at the simulation stage.

The verification of the hypotheses nessitates the collection of observations, and the design of the experiment is essentially the plan of how the observations are to be collected. The design must produce observations which are relevant to the hypotheses and are capable of giving an unambiguous answer. In general, experiments on the DSF are comparative; the responses of essentially identical experimental units exposed to specified stimuli are compared for significant differences. In the initial Area Navigation, RNAV, project (Reference 3), similar traffic samples were exposed to two route structures and five levels of percentage of RNAV-equipped aircraft in the system. The two hypotheses tested concerned (1) the differences in route structures, and (2) the effect of RNAV on the ATC system.

On the DSF, the experimental error term is primarily caused by two factors: the dynamic interrelationship of the traffic flow and the human variation of the test controllers. Human variation is composed of two components, inter- and intra-controller variation; that is, each test subject's response varies about his average level which also varies between controllers. Fortunately, prior DSF experience has shown that the inter-controller variation can be modeled as an additive effect which usually does not interact with the experimental conditions. This has permitted the use of classical block designs in many experiments to remove the inter-controller affect. In addition, if the test controllers are not randomized correctly, the inter-controller variation can invalidate the experimental results.

The number of replications at each experimental cell depends upon the precision desired and the cell's error term. Measurements

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from previous DSF projects provide a prior estimate of the variance of the error.

The flexibility of the DSF to control the test conditions provides the experimenter with the capability to develop special purpose designs. For example, the traffic flow is usually modeled as a stationary time series during a data run; however, for the Data Link project, a ramp function was used for average traffic density. In some projects, the response measurements have been collected for distinct components of the ATC system, which can be considered independent, thus providing more observations than the aggregate response.

Develop Traffic Samples

The characteristics of the aircraft movement and density in the system are specified by the experimenter. The traffic characteristics include the mix of aircraft type, performance tables, and the distributions of flights over the air routes. Either actual field-collected samples or machine-generated samples can be used. Besides the obvious requirement of realism, the traffic samples generated must be responsive to the experimental design. If comparisons are to be made between route structure designs, the traffic must be balanced over the routes in sufficient magnitude to permit valid comparisons. Samples based on field measurements often will not be balanced or have other unique properties which cause problems in the data analysis for some experiments.

Define Data Measures

One of the major problems facing the DSF experimenter (in fact, anybody studying the ATC system) is selecting the data measures which best describe quantitatively the complex ATC system. The problem is multi-variate in nature since a vector of measurements are collected. Some of the typical measures used include number of conflicts, controller communications, airport operations, aircraft time in system, distance flown, and fuel consumed. Specialized measures are often required for individual projects; for RNAV, the number of times an aircraft is broken off the RNAV navigation mode was collected. The obvious correlation between some of these measures makes it difficult to assess the true statistical and operational impact being studied. Based on the results of previous experiments, the experiment must attempt to select the minimum number of measures which completely describe the system.

Develop Training Procedures

The objective of the training phase is to train the test subjects with regard to the positions' configurations, the new concepts, and the control procedures.

Depending upon the complexity of these factors, the system measures experience a transition state prior to the desired steady state level. This activity consists of both classroom and laboratory training phases. During training, the control philosophy of the project also must be established. In one case, substantial differences in the number of operations were observed between the north and south arrival positions. Unfortunately, one group was pushing traffic as fast as possible while the other was keeping the traffic flow as orderly as possible.

Experimentation

Quality Control

Two levels of manual quality control are performed on the DSF. First, the project laboratory manager (usually an air traffic controller) decides whether the data run was acceptable based on his observations and the comments of the test controllers. Secondly, the data reduction printouts are scanned for abnormalities. If the abnormalities cannot be explained or if the laboratory manager rejects the run, the session is repeated. The manual checking of the data reduction outputs is hampered by the sheer size of the number of measures outputted. It would be advantageous to develop for each experiment automatic comparisons between the data collected previously and the new results.

Contingency Planning

Because of the exploratory nature of DSF projects, it is possible for unforeseen factors to substantially disrupt the experimental design. These problems usually become obvious early in the experimentation. In these cases, either simulation is stopped or contingency plans are developed and implemented. In a recent project, the run-to-run variation after a portion of the data runs was very large with respect to the design variable. It was suspected that the controllers were overloaded by the sectors' configurations and that the number of sectors used was too large to measure the effect of the design variable. The design was modified by

reducing the number of sectors and by using two controllers within each sector.

Data Reduction and Analysis

Data Reduction

During experimentation, the Data Collection Program records the values of a predetermined set of significant simulation parameters once every processing cycle. These data include: (1) the position, velocity, heading, climb rate, turn rate, acceleration/deceleration rate, radar tracking position, controller assignments, and status code indicating the type of navigation and maneuvering currently being conducted for each active aircraft, (2) a complete record of the simulator pilot and controller messages entered during the previous cycle, and (3) status of the voice communication lines. These data are recorded in the input format of the off-line Data Reduction and Analysis Program. The Data Reduction and Analysis programs extract the data measures related to the concept under study.

Statistical Analysis

Since most of the investigations conducted using the DSF consists of a series of runs in a formal statistical framework, the reduced results are stored and accumulated for the entire series. Additional software is available which extracts desired data, performs transformations, and outputs the results in a format compatible with the statistical programs which are generally employed such as the BIOMEDICAL and the IMSL statistical packages.

The BIOMED General Linear Program (BMD11V) has proven useful in the analysis of variance applications. Although BM11V requires the analyst to generate the coefficient matrix for the design, the program will handle a wide range of designs.

SUMMARY

This paper has provided a broad overview of the activities involved in the design, experimentation, and analysis of real-time simulations on the FAA/NAFEC's Digital Simulation Facility. The importance of good experimental design and analysis in large, complex simulations has been discussed within the context of the air traffic control system.

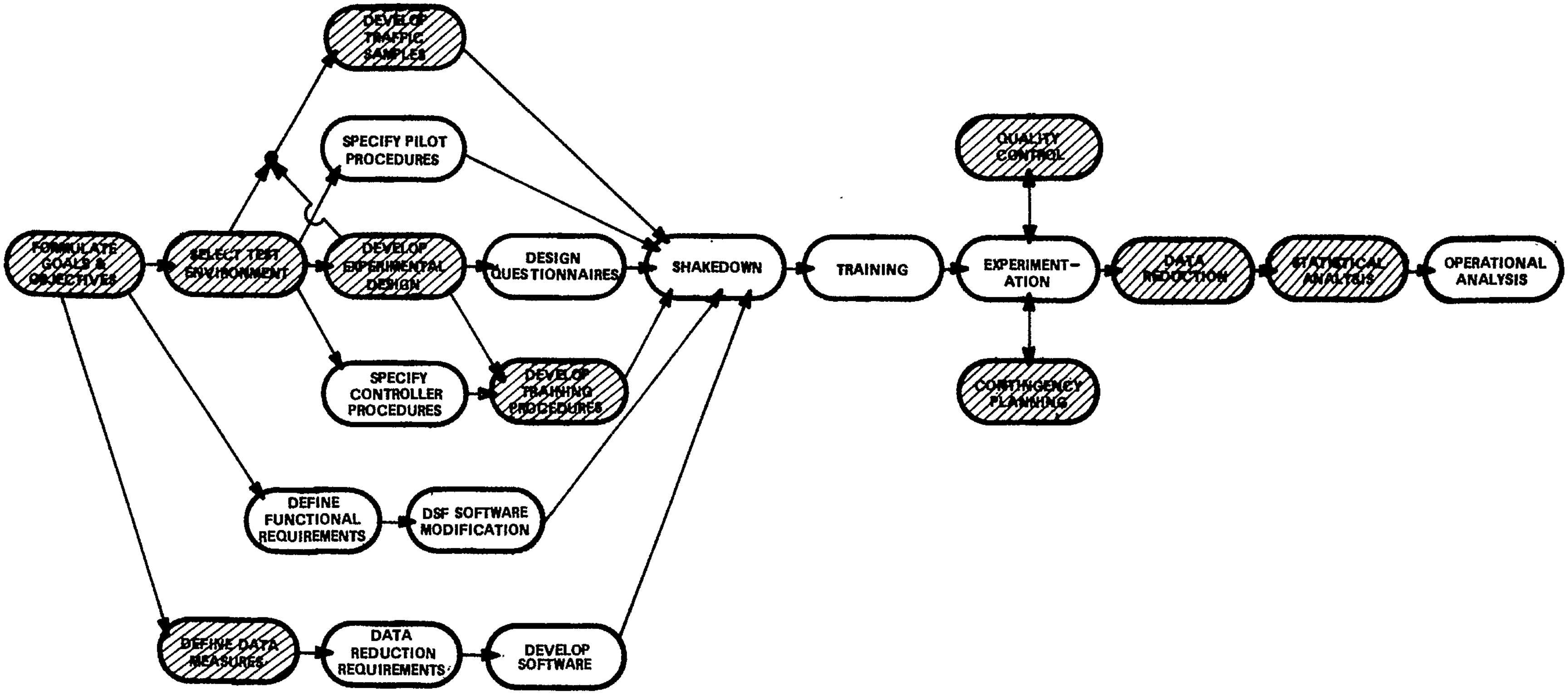

FIGURE 1 SCHEMATIC DIAGRAM OF DSF PROJECT ACTIVITIES

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