Man as Manager of Automated Resources in an Advanced Air Traffic System

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The steady growth of civil aviation has produced a corresponding increase in the size and complexity of the system for air traffic surveillance and control. To meet the operational demands forecast for the end of the century, it is anticipated that the system must not only continue to grow but also undergo a change in character, making a transition from a man-intensive to a machine-intensive system. It is foreseen that automation will be introduced to replace the human operator in several major areas such as surveillance, much decision making, and most communication. While there will remain a core of undelegable human tasks, the role of man is expected to evolve from an operator aided by machines to a manager of automated processes and a director of machine resources. This paper examines the prospective functions and duties of man in a future system, where most surveillance and control activities have been assigned to automata. The implications of this man-machine task allocation are traced in terms of normal operational and managerial responsibilities for man and in terms of the strategies and backup requirements applicable in states of equipment failure.

I. Introduction

ALMOST five years ago the Department of Transportation Air Traffic Control Advisory Committee (ATCAC) issued its landmark report on the future problems and needs of the air traffic control system.[1] A major finding of the study was that by 1995 the demand for air traffic services, measured by fleet size, number of flights, and several other standards, could be expected to increase by a factor of two to three over then current levels. While subsequent demand projections,[2,3] summarized in Table 1, have revised the estimates downward somewhat, the ATCAC forecast must still be regarded as an essentially sound prediction.

By 1985 the fleet size is expected to grow from the present 176,500 aircraft to 285,400, an increase of about 67%. Projections indicate by 1995 a nominal fleet size of 362,000 (about twice as large as today's), with some estimates running as high as 529,000. Other measures of demand for services (see Table 1) reflect similar increases by the 1995 period.

The economic impact of this growth in aviation is manifested in many ways—in construction costs for new airports, in the development of new navigation and communication networks, in the expansion of ATC system facilities, and in increased numbers of personnel to man the system. Of these, the operations and maintenance costs (primarily the salaries and benefits for controller, flight service, and maintenance personnel) are the major cost element. These costs are highly sensitive to demand and are expected to increase by about 50% in the next 10 years. By 1995 these costs would reach staggering proportions if there were no changes in the present system, which is both labor-intensive and demand-sensitive. Twenty years from now, if the present system were retained and the demand were to increase as forecast, 63,000 controllers with an annual payroll of $1.33 billion (1974 dollars) would be needed to operate the system and provide the same level of ATC services as today. Significant savings could be achieved by upgrading and extending the present system (i.e., by increasing the level and extent of automation), but still the number of controllers would remain high. Even with the major improvements now envisioned, at least 30,000 controllers with salaries and benefits amounting to $600 million per year would be needed by the end of the century to service the demand produced by 362,000 aircraft. Thus, sheer economic necessity requires that some way be found to alter the demand-workforce relationship.

Historically, the response to increased demand has been automation. Machines have been introduced into the ATC system to assist in surveillance of the airspace, to provide navigational aid, to speed and improve data processing, and to assume some of the communication load. While certain safety and capacity benefits have also resulted from these forms of automation, the driving concern has been manpower savings.

The NAS and ARTS systems now being deployed are examples of this trend to convert from a manual to a semiautomated form of air traffic control. These systems improvements (NAS for en route and ARTS for terminals) incorporate automated identification, tracking, and data display features which relieve the controller of much of the workload imposed by the former system, where preparing flight data strips, correlating position and identity, and manipulating "shrimp boats" were manual operations. Automation has also been introduced into the communication process. Notable examples are the Pilot Automatic Telephone Weather Answering Service (PATWAS), Transcribed Weather Broadcast (TWEB), and Automatic Terminal Information Service (ATIS)—all of which provide automated means for relaying weather and operational information to the pilot without direct controller involvement. In a similar fashion, automation has been introduced to handle the transfer of flight plane and aircraft movement data between ground facilities.

While the automated features of this third-generation ATC system have been generally successful in helping to meet the demand levels of the 1970's, it is apparent that the present

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Table 1 Demand projections for 1974, 1985, and 1995

			1995		
	1974	1985	Low	Nominal	High
Fleet size	176,500	285,400	275,000	362,000	529,000
Air carrier	2,500	3,400	5,000	7,000	9,500
General aviation	154,000	262,000	250,000	335,000	500,000
Military	20,000	20,000	20,000	20,000	20,000
Peak IAC[a]	16,985	27,060	27,660	37,020	54,110
Air carrier	2,275	3,700	3,800	5,330	7,240
General aviation	13,850	22,500	23,000	30,830	46,010
Military	860	860	860	860	860
Annual operations[b] (millions)	155	240	250	325	460
Air carrier	10	15	25	35	45
General aviation	105	185	185	250	375
Military	40	40	40	40	40

[a]Peak instantaneous airborne count. [b]Takeoffs, landings, and overflights.

system is only a waypoint on the road to a more highly automated system for the period 1990-2020. In 1971-1974 the Department of Transportation undertook a series of studies to examine the requirements for a more advanced system, characterized by extensive application of automation in all aspects of air traffic control. This fourth-generation system, which is in only a conceptual stage at this time, would make use of automation to achieve three major benefits for the aviation community. First, there would be enhanced safety of flight through more complete and accurate navigation and surveillance mechanisms and through machine-directed separation assurance. Second, computers would be used extensively to promote efficient use of the airspace and to expedite traffic flow. This would be brought about by computerized flow control techniques, terminal area metering and spacing, and close monitoring of flight plan conformance. Finally, and this is perhaps the dominant concern, there would be use of automated resources to decrease the dependence on manual operations and thereby to reduce the workforce needed to handle a given level of demand. By raising controller productivity (i.e., by significantly increasing the number of aircraft that an individual controller can handle at any one time) the total workforce could be kept to an economically acceptable level, even in the face of a threefold increase in demand.

The authors of this paper participated in the DOT study of this advanced air traffic system, and the observations offered here are derived from this experience. However, this paper is not a summary of study results, nor is it intended to convey current DOT or FAA thinking and plans with regard to future enhancement of the ATC system. This paper does not advocate any of the candidate system concepts now under study by FAA, and it does not purport to offer recommended solutions to ATC problems. Rather, the intent is to speculate about the nature of man's participation in a future ATC system where much of the routine operation has been delegated to machine resources. The particular concern is to examine the implications of automation for man as operator and manager of such a system.

II. Future Areas of Automation

In the most general terms, the air traffic control system consists of four major parts: 1) sensors for the collection of data; 2) processors for manipulating data and making decisions; 3) effectors for conveying the results of control decisions to the aircraft; and 4) the aircraft itself.‡ These components form the basic air traffic control loop, as shown in Fig. 1. The aircraft is the controlled element. The processors are the controlling element. The sensors and effectors are mediating elements, the former serving to convey aircraft position and identity information to the processors, and the latter acting to transmit messages to the aircraft and thereby close the control loop.§

This description is admittedly simple and purposely overlooks the great complexity of relationships which exist within and among the parts of the system. However, it does serve to delineate the separate areas in which automation may be applied and to distinguish the general features of the ATC system.

For example, looking at the ATC system in this way helps to understand why automation of sensor systems alone would not have an appreciable effect on controller productivity. The bulk of the controller's work lies not in data acquisition but in decision making, which lies in the processor portion of the loop. The limiting factor for the number of aircraft that a controller can handle is the number of decisions he can make per unit of time. The decision-making process cannot be significantly speeded up or enhanced simply by feeding the controller information more rapidly or with less effort on his part.

To date, the major areas in which automation has been introduced are the sensors and, to a lesser extent, the effectors (communication links). Sensor automation includes such features as radar surveillance, automatic correlation of position and identity data, and automatic altitude reporting. Prospective systems such as the Discrete Address Beacon System (DABS) will permit an even greater amount and variety of information to be "downlinked" from the aircraft to the ground system. The inverse form of communication (the ground-to-air effector link) has likewise been automated, but not quite so extensively. The transmission of weather and flight information to aircraft is now handled by machines in such systems as PATWAS, TWEB, and ATIS. DABS also offers increased potential for automating uplink communications. However, the transmission of control messages (clearances and vectors), which is the culmination of the decision-making process, remains a largely manual activity conducted by two-way radio.

An area which is virtually untouched by automation is that which is at the heart of the system, the processor portion, where data are analyzed, compiled, and correlated, and where air traffic control decisions are made. Near-term enhancement of the system will make use of automated resources to prompt or assist the controller in making decisions (machines aiding); but in the long run it appears to be necessary to admit

‡The terms "sensor," "processor," and 'effector" are used here as general designations for the means by which activities are accomplished. These means may be machines or men.

§There is a fifth major component, navigation aids, excluded from this system description. The importance of navigation aids is undeniable; but since they have little influence on the decision-making and control process, which is the focus of this discussion, they will not be considered here. In effect, the navigation aids and the aircraft form a second, complementary loop, which interacts with the primary control loop described above.

the machine as a full partner in the decision-making process itself and eventually to delegate a large share of routine, tactical, real-time decisions to nonhuman agencies.

The prevailing view is that automation of data processing and decision making should be approached incrementally, with each step building on those coming before. One reason for adopting an evolutionary approach is the current state and prospective growth of automation technology. The hardware and software design problems posed by ATC automation can best be solved by a modular, "building-block" strategy which will allow the system to evolve to a higher level of automation at a pace consistent with technological progress. The economics of the situation also favor evolutionary upgrading of the ATC system. The development and deployment costs of a fourth generation system are too large to be absorbed in a brief period. Finally, of course, a stepwise approach to automation is prudent for reasons of safety and manpower utilization. A gradual transition from the third to the fourth generation will allow the safety of the system to be tested carefully at each step along the way and will allow the human operators and managers time to master the new skills required.

Several schemes of incremental automation have been advanced by ATC research and design specialists over the years.[4-6] Although there is some difference among them as to details, there is substantial agreement on the major steps along the continuum from a largely manual to a highly automated system. There is also wide agreement that a completely automated system, even if feasible, would not be desirable. Even at the most advanced levels of automation proposed by these studies, there would always be a core of undelegable tasks reserved for man. Some of these human tasks would be operational, i.e., tasks where man would function as a line element in the control process. Because of the highly automated nature of the system, the number of such operational tasks would be rather small. A far greater share of human involvement would be expected, however, in the area of managerial tasks, where man would act to supervise and regulate the process of air traffic control and to coordinate and direct the utilization of human and machine resources.

Thus, in the future system, man's participation will shift from the tactical to the strategic domain. The degree of his direct involvement with individual aircraft will be greatly diminished, and his concerns will shift toward information management and process control. Routine surveillance, decision making, communication, and control activities will be allocated to machine components, whose operation will be supervised and controlled by man. The managerial role of man will include responsibility for assessing the need for corrective action in situations such as imminent congestion, equipment failure, and changing flight or weather conditions. Man will also be available for intervention and remedial action in special and emergency situations. On the whole, however, man will act essentially as a regulator and manager of an equipment complex which, in turn, will monitor and control individual aircraft. Sections III and IV will examine and differentiate the operational and managerial roles of man in greater detail.

III. Operational Role of Man

As already pointed out, the heart of man's involvement in the present ATC system is in the processor area of the system. To clarify the effects of automation in this area, let us first examine the types of activity which are performed here.

The major function performed by the processor is active control of aircraft. This is a tactical function, consisting of watching over aircraft movement, monitoring conformance to flight plan, assuring separation of aircraft, and providing guidance vectors to aircraft as required to assure safe and expeditious traffic flow. Closely related to active control is the function of traffic planning. This includes strategic activities of a long-term nature, such as flow control and issue of clearances, and of a short-term nature, such as terminal area metering and spacing and interfacility handoffs.

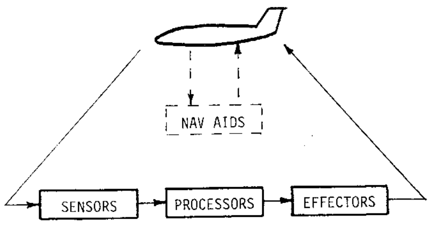

Fig. 1 Simplified ATC system diagram.

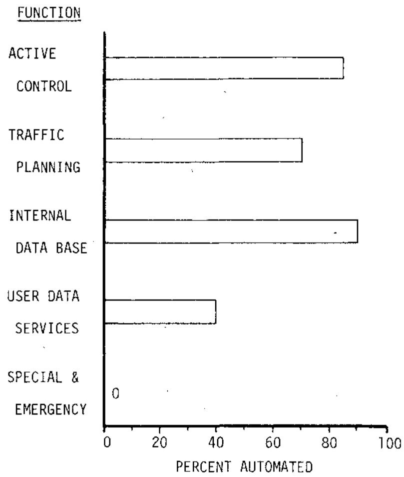

Fig. 2 Level of automation by function in a future ATC system.

These two functions, active control and traffic planning, comprise most of the decision making in air traffic control. To support these decisions, there are two major information processing functions. One is to maintain the internal system data base necessary to conduct air traffic control operations. It consists of collecting and distributing data on weather, system status, demand, and operational conditions for carrying out the control and planning functions. The data base function also includes keeping of records and operational logs, either for short-range purposes such as shift scheduling and resource allocation or for long-range purposes such as facility and manpower planning. The other major data processing function is data services, which are concerned with providing information to airspace users to support the conduct of flights. Data services include providing weather and flight planning data, processing flight plans, and issuing in-flight advisories and instructions.

The fifth major function in the processor area of the system has to do with exceptional operations. This includes providing special services to aircraft (e.g., transborder operations, military flight handling, or expediting VIP flights) and arranging for nonroutine use of the airspace (e.g., landing practice, navaid checkout, or parachute operations). This function also includes all emergency services rendered to aircraft because of airborne equipment failure, pilot disorientation, and the like.

When we speak of a highly automated system, we refer to one in which approximately 75-80% of the tasks making up these functions are assigned to machine resources.¶ It must not be assumed, however, that automation is applied in equal measure across all air traffic control functions. One purpose of the automation study conducted by DOT[6] was to identify

¶Such a system was examined as part of the DOT automation study mentioned in Sec. I. It was found that, on theoretical grounds, a 75-80% level of automation was operationally viable and economically beneficial and that substantial workforce reductions could be achieved with no sacrifice of safety or capacity.

those areas which are most amenable to automation and where the greatest benefits could be realized from the substitution of computers for men. When tasks are allocated to men and machines according to their respective performance capabilities, as was done in the study referred to here, there is considerable variation in the level of automation from function to function. Figure 2 illustrates the profile of automation across the five major functions in the processor portion of the ATC system.

Note that the active control and traffic planning functions are almost completely automated. Man's involvement is limited to setting the basic procedural standards and parameters which will be employed by the computers in monitoring aircraft movement and in regulating traffic flow. Man also is engaged in the process of monitoring flight plan conformance whenever it becomes necessary to revise flight plans or modify clearances. This is a negotiative action for which man's inherent adaptability makes him better qualified than a computer. The third major kind of human participation in this area is flow control, where he interrogates and instructs the computer in working out alternative solutions to problems of capacity and demand.

Note also that data base functions (management of traffic, operational, and weather information and records keeping) are the most highly automated of all. This is not surprising in view of the recognized superiority of computers in handling large amounts of data on a real-time basis. Man's role in this functional area consists mainly of data entry and call-up of standardized data packages.

In contrast with internal data management, provision of data services to airspace users is only partially automated. This function involves a high degree of interaction with the individual user, either to supply him with information or to assist in flight plan filing and approval. Whenever the information to be supplied is standard and the task repetitive in nature, computers would be used (as is the case with ATIS, TWEB, and PATWAS today). However, when the information cannot be reduced to a standard briefing or whenever some interaction between the user and the system is required (as in flight plan filing or amendment), the human operator is to be preferred. The machine still provides extensive support by retrieving and assembling data and by reviewing flight plans against established criteria, but the process is essentially human-directed.

A function which remains wholly within the human domain, even at this advanced level of automation, is providing special and emergency services. By nature, these are infrequent, nonroutine, and highly particular events. It would be neither practical nor economical to program an automated system to deal with occurrences of this sort. Further, this is the kind of work at which man excels. Thus, prudence, economy, and operational experience dictate that man retain responsibility for all special and emergency events, although with an assist from the computer whenever data retrieval, rapid computation, or multivariable extrapolations are required.

Table 2 Operator positions in a future ATC system

Flight surveillance and control	Issue clearances and clearance changes Monitor aircraft progress Monitor conformance to flight plan Assure separation of aircraft Control spacing of aircraft Provide aircraft guidance Perform handoffs Provide emergency assistance
Flight information services	Provide flight planning information Provide flight advisories and instructions
Flight plan	Process flight plans Coordinate special flight services
Flow control	Plan and regulate traffic flow
Data base	Maintain operational data base Maintain system records

The foregoing characterization of a future, highly automated system suggests that man and machine will work in close partnership. Therefore, at the operational level, the basic resource unit will consist of a human operator and an associated data processor, acting as a team to execute air traffic control functions.

As in the present system, the man-machine teams will be specialized, generally along functional lines. In all, there will be five specialties, as distinct from the three in the present system (en route, terminal, and flight services). The responsibilities and duties of each specialty (called a position) are outlined in Table 2. Note that this characterization does not distinguish between man and machine assignments. They will function as an operational team, with a division of tasks which follows the general lines indicated.

Only the flight surveillance and control position corresponds directly to the air traffic controller of today's system. The functional responsibilities of this position parallel rather closely those of the present terminal and en route options. The flight service option of the present system does not have a direct counterpart in the future system. Flight service duties are divided between two positions (flight information services and flight plans), both of which have expanded responsibilities in comparison with FSS personnel of today. Flow control and data base are new positions, whose duties reflect the added importance of strategic planning and data management in the more highly automated system of the future.

In summary, then, man's role as an operator in the future system will be characterized by a greatly diminished involvement in the routine of surveillance and control, which will be handled by machines. Similarly, most data processing tasks and much of the routine tactical planning will be automated. Man's primary responsibilities will be to interact with system users for data exchange and flight planning purposes and to deal with exceptional operational cases. Generally speaking, the tasks reserved for man as an operator will be those calling for interpretive judgment, complex decisions, or adaptive action.

IV. Managerial Role of Man

The distinction between man as an operator and man as a system manager is not simply a matter of level of responsibility or position within the manpower hierarchy. There is a fundamental difference in the type of activity performed by man in each of these roles.

Man as operator in the future system will be concerned with the functions and tasks which have been reserved for human performance. Man, like his machine partner, will act as a line element in the system to control aircraft and to provide services to airspace users. The activity of man, the operator, will focus upon individual aircraft, with which he will deal directly and for which he will perform his share of the operational tasks necessary to accomplish system functions.

Man as manager, by contrast, will not be concerned with individual aircraft *per se*. His activities will be directed toward regulating the process of air traffic control and toward utilizing the resources of the system to accomplish the ends of safety and expeditious movement. Some of the resources to be managed will be computers, but some will be human, i.e., the line operators of the system.

Thus, managers and operators will represent two distinct spheres of human activity in the future system. Operators will deal with aircraft as individual elements and will carry out, in concert with machines, the work of air traffic control. Managers will deal with aircraft in the aggregate (i.e., as demand or load) and will be responsible for the disposition and direction of man and machine resources to handle demand.

The notion of aircraft in the collective sense, as demand or system load, is the key to understanding the role of man as manager. All of the aircraft operating in the system at any given time generate a demand for services, which can be expressed as a requirement to perform some set of air traffic control tasks. Some of these tasks are to be performed by automated resources; others are for human operators.

The first type of management function to be performed is to match the capacity of system resources to the total workload imposed by demand. This function, called "load control," has to be performed at every level of the system—at the individual operator stations, within facilities, for major regional jurisdictions, and for the system as a whole. Note that the management function of load control is not directly concerned with performing any operational tasks; these will be handled by human and machine operators. The function of load control is twofold: to assure that the resources available are adequate to service the demand and to assure that no aircraft requiring service is neglected for want of appropriate resources.

A second kind of management function is resource assignment, which is concerned with the appropriate and equitable distribution of task assignments to individual man and machine operators. As aircraft require service, the manager responsible for resource assignment sees to it that an operator is designated to perform the necessary tasks within appropriate time limits. There is a close relationship between load control and resource assignment. Load control assures that the total resources are adequate to meet total demand. Resource assignment is the management of these resources by distributing the workload among available operators and by allocating individual aircraft to operators. Of the two, load control is the more strategic function, in that it entails long-term planning and anticipatory action. Resource assignment is a more tactical function, involving a dynamic and essentially real-time response to specific demands imposed by aircraft.

While the first two management functions are essentially concerned with the quantitative relationships of demand and resources, the third is a quality-control function. It is called "service assurance." The purpose of this managerial activity is to monitor the results of air traffic system processes and to assure that the established standards of safety and expeditious movement are being met for each aircraft. Thus, load control and resource assignment operate at the input side of the system to manage resources against demand. Service assurance operates at the output side to monitor and regulate the quality of services rendered. Service assurance may be thought of as a feedback function, which serves to alert those responsible for management at the input side to deficiencies in the way resources are being allocated to meet demand.

The fourth, and final, management function is configuration management. This form of managerial activity is directed toward maintaining the operation of the system in the event that automated resources fail or malfunction. It is the responsibility of configuration management to detect and diagnose equipment faults and to take remedial action by calling on reserve resources or by reallocating functional assignments among system components.** Note that here, as in all other managerial activities, the configuration management function is not to perform line operational tasks in backup modes but to direct and manage the deployment of resources.

**In a sense, this is simply a special case of resource assignment under failure conditions.

The role of man as manager of the air traffic control system can thus be summed up as those activities which provide answers to the following questions. Are there sufficient and appropriate resources to handle the demand? (load control) Is the workload appropriately and equitably distributed across the available resources? (resource assignment) Is demand being satisfied in an acceptable manner? (service assurance) In the event of failure, how can resources be reassigned or redeployed? (configuration management)

Management is customarily accomplished by a hierarchical organization, in which lower levels serve to implement and direct the activities prescribed by those above. The management structure of the future air traffic system will almost certainly be organized in such a pyramidal fashion, probably with three distinct levels.

At the lowest level, managers will oversee directly the human and automated resources carrying out operational tasks. This level is called "supervisory," and is roughly equivalent to the watch supervisor of today's system, although with somewhat expanded concerns. Supervisors will perform three basic types of managerial activity—load control, resource assignment, and service assurance.

The second level of management is executive in nature. That is, the concern is not with direct supervision of individual resources but with the coordination and direction of all resources within a given facility, both in normal modes of operation and in degraded states. Managers at the executive level will perform, on a facility-wide basis, the basic functions of load control, resource assignment, and service assurance. They will also perform the fourth type of managerial activity (configuration management) by arranging intrafacility and interfacility backup in failure modes of operation.

At the uppermost level of management, there will be the system directors, whose scope of interest will extend across regions or the entire country. The director level will be concerned with the overall management of system resources and with the operating relationships of all facilities within their designated jurisdictions.

As a final note on the managerial role, it should be pointed out that, while management is foreseen to be a major area of human involvement in the future system, this does not imply that it will be a manual activity. The proper and timely exercise of the management functions suggested here will require large amounts of information, available on a real-time basis. Large data banks and sophisticated computer routines will have to be put at the manager's disposal to support his decision making and to implement the courses of action he selects. In fact, the higher up the management hierarchy (i.e., the further removed from direct contact with line operational elements), the more will man have to depend upon computers as sources of information, as working tools, and as channels for implementing managerial decisions. Thus, automation should not be thought of as an isolated technological advancement affecting only the operational level of the system. The use and influence of computers will pervade all areas of man's involvement in air traffic control.

V. Reliability and Performance Assurance

Any technical system whose operation involves the safety of life and property must operate in a highly reliable manner. This is all the more true for common carrier transportation systems, and for air traffic control in particular. Since few pieces of hardware and even fewer items of software are certain to be failure-free, some means must be provided for making such a system operationally safe, even in the face of inevitable failures. As air traffic control systems have evolved, concepts of system backup have evolved in parallel. Basically, there are three types of backup: 1) redundancy of hardware and/or software, 2) operational (or functional) redundancy to provide alternative means of accomplishing a particular function, and 3) procedural backups to make the operational processes of air traffic control more fault-tolerant than would otherwise be the case.

Such backup provisions can be exemplified by a look at the present generation of air traffic control systems. In these systems, automation through use of computers is limited to data acquisition and processing. Virtually all control decisions are manual. For example, aircraft are automatically radar-tracked and displayed in plan view along with alphanumeric information (such as altitude) necessary for control. However, decisions concerning the progress of each aircraft and possible conflicts between aircraft are accomplished by human air traffic controllers. Where negotiations related to control alternatives are needed, they are accomplished by voice telephone or radio, either with other controllers or with the aircraft crew. Controllers decide what additional information they might need and apply their own judgment and experience to effect safe control.

There is a fair degree of equipment redundancy in this sort of operation. Broad-band radar is available to back up radar PPI displays. Communications receivers and transmitters are replicated. Backup programs can be reloaded in the event of a computer "crash." Operational or functional redundancy is present as well. For example, failure of a computer to maintain alphanumeric display of aircraft altitude is backed up by the controller's capability to acquire this information via air-ground radio. Finally, the operational procedures generally in use avoid placing aircraft in positions where hardware or software failures could create imminent hazards. For example, aircraft are invariably turned onto common final approach paths at different altitudes so that, should ground-air communications fail before safe in-trail separation is established by the controller, the aircraft will remain safely at different altitudes.

The plans that controllers make to maintain safe operations in the face of possible or actual system failures are called "performance assurance strategies." The ways that controllers transition from radar to nonradar procedures in the event of radar failure and the ways they avoid having more than one or two aircraft requiring immediate attention at any one time are examples of such performance assurance strategies.

In the current system, where all decisions are made on the basis of human judgment and experience, these performance assurance strategies are largely implicit. Controllers perceive some sort of system failure as being likely or possible, and they control their traffic so as to be able to maintain operations in the face of such failures. In the event of failure, the controllers assess the situation and system status and take action to maintain safety, using their experience and judgment. Because of the high levels of proficiency, experience, and judgment of air traffic controllers, a safe and operationally reliable air traffic control process is generally the result.

The evolution of the air traffic controller to the role of a systems operations manager, who is not directly involved in the moment-by-moment control of events and activities, will require that most, if not all, of the routine decision making of air traffic control be automated. That is, computer-based algorithms will have to make the control decisions associated with sequencing, metering, separation assurance, conflict prediction and resolution, and so on.

What of the performance assurance strategies appropriate to this sort of operation? These strategies are largely implicit in the ATC system of today; they exist in the minds of the controllers. Computers generally do not do much of anything implicitly. Whatever performance assurance strategies are appropriate to an automated operation must be made an explicit part of the operating software.

For automation to be acceptable to controllers and to the public at large, it seems likely that at least two things will have to happen. First, effective operational reliability will have to be ensured on a logical level rather than a probabilistic one. That is, essentially all of the possibilities for failure must be recognized in the system design stage and backed up as appropriate. Second, there will have to be a human in overall charge of each element of the air traffic control operation. He must have enough control authority to be willing to accept overall operational responsibility. As pointed out earlier, his role would likely include supervising automated functions, comparing actual with expected performance, changing the operating rules where appropriate, and reallocating resources where necessary. The man functioning in these capacities would be a manager in the fullest sense of the term.

Now, one purpose of automation is to enable the air traffic system to handle an increased number of aircraft without a corresponding increase in the operational and managerial personnel manning the system. This means that the number of men in the system will be sufficient to operate the system at peak capacity, providing that the machine components are also carrying out their assigned portion of the total task load. But what if some of these machines fail? Can man be expected to take up the slack? Almost certainly no, and for two reasons. First, there would not be a sufficient number of men on duty to take over and perform manually the tasks normally assigned to machines. (The notion of having a standby reserve of manpower ready to take over when automated resources fail is too economically wasteful to contemplate.) Second, and more important, how can man practice and retain the skills to perform manual backup in a system where such tasks are normally done by machines? And even if this were practical, would it be possible to reconfigure from the automated to the manual mode in a sufficiently short time to prevent degradation of the safety of the system? Thus, manual backup to automated functions does not appear to be a viable proposition. To put it another way, automation is an irreversible process. Once a higher level of automation is obtained, reversion to a lower level cannot be adopted as an operational regime without suffering some loss of safety or capacity or both.

From this discussion, two firm design requirements emerge for the automated air traffic control system with man in the role of manager, First, system performance—at least performance sufficient to insure safety—must be assured at a logical level by the appropriate combination of equipment, operational, and procedural backups. Second, the backup to an automated function must, itself, be automated. The design solution to equipment failure in a highly automated 1995 system is not to revert to a semi-automated 1970 mode of operation.

To meet these requirements, the failure modes of the system, the strategies for accommodation of hardware /software failures, and the mechanisms for recovery in the event of failure must be explicit, not implicit, as with current operations.

This brings us to question the current state of the art in analysis of operational failure modes of a complex system and in computer system reliability and computer program certification. At present, there is no completely satisfactory way to ascertain that all possible operational failure modes of complicated systems have been identified. It is common to use methods of fault-tree analysis, functional analysis, operator task analysis, and plenty of operational insights and judgment to arrive at a statement of failure modes that is comprehensive enough to cover the most likely failure modes and, hopefully, the most critical ones. No way is known to the authors of ensuring that this is the case for a complex interactive system.

The situation in computer system reliability is somewhat more promising. For relatively small computer programs, logic trees can be constructed to map out the entire range of possible states of the algorithm. All areas of possible behavior or misbehavior can be identified. Once this is done, acceptance test programs can be constructed, and fault recovery programs can be written.

For large computer systems with complex programs, the practical means of doing this are not yet in hand. This is an area of active research at present, and advances in the current state-of-the-art can be expected. It will take years—how many no one can say—before guarantees of fault-free operation can be made for complex real-time computer systems, such as those upon which automated ATC would be based. It seems likely that the insights and methods developed in handling computer system reliability problems will eventually be applicable to the more complex problem of ensuring operational reliability for the complex and interactive process of air traffic control.

VI. Conclusion

It seems that the evolution of the air traffic controller into the role of the man as manager of a complex real-time system will require substantial advances in computer system reliability, and in system design methods themselves, to ensure that a highly automated ATC system will be operationally fault-tolerant enough and demonstrably safe enough to be acceptable as a common-carrier transportation system.

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