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Research Issues in the Transition to Free Flight

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Abstract: In the late 1990s major changes in the philosophy of air traffic control are underway. The traditional approach to managing air traffic is characterized by central control of flight operations by ground based personnel supported by ground-based technology. Future management of air traffic is described as "free flight" and will feature collaborative decision making among pilots, ground based controller personnel, and air line operations control centers - all supported by space based technology with significant airborne and ground components. The effective realization of free flight requires advances in communications, navigation, surveillance, and human factors technology and procedural changes. Some research required to support these advances is described in this paper.

Keywords: air traffic control, large-scale systems, discrete event systems, distributed control, decentralized control.

Introduction

There is probably no more complex large scale system of overriding social and economic value than what might be called the air transportation system. Its economic impact of the world's economic and commercial success is measured in hundreds of billions of dollars and has a direct impact on a substantial fraction of the world's population with realized impacts in more develop countries and great potential for people in less developed areas. Air transportation has evolved from earlier transportation modes on land and sea. It has evolved almost exclusively during the 20th century and laws of physics suggest that it will certainly be the last major mode of travel. Unless one expects some "star-trek" - like evolution of molecular transport, land, sea, and air is all there is! As early as the late 1780's there were air transportation experiments but heavier than air craft really are modern phenomena.

At first the only things a pilot needed to worry about hitting when flying were objects on the ground, or the ground itself. From the earliest days of powered flight just after the turn of the century, until well after World War I, flying was a primitive business indeed. Avionics consisted of a magnetic compass, possible a sextant for locating ones position relative to the stars, and ground based navaids including rivers and roads and even bond fires to mark routes for aviators day and night. Aviation has continued to track and take advantage of advances in other fields of science and technology. Materials, electronics including computers, and human factors are probably the primary scientific areas which have impacted aviation during this century.

Between the two World Wars wireless radio underwent substantial development in the commercial sector and telephony matured at an incredible rate. Unfortunately, component and system miniaturization had to wait until well after World War II and so much equipment which would have had substantial technical value in the cockpit was simply too big and heavy to be carried in aircraft at first. Ground based electronics for airports, airport lighting, pavement technology, all progressed at a rapid pace. However, it was the advent of ground-based radar during WW II which provided an entirely new surveillance capability for aviation. Military aviation was the first to benefit from this effort followed closely by civilian aviation. Vacuum tube technology also advanced to provide rugged packaging for electronics which could withstand the rigors of hostile environments such as those found in warplanes and ships. In parallel to this was research aimed at the civilian telecommunications application area which finally led to incredible advances in circuit miniaturization which would change the way aircraft would fly forever. In parallel with these technical developments, procedural approaches to air traffic control advanced apace with most of the effort devoted to procedures and

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systems to keep aircraft separated from each other at safe distances. Radar allowed ground personnel to really control the flight paths of airplanes. In this environment, pilots concentrated on the mechanical ("stick and rudder") aspects of flying and could let separation and gross navigation issues be handled by colleagues on the ground who were kept informed about aircraft location using the newly implemented radar sensors and display devices, crude as they were.

It was not until the late 1950's that the next qualitative change occurred. With the advent of commercial jet transport aircraft which could fly at substantially higher speeds than their propeller driven counterparts, demands on the ground based facilities grew dramatically. Possible conflict situations needed to be identified sooner, longer time horizons were needed to ensure safe operation in ever more congested airspace and more complex strategies needed to be created to handle the mix of aircraft types with their various operating characteristics. At the same time, advances in materials, partly created as a result of war efforts, ensured that engines and airframes could survive longer, higher, and more stressful flight situations which changed average flight time and distance and again introduced more complex flight operations into the national airspace system. At that time it would have been presumptuous to consider this complex of elements to be part of a system, but they certainly did interact in an environment which needed control to assure safe operation.

From the late 1970's on, digital electronics, on board computing power, weather radar and new modeling and forecasting techniques continued to have dramatic influences on air traffic control and the ability to safety and efficiently use precious airspace and surface resources to move people and cargo from place to place throughout the world. The control of air traffic was enlarged to include not only separation assurance but also flow planning between airports and regions. Procedures and outstanding work of human operators continues to provide remarkably safe and effective air transportation over ever greater portions of the earth. New advances in commercial electronics, military electronics, materials, and understanding the of interaction of people and machines all eventually found useful application in air transportation. However, during much of the 1970s and 1980s the ground based centralized control paradigm was pervasive. In the United States in 1981 the U.S. President Reagan fired many of the air traffic controllers as a result of a major labor dispute. Relative safety was preserved more due to remarkable adaptability of the remaining and newly trained controllers and the extremely conservative nature of the procedurally based ATC system, than because of new technology suitable supported by good system design. Airlines suffered due to inefficient use of airspace and the economics of air travel were hard hit late in the 1980s and early 1990s because of the lack of outstanding systems design and implementation. However, a relatively safe air transportation activity remained in place during those years. Accident rates were maintained at a rather low level and incremental improvements continued to be introduced. There were two disturbing aspects of ATC operations during these years, at least in the United States. One was that accident rates, although low, were not improving. The other was that there was no real architecture into which new concepts or proposed technologies could be inserted in a planned way. Advances were made on a rather ad-hoc basis. It was also during this period that the United States, always a leader in ATC, began to lose its leadership role. In other countries, especially in Europe, advances and innovations occurred in national ATC systems. In the U.S. political orientation dominated what should have been a highly technical leadership focus.

This, then, is the background into which "free flight" emerges as the control paradigm of the future.

The RTCA, an American industry group working in the public interest on many aspects of aviation has defined "free flight" as follows: A safe and efficient flight operating capability under instrument flight rules (IFR) in which the operators have the freedom to select their path and speed in real time. Air traffic restrictions are only imposed to ensure separation, to preclude exceeding airport capacity, to prevent unauthorized flight through special use airspace and to ensure safety of flight. Restrictions are limited in extent and duration to correct the identified problem. Any activity which removes restrictions represents a move toward free flight. (RTCA 1995)

This definition implies that there is no such thing as "perfect" free flight but that incremental changes can bring the system closer to this paradigm.

Air Traffic Management

Although the general public refers to air traffic control when they think of the system by which air traffic is managed throughout the world, the technical term for what they are thinking about is air traffic management (ATM). The overall purpose of ATM is to ensure safe and efficient movement of aircraft from point to point. Safety is self explanatory but efficiency depends on the viewpoint of the speaker. We shall explore some ideas of efficiency below. ATM is divided into two parts, air traffic control (ATC) and air traffic flow management (TFM). ATC is the part of ATM which enhances safety primarily by assuring appropriate aircraft separation both in the air and on the ground. The function of TFM is to ensure efficient, equitable, effective air traffic flows from origin to destination and to enhance system effectiveness. Within in the United States, the national airspace system (NAS) refers to the entire spectrum of resources which are instrumental in air transportation. It is only recently that it would be appropriate to think of the NAS as a system at all. It evolved from a set of components which were created without benefit of an architecture into which each component fit and was operated by very clever, dedicated people. It was done in a manner that this collection of components exhibited some characteristics of a system, some of the time. The advent of free flight in the United States, as a systems concept, is accelerating the creation of a real national airspace system complete with an architectural framework.

Air transportation is not only a national activity. Aircraft which fly from the airspace of one country to that of another need to be equipped and procedurally prepared to operate throughout the flight envelop in both environments. International standards are necessary and political and technical agreements underlie the operation of both commercial and private aviation across national boundaries. Not the least of these standards is language. Numerous accidents and incidents are directly attributable to language difficulties involving communication within the cockpit and between the flight deck and ground controllers. Although this situation is not as prevalent in the United States as in other parts of the world, we also find accidents in the US which are caused by failure of non-US carrier pilots to effectively communicate in English with US controllers. It is interesting to note that technical difficulties with English are only one part of communication problems. Cultural influences (Quigley and McElwain (1997)) are also key contributors to aviation safety and, although outside the scope of this paper, need careful analysis if we are to seriously affect already good safety records, in both commercial and private aviation.

It is seen that emphasis on the NAS needs to be taken in the context of international issues in flight. Although the concept of free flight, as it will be defined later in this paper, was created in the United States, its implications for air transportation world-wide are extensive.

Feedback in the NAS

Although air traffic control is obviously a field which should be of interest to control systems engineers, there have been relatively few control specialists involved in the design of ATC systems and analysis of ATC problems (Kahne, 1993, Kahne and Frolow, 1996). The relatively recent formalization of concepts of discrete event dynamic systems (DEDS) originated by Ho may well lead to more powerful analysis techniques suited to ATC analysis, but it is fair to say that this has not yet happened with any degree of depth (Ho, 1992). Part of the problem is that the practitioners of ATC tend not to be analysts, but rather problem solvers. This author has always been impressed with the remarkable capability of human controllers working with rather unsophisticated equipment to safely and efficiently control such a complex system. Accident rates are low and effective use of NAS resources is impressive - not optimal by any means, but impressive.

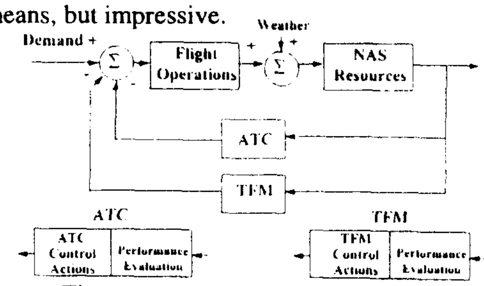

Fig. 1 ATM as a Feedback System

Figure 1 shows an over simplified representation of national present-day ATM in the form of an easily recognizable feedback system. As shown in the figure, NAS (national airspace system) resources includes airports, airspace, hardware and software on the ground and in space, human resources throughout the system, etc. Flight operations includes all aircraft in the system including on-board avionics and personnel. ATC and TFM are the air traffic control and traffic flow management hardware and software and personnel with specified control and management functions, often procedurally driven. The demand on the system includes requested access to the NAS by commercial, military and private aircraft and other uses of NAS resources. There is noise in the system as represented by weather and other uncontrollable elements. There is little chance that such a simplified model will provide detailed insight into system operation but it does suggest the importance of feedback throughout the systems and does tend to focus our attention on the major elements of it.

System operation as presently realized uses NAS resources as a result of flight operations and external forces in response to demand modulated by ATC and TFM control decisions. Both ATC and TFM organization carry on continuous analysis of performance of the NAS and dictate control decisions based on this analysis. If the system is not managed properly, there will be no NAS resources available to handle new demands or the NAS resources will be underutilized resulting in costly inefficiencies. Airlines in the US have claimed that much of their financial difficulties in the early 1990s was directly attributable to inefficient use of NAS resources as a result of poor management of those resources by the federal government. In Europe there are similar concerns.

Airlines measure their operational performance in terms of utilization of airspace capacity, system delays, and operating costs. For optimal performance it is necessary that system optimization be considered rather than just that of one airline. Even though the airlines and private users compete for NAS resources, and even though the federal government in large measure controls these resources, and even though there are strong laws within the US preventing collusion between competitors (antitrust laws), it is necessary that all these organization cooperate if there is to be anything like efficient use of the NAS. Clearly there are important national political considerations as well as international (and sometimes bilateral) ones in this matter.

We have alluded to the availability of NAS resources as the central issue for control of the NAS. It is convenient to consider system capacities as a vehicle to understand availability of resources. Capacity refers to the capability of an element of the NAS to respond to demand. It is a complex notion to define precisely and one which is not precisely understood. Airspace capacity, airport capacity, aircraft capacity are all important parameters when considering system capacity. Demand is an easier concept. One can more easily determine predicted "demand on" than predicted "capacity of" some element of the NAS.

Consider as an example the capacity of an airspace sector. What are the relevant issues in airspace sector capacity? Geometry of the sector, location of the sector with respect to other sectors, the nature of the demand on the sector (e.g. are all aircraft requesting access to the sector flying in the same direction at different altitudes and lateral positions or there planes which are trying to cross at different angles and at the same altitude), current and forecast weather; these are all obvious capacity issues. But how about the equipage of the aircraft themselves, the current state of surveillance equipment used to monitor sector activity, even the state of mind of the controller personnel and pilots? Do these also play a role in defining current sector capacity? Certainly these latter factors are important and certainly one cannot adequately calculate or forecast sector capacity without detailed knowledge of these data. Indeed, sector capacity underutilization is often caused by uncertainly in some of these factors. This requires that procedural rules be implemented to handle worst case scenarios to ensure safety.

It may help to put the capacity issue in perspective at least in the United States by noting that there are nearly 200,000 civilian aircraft in the U. S. of which something less than 10% are in the air carrier fleet while the rest are general aviation aircraft. In addition to these there are another 15,000 aircraft owned and operated by the US military. Clearly these aircraft are not uniformly spread across the country and of course they all take off and land from airports. The opportunities for airspace capacity limitations is substantial. Half the world's aircraft exist outside the United States. European airspace is highly congested at many times of the day and since European and Asian air traffic is growing faster than in the United States with the Asian region far out in the lead, we can expect serious capacity problems to result in many places in the world in the near future.

Accidents and Safety

Aviation has an enviable safety record but also has recorded horrendous mass fatality accidents. The air accident which resulted in the greatest number of fatalities occurred on the airport surface of the airport in Tenerife in 1977 when two loaded 747 commercial transport aircraft collided with the resulting death of 583 people. It is interesting to note that runway incursion accidents do not represent a large fraction of aircraft accidents resulting in fatalities, even though the worst accident was of that type. The most common type of aircraft accident involving fatalities is CFIT (controlled flight into terrain) which most often occurs during planned descent. There are many reasons for this including pilot error, faulty navigation equipment, air traffic control communication or procedural errors. Crew resource management factors play an important role in such accidents as well.

Technology continues to be an important contributor to aviation safety. Since the introduction of TCAS (Traffic alert and Collision Avoidance System), aviation in the United States alone has experienced a decline in near midair collisions from 348 in 1991 to 202 in 1996. Numerous other technical advances have make aviation safer but there continue to be substantial opportunities for improvement. Although the accident rate has been maintained at a very respectable level remaining below about 3 accidents per million departures world wide, the number of departures has increased very rapidly resulting in ever more accidents each year. In 1965 there were approximately 2 million jet aircraft departures in the world per year. That number has increased by a factor of eight during the past 30 years, with little improvement in the accident rate. All safety experts agree that the only way to ensure continued safe air travel to dramatically reduce the accident rate in the future. All safety efforts have this goal.

National and international organizations created to manage, oversee, and ensure safety in the air form an entangled web of bureaucracy which is at least as complex as the problem they are trying to solve. For example, the European airspace management structure has numerous overlapping authorities including the European Union, Eurocontrol, the Joint Aviation Authorities, European Civil Aviation Conference, International Civil Aviation Organization. It is hard enough in the United States with just the FAA being responsible for aviation in the NAS. Of course the FAA deals with most of the other organizations as well but the European situation is more like what we would expect if each of the 50 states in the US had their own aviation authority, their own airspace, their own fee structure, procedures and laws. Because of the nature of flight, each aircraft flying between two regions needs equipment and procedures which are compatible with expectations in each region. Safety can suffer if a particular piece of equipment needed for safe flight in one region is not properly maintained or provided in another. In fact the state of equipment on a plane will determine in part where the plane can fly and what training is required of the crew to fly in different areas.

Technology

It has only been recently that countries outside the United States have taken the lead in certain technology areas of importance to aviation safety. As is generally true for fast moving technology, experiences in one country or region can lead to another region skipping a "generation" and getting ahead of the early leaders. Maybe the best example of this is the cellular telephone system in developing countries obviating the need to create a ground based wired infrastructure as has evolved in the US.

Within the United States, the air traffic management system was traditionally put together as a series of components created to meet some need but often not being planned as part of an architecture designed to achieve specified user needs and expectations. A new component would emerge from an entrepreneurial effort and somehow be force-fitted into the existing structure. System integration was the formalization of this process but not a fully satisfactory one. The focus was on ground systems partially because space based technology required tremendous resources which few suppliers could afford. Seldom were operational concepts the source of new ideas, rather the new ideas were created and then user needs were found which might be satisfied by the new machines.

In a well defined system architecture the following components must be included:

1. Functional Architecture - what parts of the system are expected to accomplished specified function?

2. Technical Architecture - how do the various pieces fit together technically?

3. Data Architecture - what data is needed at various points in the system?

4. Reference Model and Standards - what national and international standards are appropriate for various system components?

Maybe a good example of how these ideas are applied in ATM is the ever improving accuracy of navigation subsystems being installed or retired from the NAS in the United States. Modern navigation systems are evolving from entirely ground based systems to entirely space based systems. The old OMEGA/VLF navigation technology provided, with reasonable reliability, accurate location information to about 5.6KM. On-board inertial navigation systems improved that to about 1.9KM after one hour of operation. LORAN C made further improvements to about 460M. Space based system accuracies made substantial improvements depending on the system being considered with GPS + GLONASS accuracy of about 100M, Precise Positioning Service GPS at about 21M and differential GPS yielding accuracies of the order of 1M. It was not uncommon for these technologies to be in place before the accuracies they provide could be effectively used within the ATM system. So many of the issues are institutional and procedural that the pace of technology often exceeded the pace of effective utilization.

One of the classic example of a driving technology is global positioning systems. The US version of GPS encompasses 24 satellites orbiting in six different planes, each with a 12 hour period. The orbits are at about 20,200 KM and are placed so that at any moment, one can expect to have between 5 and 9 satellites in view of a ground based receiver. The system is operated by the US Air Force which maintains the existing satellites and replaces those which outlive their useful life. The GPS signals are at 1572.42 MHz and 1227.6 MHz and code division multiple access coding is used. A sophisticated algorithm is used to correct for atmospheric distortions of signals.

We do not have an opportunity in this paper to speculate on the development of GPS, a US military creation which is now generally available world-wide, albeit with some inaccuracies introduced for what are claimed to be national security reasons. This ultimate authority over GPS has led other nations to create their own satellite based systems, GLONASS being the Soviet/Russian version. The technical difficulty, of course, is that different receiving equipment is needed for different technical systems and users are reluctant to continue adding equipment to handle the ever expanding number of satellite positions systems. It is understandable that non-US governments may be skeptical about the wisdom of relying on the US military for the integrity of their commercial aviation industry. Governmental assurances only go so far!

CNS

Advances in communications, navigation and surveillance have resulted from creation of and application of new technologies. Just as the invention of the laser gyro stimulated new airborne inertial navigation systems, advances in solid state electronics have resulted in greatly increased functionality in navigation and surveillance. One the most dramatic effects has been the role of onboard aircraft intelligence in air traffic management. In the early stages of ATM in the 1940's aircraft were primarily objects to be communicated with, kept under surveillance and navigated by dead reckoning using theodolites and other mechanical devices. In the near future the commercial transport aircraft will be an integral component of a distributed control and intelligence system. On-board avionics systems will contain more information about the aircraft condition, location, and intention, than any ground based component of ATM. Many top of the line aircraft have these capabilities today and both ground and space based systems are rapidly being created to take advantage of advances on the flight deck of today's fleet. This evolution to the distributed intelligence model has not come quickly and is not yet fully implemented but it is inevitable and far from speculative.

Recently aircraft surveillance was characterized by radar images combining data from both primary and secondary radar sensors and by voice position reports from pilots. Indeed, this mode of surveillance is in use at least in a back up mode on most aircraft today. The future is ADS (automatic dependent surveillance) in which the aircraft knows its position quite precisely from satellite based systems. ADS-B (B for broadcast) is the on-board system which reports in a broadcast mode to nearby aircraft and ground sensors, if available, its exact position and intentions. This information may be displayed both on other flight decks and a controller stations on the ground. Other systems such as TCAS can use this data to determine if safety parameters are being met and if not to suggest possible avoidance procedures to reestablish safe separation. Secondary surveillance radars on the ground can often augment ADS but in oceanic regions ADS will operate independently of other technologies.

Present day navigation relies on ground based technologies such as VOR/DME (VHF omnidirectional ranging and distance measuring equipment) devices, ILS (instrument landing systems) and in a few locations MLS (microwave landing systems) for departures and landings at airports. The future of navigation is satellite based systems using precise positioning data along predetermined arrival and departure routes at airports and along user preferred routes in enroute airspace. GPS supplemented by WAAS and LAAS in the United States and equivalent systems elsewhere will be the navigation aids of choice with procedures and ground based backup as needed in the early years. Much additional research is needed to determine how to phase in this type of navigation and to determine appropriate roles for humans and machines in this complex environment.

Today's voice communications systems using VHF and HF in continental and oceanic regions, respectively, are very wasteful of bandwidth and have serious access and reliability problems. Tomorrow's digital communications links (datalink), secondary radar based systems, aeronautical telecommunications network infrastructure. and new advances in coding and other communications technologies will result in a safer, more robust, less wasteful communications resources for both human and machine interchange of information. Maybe the most dramatic changes will occur in oceanic regions where there is no ground based system possible and where, for years, there has been heavy reliance on HF voice communications with quality of service often below that of even amateur radio! There have been numerous accidents and breach of safety standards due to off course aircraft flying under these conditions. In the new environment, oceanic air travel will be subject to the same CNS services as will be found over continents.

The European and African Situation

Since this conference is being held outside the United States, there area few observations which should be made about these regions. The recent midair collision between military aircraft from the United States and Germany has heightened awareness of the difficult ATC conditions now prevalent over the African continent. Most accidents are the result of a chain of events or a confluence of circumstances which each contribute to the circumstances which result in the accident. Although the results of various investigations are as yet preliminary it appears certain that three circumstances were major contributors to this tragedy. It involved a US Air Force C-141 and Luftwaffe Tu-154 neither of which was equipped with TCAS, the collision avoidance system mandated on all passenger air transport planes in the United States and in many other parts of the world. A significant contributor also appears to be faulty telephonic communication among ground controllers and the aircraft. A flight plan filed by the Luftwaffe crew was never transmitted to the ATC personnel responsible for the sector in which the collision occurred. The result was two planes with no idea about the presence of the other in or near its air space. A contributing factor to the general disarray of air traffic control in Africa is the tendency to ignore language standards on the continent. The primary language of ATC is

English and the primary foreign language in much of Africa is French. During a recent personal experience of spending some eight hours on the flight deck of a Boeing 747-400 flying the entire length of the African continent and it was evident how language incompatibilities between cockpit crews and ground controller personnel can create serious loss of situation awareness for the crews. Fortunately modern avionics can ensure that the crews know where they are but unfortunately they cannot know where others are outside of TCAS range and of course, not know anything at all about non-TCAS equipped planes without clear and extensive communication with ground personnel. For long distance transcontinental flights the procedural rules of flight can help to ensure safety but there are few if any fall back systems to help in case of bad weather or other disturbing influences on the flight plan.

In 1996 there were 77 reported near mid-air collisions (NMAC) over Africa and, according to the International Federation of Airline Pilots Associations (IFALPA), the majority of airspace over Africa is "critically deficient" in air traffic control. There are clearly solutions needed in African airspace, not all of which are technical.

The African situation points up the importance of cultural and non-technical issues in aviation safety. One of the larger research challenges to free flight is to ensure that non-technical issues are addressed appropriately in additional to the technical ones. (Quigley and McElwain, 1997)

Summary of Research Issues

As we have explored the evolution of ATM to a free flight paradigm, a number of research needs have become apparent. Much of the research focus is on the changing role of the human part of the system. As we get away from the "order-giver" and the "order-taker" model of ATM new skills are required of the humans in all parts of the system. The nature of instrumentation and automation aids is changing both on the flight deck and one the ground. Safety remains the driver for new technical advances and for changes in expectations in human performance. The role of the airline operations center personnel is growing in importance and the need for constructive cooperation between various elements of the overall system is more apparent than ever. Relative needs for voice and data communication are at the heart of the communication issues. Although it has been observed that the "party line" voice communication is a valuable situation awareness enhancer, inefficient spectrum utilization remains a resource constraint in many situations. Non-verbal data inputs to flight crews generally detract from time for visual surveillance of nearby air space. Reading data off a flight management system computer takes time from scanning important navigational display devices in the cockpit. Electronic flight strips at a controller position are not equivalent to handling paper flight strips - there are some better features of electronic flight strips and some worse. Thus the research issue is how to optimally schedule time of the ATM participants.

An inadequate understanding of system element capacities makes it hard to estimate overall system capacity and do detailed planning to maximize system efficiency and determine needs for increased capacity. The persistent conflict between component optimization and overall system optimization represents a challenge, especially in a public resource allocation problem. Aircraft with different equipage and national airspace systems with different capabilities, introduce many operational deficiencies which need to be understood and mitigated through optimal procedures and resource allocation.

The free flight paradigm shifts responsibilities from one node (for example the ground based ATC operators) to others (for example the cockpit crew). What sorts of models are suitable to modeling this situation and analyzing various scenarios to better understand who should be doing what in the overall system?

There are roles for control engineers in these research areas. Researchers with experience and sensitivity to issues in large scale systems are in a particularly favorable position to contribute.

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