Annual Reviews in Control 000 (2016) 1–14

Contents lists available at ScienceDirect

Annual Reviews in Control

journal homepage: www.elsevier.com/locate/arcontrol

Review

Dynamics and control technologies in air traffic management

P.K. Menon*, S.G. Park

Optimal Synthesis Inc., Los Altos, CA 94022 USA

ARTICLE INFO

Article history:
Received 29 August 2016
Accepted 19 September 2016
Available online xxx

Keywords:
Air traffic management
Global satellite navigation system
Air traffic throughput
Trajectory optimization
Optimal control theory
Model predictive control
Discrete event systems
Trajectory-based operations

ABSTRACT

Dynamics and Control technologies play a central role in the development and operation of decision support systems of modern air traffic management systems. Recent emergence of Global Navigation Satellite Systems and satellite-based augmentation systems have enabled higher precision execution of aircraft trajectories, opening-up the potential for the implementing more quantitative air traffic management approaches. Already, this navigation capability is enabling higher traffic through puts, and safer operation of aircraft in the proximity of the terrain at several major airports in the US. This paper discusses the aircraft trajectory optimization, conflict resolution algorithms, and traffic flow management problems which form the essential components of the evolving air traffic management system. It will be shown that Optimal Control Theory, Model Predictive Control and the Discrete Event Systems theory form the underlying analytical machinery in this domain. Finally, the paper will outline some of the algorithms for realizing the Trajectory Based Operations concept, currently being developed for future air traffic management.

1. Introduction

Air traffic volume has been steadily increasing over the past 4 decades, accelerated by the worldwide deregulation of the industry in the 1980′s. According to the IATA (www.iata.org), nearly 3 billion passengers and over 50 million metric tons of cargo were transported by air in 2013. During that year, Aviation supported 57 million jobs and generated over US$2.2 trillion in economic activity, worldwide. By some estimates, world aviation is expected to grow by 25–30% in the next decade. The accompanying increase in the number of aircraft utilizing the air transportation resources will require substantial modifications to the present air traffic control configurations and procedures. Even if the air transportation safety metrics manage to remain at the present levels, this large increase in traffic volume will adversely impact the system throughput. In anticipation of this fact, Federal Aviation Administration (FAA) in the United States (US) and the EUROCONTROL Organization have initiated the NextGen and the SESAR programs, respectively. The objective of these efforts is to facilitate a safe path to scaling the air traffic control system without compromising performance. In view of the sweeping changes that are required to enable this transition, the system has been renamed as the Air Traffic Management System in recent years.

The objectives of the next-generation air traffic management systems are to transform the system from a largely reactive system to one that employs predictive operations. This will involve automating some of the system functions, and developing decision support systems for others. The NextGen system is expected to eliminate wasteful surface and airborne procedures such as holds at taxiways and runway thresholds, allow continuous climb to cruise, eliminate airborne traffic flow metering or holds, and continuous descend arrivals. Moreover, it is expected that the emerging system will allow for more collaborative traffic flow decisions, involving all the stakeholders.

It is generally agreed that the initial impetus for the development of modern radar-based air traffic control technology began in the US with a series of highly publicized accidents, the first one being a mid-air collision over the Grand Canyon at 21,000 feet altitude, on June 30, 1956 at around 10:30 am Pacific Standard Time, between a United Airlines Douglas DC-7 and Trans World Airlines Lockheed L-1049 Super Constellation. The main impetus for air traffic control system developed was to meet the aircraft conflict detection/resolution objective.

As the traffic volume started increasing in the 70′s, the demands on the available airspace and airport capacities in the vicinity of major population centers during peak traffic hours were often exceeding capacity. The demand-capacity mismatch became even more acute in the presence of adverse weather conditions. Traffic flow management initiatives attempt to address this demand-capacity mismatch.

Currently, the air traffic management system is human-centered, in which the controllers monitor the air traffic through radar-transponder based surveillance and VHF/UHF radio communications with the pilots to ensure conformance with filed flight

* Corresponding author.
E-mail address: menon@optisyn.com (P.K. Menon).

http://dx.doi.org/10.1016/j.arcontrol.2016.09.012
1367-5788/

plans and approve any changes to them, while ensuring the separation between aircraft. The airspace segmented into the air traffic control Centers and Sectors, with individual Sector Controllers ensuring aircraft separation while aligning traffic flow objectives with Center-level traffic coordinators. The terminal areas may similarly be segmented into Sectors. Such an approach breaks the traffic control problem down into a series scalar flow and separation control problems, amenable to manual control requiring virtually no automation.

As the traffic volume increases, the air traffic management requires the coordination of more complex simultaneous interactions between multiple traffic streams to ensure conflict free merging and spacing to ensure efficient traffic flow. Purely manual control is not being practical without substantially increasing the number of sectors with the attendant communication and coordination difficulties. Moreover, since the traffic flow management is based on predictions, decision support tools based on sound analytical algorithms are essential for implementation.

Recent availability of widespread Global Navigation Satellite Systems (GNSS) and satellite-based augmentation systems such as the WAAS in the USA, EGNOS in Europe, MSAS in Japan, and GAGAN India, together with the emergence of wireless data communication technologies have provided the basis for substantial increase in the precision of executing aircraft trajectories. In addition to allowing more precise management by human controllers, these technologies offer the potential for automating several of the lower-level controller tasks, elevating the human controllers to role of traffic managers. Just as automatic flight control technologies have enabled substantial reduction in pilot's cockpit workload, emerging automation tools are expected to reduce controller workload and enhance throughput. High-level decisions may continue to be under manual control, with more routine activities such as separation assurance being handled by automation both on ground and onboard aircraft. By reducing the potential for human error, such automation tools may enhance the overall system safety.

The parallels between flight controls and modern air traffic management is striking. In the flight control arena, the cockpit automation began in 1912 with a two-axis autopilot developed and demonstrated by Lawrence Sperry(McRuer, Ashkenas, & Graham, 1973). It was then followed by the development of stability augmentation systems for emerging large and high-performance aircraft. Altitude hold autopilots appeared during the latter part of World War II. The cold war produced rapid advances in the flight control technologies, culminating in the availability of the first fly-by-wire airliner in the 1970′s with an onboard flight management system. Flight control technology has now reached a highly advanced state with the full authority fly-by-wire digital flight control systems being standard equipment on modern-day airliners. In these aircraft, the pilot's role is largely that of a flight manager responsible for selecting the modes and commands to be executed by the flight control system. The pilot is expected to intervene only if the automation is unable to deal with the situation at hand. On some of the more advanced large aircraft, it is possible to auto-taxi to the runway, takeoff, cruise and land automatically, with moderate degree of pilot interaction.

Automation in air traffic management appears to be following a similar developmental pathway. Research over the past three decades have been focused on developing decision support systems for the controller, wherein the automation synthesizes advisories based on the sensor data, which the human controller then decides to either discard or implement. Algorithms from the Systems and Control discipline are at the heart of these advisory systems. Techniques such as model-predictive and optimal control, linear and nonlinear programming algorithms, dynamic programming and advanced state estimation techniques are all being employed in these algorithms.

As user experience is being accumulated with this approach to graduated automation, down the road, it is likely that human controllers will be relieved of some of the lower level tactical functions such as separation assurance and en route flow control, allowing them to focus on more strategic air traffic management objectives. The air traffic automation system will then form the "outer loop" around the flight control systems onboard individual aircraft to automatically meet most of the tactical air traffic management objectives, with minimal supervision from human controllers.

The emergence of low-cost unmanned aircraft systems (UAS) is accelerating the trend towards automation, due to the sheer number of aircraft that will soon the airspace, both at low altitudes and higher altitudes. This fact has prompted some industry experts to speculate that it is higher likely that extensive air traffic management automation may occur sooner than anticipated. Systems and Control technologies will be central to this transition.

2. Airspace organization and air traffic management

Air traffic management techniques discussed in this paper applies to controlled airspace governed by the Instrument Flight Rules (Federal Aviation Administration, 2016), covering the Class A en route airspace between 18,000 and 60,000 feet Class E transition airspace between 10,000 and 18,000 feet, and the lower altitude Class B regions around major airports. Flight operations in airspace categories such as Class C, Class D, and Class G are covered under different sets of regulations. Every aircraft operating within Class A and B airspace are required to file flight plans with the FAA, and must have approved flight plans before undertaking their operations.

Flight plans generally specify proposed departure time, cruise altitudes, key waypoints along the route, and the destination airport. The expected time of arrival may also be specified in some cases. Air traffic managers analyze the flight plans relative to the traffic demand, and approves or rejects the flight plans. In some cases, amendments may be requested to ensure compliance. Approved flight plans are executable without delays under prevalent weather conditions. However, unexpected weather phenomenon such as storm fronts and other dynamic weather can cause airborne aircraft to request deviations from their original flight plans, potentially causing demand-capacity imbalances, especially near population centers. Air Traffic Management attempts to ameliorate these imbalances while maintaining the FAA-mandated separation between aircraft. Specific responsibilities of the ATM are:

1. Prevent conflicts and ensure adequate separation between aircraft (for maneuvering and wake vortex avoidance)
2. Meet traffic flow control objectives such as matching the demands with available capacities, maximizing throughput and minimizing delays under normal and abnormal operations.
3. Enable access to favorable weather (Tailwinds in Cruise, Headwinds and small Crosswinds for takeoff and landing) and help navigate around unfavorable weather (Icing and Convective Weather)
4. Facilitate navigation around restricted/special use and military airspace, and aviation hazards on the ground
5. Facilitate minimal-delay departures, arrivals, and taxi to and from gates
6. Promote operational procedures for noise abatement and minimizing emissions to minimize the environmental impact of aviation.

In the United States, the FAA has the responsibility to ensure that aircraft operators accessing the national airspace adhere to all the Federal Aviation Regulations. Some of the areas where dynamics and control technologies that impact various aspects of