

A Framework for Modeling Air Traffic Control Systems

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ABSTRACT

The strategic planning and tactical execution of Air Traffic Control (ATC) provided by Air Navigation Service Providers (ANSP) are often not aligned and lead to inefficiencies in the Air Traffic Management (ATM) system. This paper proposes an analytical framework for the air traffic control system based on a system-of-systems paradigm, with a hierarchy of nested and cascaded feedback control loops—one or more for each type of control service. The framework is then used to assess the stability and response to random variables, such as poor weather and equipment failures. The performance of each control loop is then described qualitatively and validates the framework for investigating the benefit of new policies and technologies.

INTRODUCTION

Except for a brief period after the September 2001 tragedy, air traffic in the US has grown significantly leading to increased congestion and delays. According to the Joint Economic Committee Report, flight delays and congestion cost US airlines \$41 billion in 2007 [1]. Another report estimates that flight congestion and delays at New York City's three airports cost the regional economy \$2.8 billion in 2008 [2].

Airlines are cutting routes to deal with the economic recession. The outcome is packed airplanes with load factors near 85% for the top nine US airlines in July 2009. Despite the cuts in capacity, the on-time performance has improved to only 78.9% for 2009 [3]. The ICAO, however, predicts this phenomenon will change as the economy improves. Modest growth of ~2.6% is forecast for the US in the next 2 years [4].

Indeed, the National Airspace System (NAS) is unable to meet today's demand, and will likely fail with the projected increase in traffic. Weather events compound the problem, and new airports and runways will not improve the situation without improvements to the current capacity limitations.

Delays increase fuel burn, cycle times, and crew times, which increase the airlines' O&M costs significantly. A congressional report estimates the airlines spent \$19.1 billion in additional fuel, crew and maintenance costs due to delays in 2007 [1]. ICAO projects that the world scheduled air carriers will lose \$8.9 billion in 2009 [4]. These losses threaten the airlines' survival. Moreover, the impact on the environment is dramatic. For every unit of fuel burnt, approximately 3.16 units of carbon are released into the atmosphere.

CAUSES OF DELAYS - There are three main reasons for air traffic delays: infrastructure, weather and traffic. Among the three, equipment and weather are the most frequent.

Infrastructure - The current NAS infrastructure was built in the 1950s and is aging. We still use 1960's communication technology, and the equipment has not kept pace with technology. The Global Positioning System (GPS) has not been fully applied to aviation, even though it is ubiquitous in cell phones and car navigation [5]. The current NAS is still dependent on ground-based navigation aids, and because of coverage limitations, airspace users are forced to stay within the range of surveillance radar and follow a "single highway" This results in congested highways and gives rise to intractable routing conflicts.

Weather -A NextGen Joint Planning and Development Office (JPDO) report estimates that 70% of the NAS

delays are caused by weather in the continental US [6]. This is due to obsolete equipment, inferior weather prediction tools and inconsistent use of weather information in decision making.

DEALING WITH THE SITUATION - Air Traffic Control (ATC) is a service provided by ground-based controllers who direct the flow of airplanes on the ground and in the air [7]. Whenever conflicts arise due to weather or the limited means of managing large traffic volumes, controllers ensure safe aircraft separation by delaying the aircraft on the ground or introducing additional space between aircraft to slow the traffic flow. Additional tools include holding aircraft in a particular sector or rerouting to less congested airspace. All of these actions are necessary because of the equipment and weather prediction tools are inadequate for the methods of traffic control and the volume of traffic.

Both the United States and Europe have realized the need to address these inefficiencies, and have launched NextGen and Single European Sky ATM Research (SESAR) initiatives.

NextGen – The US has launched NextGen initiatives to enhance safety, increase efficiency and capacity, and reduce the environmental footprint. It is a curb-to-curb process that includes the activities inside the airport (security, baggage handling, et cetera) as well as with aircraft. If not repaired, the FAA estimates the broken air transportation system will cost US taxpayers \$22 billion by 2022, and will likely grow to \$40 billion by the 2030 [8].

SESAR – Similarly, Europe has launched SESAR with ambitious goals of a threefold increase in system capacity by 2020, improvement in safety by a factor of 10, a 10-percent reduction in environmental impact per flight, and a 50-percent reduction in ATM costs. SESAR is a gate-to-gate effort that accounts for the difficulties of multiple airport ownership in multiple countries. SESAR will cost an estimated €30 billion, including deployment [9].

An Air Traffic Control system is a complex system to model. Yet, a theoretical model must be developed to study the current performance and identify and validate future improvements in policy and computer automation technology.

SCOPE OF THIS PAPER – The current work was initially motivated by the need to identify the cause of the inefficiencies in the existing ATC system. From this work it became evident that the following questions must be answered to achieve the increased capacity, safety enhancements, and reduced environmental footprint promised by NextGen and SESAR.

1. Is there a framework that abstracts the function of the current Air Traffic Control System?

2. Can the effects of improvements proposed by NextGen and SESAR be analyzed in this framework in the presence of external stimuli?

The external stimuli that affect the system include:

- Adverse Weather (Wx)
- Infrastructure limitations and equipment failures
- Pseudo-random traffic volume

This paper introduces a framework for evaluating and assessing the current ATC system and future improvements. The proposed model is based on a system-of-systems paradigm, with a hierarchy of cascaded feedback loops—one or more for each control service. The model is developed by first identifying the basic control loops for each level and type of service.

The scope of the paper is limited to describing the abstract model and then mapping the current air traffic control system to this representation. The framework is then used to assess the stability and response to random variables, such as weather and equipment failure. The model is then used to analyze NextGen improvements, such as 4D-Weather cubes and ADS-B, to identify the benefits of weather and equipment improvements. The analysis is restricted to commercial airline operations.

This paper differs from prior work by functionally partitioning the current ATC system into strategic planning, tactical planning, and tactical execution. The impact of Information Technology and some pilot-oriented tactical functions are described in [10]. The future NAS operational concept is described at a higher level with feedback loops in [11]. Traffic Flow Management is modeled using mathematical models that are useful for simulation purposes in [12]. Modeling of cognitive tasks of the controllers is described in [13]. The merits of centralized versus distributed ATC systems is discussed in [14].

THE ABSTRACT MODEL

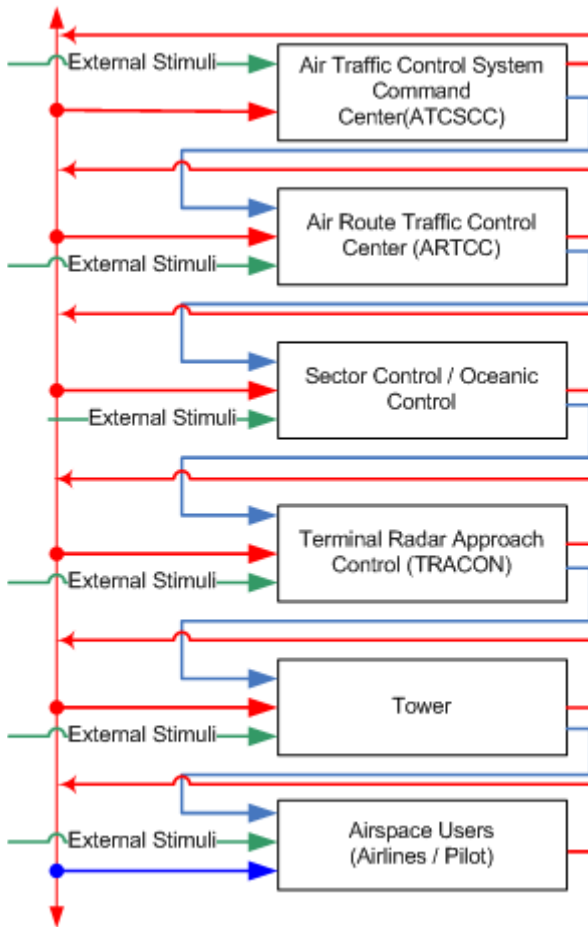


Fig. 1. Abstract model of ATC flow

The ATC system can be visualized as a hierarchical system, with the Air Traffic Control System Command Center (ATCSCC) being at the top and the Air Route Traffic Control Center (ARTCC), Sector Control, Oceanic Control, Terminal Radar Approach Control (TRACON) and Tower control at the lower levels. Since changes to the existing ATC structure are not considered in the NextGen documents, the abstract model assumes the ATC structure will remain the same.

In the abstract model, as shown in figure 1, all of the processed inputs from a higher level are shown in blue. This is to show the hierarchical nature of the information flow. In this abstract model, the functionality of the TRACON is assumed to be a subset of the Sector Control and hence lower in the hierarchy. The functions of each of the components are described in the next section.

The model depicts the feedback that occurs at various levels whenever a significant event happens that can threaten the stability of the system. Real life examples include a weather system that is localized to a particular hierarchical level and can result in conflicts. The

feedback loop shown in red terminates at a common communication channel that facilitates information exchange. This communication channel is shown in red on the left side of the diagram as a bi-directional arrow.

The communication channel is bi-directional as there is a need to skip levels when a significant event happens. Another reason is to accommodate the net-centric solutions that are proposed for both NextGen and SESAR.

The green arrows represent external stimulus such as weather events, ground equipment breakage, or traffic congestion that can alter the traffic flow and affect the balance between the demand and capacity of the system—which in turn can threaten the stability of the system and the safety of the users. The green arrows also represent user inputs to the system such as flight plans or schedule changes that are part of the Collaborative Decision Making (CDM) process.

The Airspace users are at the bottom of the hierarchy and are mostly recipients of information and instructions. In special instances, when an airspace user experiences a significant event (emergency or fuel constraint) they can trigger feedback into the system. Under normal circumstances, however, airspace users are consumers of information and, for that reason, the arrow is shown in blue flowing from the communication channel.

This abstract model will be used to map the current ATC system flow and analyze the changes proposed for NextGen in the United States.

MAPPING THE CURRENT AIR TRAFFIC CONTROL FLOW

Air Traffic Control consists of multiple actors. ATCSCC is the nerve centre where centralized decisions are made. The ARTCCs, which control airspace for thousands of miles, plan for traffic for the sectors under each center's jurisdiction. The primary purpose of the ARTCC is to ensure the sector controllers' workloads are balanced. A Sector Controller monitors the traffic within a sector and hands over control to the adjacent sector. The Oceanic Controllers control the airspace across the ocean boundaries using procedure control and are often dependent on pilots' reports of time and location. When a flight enters the terminal area—the area closest to the airports, where traffic is usually heavy—the Sector/Oceanic Controller hands the control over to the Terminal Radar Approach Control (TRACON) who sequences the aircraft for arrival and then transfers control to the Tower. The Tower Control assigns runways and controls the traffic to the taxiway exits. The interaction between these control actors is best analyzed functionally by the role each plays in controlling the NAS—strategic planning, tactical planning, and tactical execution.