Technology Transition in the Next Generation Air Transportation System (NextGen): Co-existence of Centralized Legacy Systems and Distributed Operational Concepts

Our current air transportation system depends on centralized, voice-communication-based control of aircraft, and it suffers from escalating delays and the inability to support long-term economic growth [faa13]. Aircraft operations must adapt to increasing environmental concerns as we move toward Green Engineering [nsf03]. This is in addition to the challenges expected to be faced by air transportation system in the near future in response to Uninhabited Aerial Systems (UAS), which are expected to enter the airspace in large numbers in the coming decade. UAS will present special challenges to safety and security as their numbers grow, and will have to share the nation's skies with current aircraft. With the number of runways and major airports constrained, the number of flights escalating, the introduction of autonomous UAS into the system, the stress on the current system will accelerate. In the meantime, the ATC operates inefficiently, with huge unnecessary costs to airlines, industry, and consumers. Airlines are already facing economic pressures, which are expected to increase with increased fuel costs. In response to this, the FAA has launched the Next Generation Air Transportation (NextGEN) initiative, which will increase capacity and reduce delays through the introduction of new technologies and procedures [faa13].

However, transitioning technology into the current National Airspace System (NAS) has been found to be extremely complex for many socio-economic, political, and human reasons. In 1996, continued development of the highly anticipated next generation air-traffic control system, the "Advanced Automation System," was cancelled [you01], the result of failure to manage complexity in the software design and development. We would be remiss not to understand and address the important elements learned in this approach, and its impact on the ability to transition new critical system software into the current NAS [faa01]. It is important that enabling technologies and operational concepts that are developed for the NAS be evaluated for their societal impact and ease of transition.

Currently, we conceptualize NextGEN as a set of aircraft operating under a shifting locus of control, whose trajectories may be selected by pilots on the basis of recommendations by highly reliable, yet imperfect automation, but are ultimately supervised by an air traffic manager. All elements within the airspace share extensive verbal and (through displays) visual information. The ability of all human elements to maintain sufficient situational awareness commiserate to their authority is an element of extreme import in the transition of any new technology or operational procedure.

A shifting locus of control can yield the desired increases in efficiency via the redesign of centralized approaches to traffic management into decentralized or distributed operations which will be enabled by novel and high confidence surveillance, communications, navigation and information management technologies. However, revolutionizing a high-availability, safety-critical infrastructure system is a non-trivial task, as operation of the present system must continue simultaneous to the upgrade process. Functionality cannot be lost at any stage of the upgrade, and backward compatibility must be furnished along with quality guarantees. This is further exacerbated by the many stakeholders, along with public and private infrastructure investments, (sunk) economic issues and societal impact, all of which are difficult to accurately quantify. Any transition plan must include a stakeholder analysis dovetailed with an evaluation of incentives to necessary to encourage technological deployment.

In order to demonstrate the feasibility of NextGen operational concepts which involve decentralized or distributed control architecture, we must develop processes and methods of assuring safety, security and reliability properties in a safety-critical cyber-physical system which possesses heterogeneous components with differing capabilities, as well as demonstrate their compatibility with current centralized operational concepts. The characteristics of an air vehicle network populated by commercial, military and general aviation aircraft that can be either human-piloted or computer-controlled, must be accurately modeled, analyzed and validated, including the interaction between components, such as autonomous and non-autonomous vehicles. Qualities such as safety, security and reliability must be maintained throughout the development, operation and evolution of such a system, in the face of control, computational, and communication challenges inherent to atmospheric flight in a shared environment. Our goal is to develop techniques that enable the validation and eventual certification of safety properties for decentralized (or distributed) operational concepts in a mixed equipage, human supervised Next Generation air transportation system, via (formal) modeling and analysis through the use of globally applicable *criteria* [mbn10]. These *criteria*, if met by the operational concepts or algorithms, will guarantee, upon composition with the mixed equipage, human supervised NAS, the necessary global safety properties.

In order to develop *criteria* which address not only technical concerns, but also socio-economic concerns, we must study previous attempts at technology transition in the National Airspace System. The needs of all relevant parties in these past attempts at technology transition, roughly grouped in the following fashion: (1) Operators (such as pilots, controllers, maintenance personnel, etc.) who work to enable the new system and technology, and who have external societal pressures (i.e. labor unions, airline shareholders etc). (2) Regulators (i.e. FAA, ICAO, etc.) who will have to gauge whether the new system is viable and (3) End users (such as passengers, people who live near airports etc.) who will be affected via issues of trust, efficiency and environment must be addressed in any criteria developed. This socio-economic aspect of the criteria will allow for the identification of factors critical to the technology transition process, and thereby give insight into relevant success metrics. These metrics can then be incorporated into the technical criteria requirements derived for the given NextGen ConOps, and can be used to guide and streamline the transition process,

We believe that utilizing a game theoretic approach to designing *criteria* for algorithms or concepts of operations which have competing stakeholders and quality concerns will facilitate the smooth and safe transition of novel air traffic management strategies into the current NAS. For example, if we consider integrating a decentralized algorithm for separation management for a certain class of aircraft which have ADS-B out enabled transponders, who are thus able to pinpoint their position to a greater degree of accuracy than non-equipped aircraft, we can effectively reduce controller workload as well as increase aircraft trajectory efficiency (for the enabled aircraft). We then need to develop *criteria*, such as communications and data (cyber)-constraints on the reliability of the ADS-B OUT measurements, as well as physics-based constraints on the velocity control algorithm onboard the enabled aircraft that specifies the maximum degree to which an aircraft can alter its own trajectory, in order to ensure that these enabled aircraft compose safely with non-enabled aircraft that are still managed by an air traffic controller in a centralized fashion [nhh09]. These criteria must then be blended with stakeholder concerns such as pilot workload and enforceability of software assumptions (such as the ability of the pilot to override the software's limits on the velocity controller) in order to assess the overall safety of the global system. For there to be a stable solution in this setting, there must exist a Nash Equilibrium (a Point of Stability) for this blended criteria concern [b099], which can then be assessed as a metric for certification purposes.

From a networked communications (or cyber) point of view, there is a vast technology transition that must occur to enable these decentralized operational concepts or algorithms. In the present-day air traffic system, communication is primarily between aircraft and the ground. The future distributed operational concepts envisioned here will require timely and secure inter-aircraft communication. For instance, to optimize trajectories in a safe fashion, a given criterion would be that the aircraft exchange information, such as wake vortex data and local weather data, with each other at a guaranteed minimum rate, with required measurement accuracy. This inter-aircraft communication will be utilized to improve the quality and the quantity of information available for decision-making, as well as the types of onboard (distributed) algorithms that will allow for improved operational efficiency of the entire NAS. However, significant challenges remain in achieving timely, secure and reliable inter-aircraft communication, and also in utilizing such communication for control purposes [ukn09]. The rapid changes in aircraft locations, as well as changes in weather conditions will change the quality of communication links over time, making it difficult to satisfy the reliability, security and timeliness criteria required in order to utilize these ultra-efficient, distributed algorithms and operational procedures.

Physical criteria will also greatly influence the ability of aircraft to engage in distributed operations. Clearly, different types of traffic will have different requirements. For instance, control loops closed over wireless will need reliable real-time communication among nearby aircraft to exchange relevant state information [nhh12], while value-added Internet traffic for infotainment can potentially be delayed without any impact on the safety of aircraft operation. Suitable networking and communication mechanisms will have to be developed to deliver the required information, while satisfying the various physical requirements exhibited by each aircraft's performance characteristics.

References

[faa13] FAA, Office of Investment Analysis and Operations Research Division, "NextGen 2013 Implementation Plan", http://www.faa.gov/nextgen/implementation/

[faa01] FAA, *Software Development for the National Airspace System*, Dept. of Transportation, Washington, D.C., June 1, 2001, FAA-STD-026, http://www1.faa.gov/aio/common/documents/Safety/FAA026.htm.

[nsf03] National Science Foundation, Conference Report of Green Engineering: Defining Principles, San Destin, FL, May 18-22, 2003

[you01] D. Young, U.S. House Committee on Transportation and Infrastructure press release, http://www.house.gov/transportation/press/press2001/release15.html.

[mbn10] César Muñoz, Ricky Butler, Anthony Narkawicz, Jeffrey Maddalon, and George Hagen, A Criteria Standard for Conflict Resolution: A Vision for Guaranteeing the Safety of Self-Separation in NextGen, Technical Memorandum, NASA/TM-2010-216862, October 2010.

[bo99] T. Başar and G. J. Olsder. Dynamic Noncooperative Game Theory. SIAM Series in Classics in Applied Mathematics, Philadelphia, January 1999.

[ukn09] D. Uhlig, N. Kiyavash, and N. Neogi, "Fault Tolerant Triangulation in Distributed Aircraft Networks with Automatic Dependent Surveillance Broadcast", International Journal of Systems, Control and Communications, eds. C. Hadjicostis, C. Langbort, N. Martins, and S. Yuksel., June 2009.

[nhh12] Natasha Neogi, George Hagan and Heber Herencia-Zapana, "Comparison of Aircraft Models and Integration Schemes for Interval Management in the TRACON", IEEE Digital Avionics Systems Conference (DASC), Williamsburg, VA, October 2012.