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AUTONOMY AT SCALE

Intelligent Machines Advancing Technology to Improve our Future

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USE CASE: AIR TRANSPORTATION

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An expanding and diversifying airspace is not a new phenomenon in the United States. Total worldwide air traffic doubled between 1985 and 2000, and again from 2000 to 2015[1]. This level of growth is expected to continue over the next few decades—with significant growth being driven by first time passengers. According to Boeing CEO Dennis Muilenburg, 80% of the world population has never been on an airplane and in 2017, 100 million people in Asia experienced air travel for the first time[2]. Over this 30 year period, the airspace increased in diversity with the growth of regional and small business jets, a range of aircraft equipment, and congested skies above major metroplexes.

Increase in both demand of traditional aircraft (general aviation and commercial) and diversification of airspace will have a compounding effect on the number of air traffic controllers needed as well as their responsibilities. Specifically, operations at the Federal Aviation Administration (FAA) and contract towers are expected to grow at 0.9% per year over the next 20 years (2018–2038)[3]. Coupled with new entrants such as unmanned aircraft systems (UAS), commonly referred to as drones, and the increased frequency of commercial space launch and reentry activities, the demand on both the system and controllers will only continue to rise.

To further complicate this picture, the traditional definitions and clear lines between surface and air transportation will likely become murkier over the next few decades. As new technologies enable the proliferation of new applications of air transportation, such as urban air mobility (UAM) and increased UAS traffic, they create a new level of complexity. While both of these technologies are airborne, in urban applications they may fly below 200 feet in corridors that are likely to be the same as those that autonomous surface vehicles pilot. It could be argued that UAS and UAM traffic is better defined as additional layers of surface traffic, instead of air traffic as we currently define it. The ultimate classification of technologies that operate in this liminal space will have vast implications on regulatory authorization, certification, and public adoption.

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Current and Emerging Technologies

The advancement of technology and increased use of automation will likely impact aviation only after surface-based systems have been proven safe, efficient, and broadly accepted by the general public. Given the complexity of the national airspace (NAS) and emphasis on safety, even with broad public acceptance of autonomy in other forms of transportation, it is unlikely that a fully autonomous NAS will replace humans in aviation applications for some time, but instead augment and/or complement human activities.

Across all applications of autonomy in air transportation, a consistent set of technology advancements will be necessary for assuring safe and reliable operations:

- **Ubiquitous highspeed connectivity** — The next wave of highspeed connectivity will be driven by 5G wireless, but autonomous air transportation demands seamless worldwide ubiquity. To achieve this, a global solution for space-based highspeed communications is required.
- **Advances in materials and structures** — Many of the new applications of autonomous air transportation will necessitate clean and safe forms of propulsion. This need will drive research into materials that expand the stored energy capacity of batteries, increase the performance of airframes, and enhance the efficiency of electric motors.
- **Resilient PNT** — While global navigation satellite system (GNSS) solutions are a seamless part of our everyday life, they provide very little resiliency or redundancy. More robust space-based systems, coupled with complementary technologies, will be essential to enabling air transportation autonomy at scale.
- **Robust computing infrastructure** — Regardless of the advances in highspeed connectivity, the need for systems capable of performing complex computer operations at the edge will be essential for ensuring safe operations. Advances in graphic processing units (GPU) and low-power architectures (such as ARM) are likely to drive edge computing applications required for autonomous operations such as sense-and-avoid and guidance/navigation.
- **Cyber-security operations** — For the public to trust a partially or fully autonomous system, there must be reasonable assurance that the system is secure against malicious actors.

Figure 1: Increased diversity of the airspace leads to new demands on both the systems and operators.

Increasingly Diverse Operations

The NAS infrastructure and procedures, as currently designed, limit the ability to smoothly integrate new entrants into the airspace. The current wave of new entrants is led by UAS, with an expected total number of UAS surpassing 2.4 million by 2022[4]. While a majority of these systems will operate outside of FAA-controlled airspace (below 400 feet), a number of forecasted UAS missions will require both manned and unmanned aircraft to operate in the same airspace. Beyond UAS, other new or expanding operators, such as commercial space operations, will put additional pressure on the existing airspace. While space launch has existed for over 50 years, the recent increase in commercial launch and reentry capability and the demand for their services is broadening the need to ensure equitable distribution of airspace to all users. A single launch from the Cape Canaveral Air Force Station can cause hundreds of thousands of dollars in redirect costs for airlines[5]. Airspace demands are only expected to increase over time as the frequency and complexity of launch and recovery operations grows.

While UAS and commercial launch operations are having the most immediate impact on the diversity of the airspace, additional operators will continue to enter the airspace over time and increase complexity. This includes UAM operators that intend to bring electric vertical takeoff and landing (eVTOL) vehicles to urban environments as a means of on-demand local transportation. By themselves, UAS and UAM require stand-alone traffic management systems that integrate with the NAS in a way that ensures the safety and equity of all parties, both legacy and new.

The demands of new and emergent technologies create a need for an airspace that allows seamless integration of a diverse set of operations, each with different equipment, missions, critical challenges, and concepts of operations. This integrated system must be able to rapidly and flexibly adapt to changes in the amount and type of demand. Research underway at NASA is bringing us closer to achieving this reality through the Air Traffic Management eXploration (ATM-X) program[6].

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QUANTUM OPTIMIZATION FOR AIR TRAFFIC MANAGEMENT

Many of the next advances in Air Traffic Management (ATM) will involve understanding and utilizing continuous optimization: the process of employing localized controls to improve the larger NAS behavior. For instance, the Terminal Flight Data Manager (TFDM) program manages departure aircraft by providing timely gate pushback to minimize the time spent taxiing on the surface. When employed, this mechanism reduces congestion at the airport surface and the airport operates more smoothly. This increased operating efficiency produces ripple effects for both an airport's departing and arriving flights, as well as the other aircraft on the departing and arrival routes. In another example, the DataComm program will enable flights to obtain dynamic, detailed rerouting information to avoid hazards, such as convective weather. Rerouting one flight may impact flights already on that new route, and thus force deconflictions for the affected flights. Those deconflictions may cause a cascade of impacts for flights affected by the deconfliction.

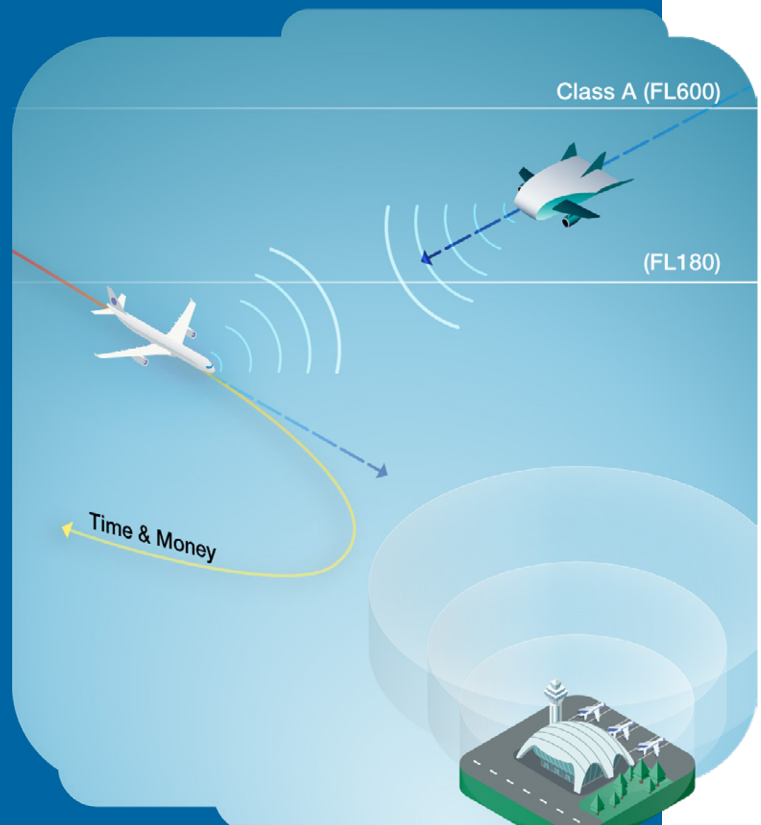

Figure 2: Emerging computing architectures create the potential for applying greater optimization and the potential for enhanced system efficiency.

Flight paths within the NAS are interrelated. The ability to modify paths and predict the consequences of these changes is critical to implementing upcoming ATM technologies. Solving this complex, large-scale problem is challenging in its own right; solving it in continuous operation requires significant algorithmic engines. Quantum annealing is one technique to address this complex challenge. Quantum computing also

has the potential to solve large scale problems that are not amenable to classic computation. Noblis has already prototyped one use case for this technique on a DWave Quantum Annealing Computer (https://www.dwavesys.com) hosted at NASA's Ames Research Center (https://www.nasa.gov/ames).

Coordinating the landing of aircraft is one of the most involved operations in air traffic control. Aircraft are at an extremely sensitive stage of flight while flying at their closest proximity to other aircraft and infrastructure. Managing successful landings involves complex temporospatial operations such as rescheduling, holding, and interleaving flights. The complexity of this operation rises rapidly with the number of aircraft involved. Noblis approached this problem with a goal to plan the flight trajectories for multiple aircraft flying to a common runway. Using a relatively simple set of rules, we were able to employ the quantum annealer to create high-fidelity flight plans that safely separated the aircraft, respected standard airflow around the airport, and successfully guided the aircraft to the runway.

Additionally, we have been applying the quantum annealing algorithm to support other areas including en route path insertion and weather and other hazard rerouting—integrating both flight-specific and atmospheric characteristics. We have also begun to deploy this algorithm beyond conventional aircraft to support UAV planning, including managing high-density UAV traffic such as on "Drone Highways." Management of UAV traffic is of particular interest as the number of UAVs in operation may soon dwarf the number of conventional aircraft. To address this challenge, we have been investigating specialized path-planning algorithms for use in areas where conventional aircraft and UAV may be in close proximity, such as airports and future cargo pathways. Ultimately, we aim to optimize per-aircraft flight dynamics across the entire NAS.

Human over the Loop

With increased automation comes the potential side effect of displacing human jobs; as the technology continues to advance, more advanced skills run the risk of being automated. While the technology may one day exist to automate the role of an air traffic controller, careful consideration must be given to determining the degree to which autonomy should be incorporated in the NAS or other traffic management systems. The concept of having a human "over the loop" to ensure the safe operation of the airspace will help minimize risks associated with increased automation. Beyond ensuring confidence in an automated system, the human-over-the-loop approach to autonomous traffic management does not displace the human controller, but instead redefines their role and frees them from mundane and repetitive tasks so that they can focus on systemwide assurance and safety.

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Human over the loop can be achieved by using new technologies to augment the human controller rather than replace them. As an example, system-level flight plan optimization calculated through advanced learning systems can be presented to the human controller with a subset of optimized traffic route options. The controller would maintain responsibility for selecting and assigning the optimal route. Maintenance of a degree of human control will help autonomy within the NAS gain broader acceptance. Even with a human over the loop, any automation applied to the NAS would need to be implemented inside a verifiable operating envelope, certified by a regulating body. Approaches to certify "black box"-type algorithms, such as neural networks and deep learning, would need to be established. This level of automation would require a long-term plan for integration into the airspace. First, low-end functions would be automated within a bounded envelope. Over time, as confidence in the system grows both with the users and general public, higher-level functions begin to be automated. During this phase, we expect both the autonomous system and a human would work hand-in-hand—with the human having the ultimate control over the entire system. As trust in these systems grows, system-wide functionality could potentially be handed over to autonomy. NASA's Strategic Implementation Plan for Aeronautics predicts this path to acceptance of a more autonomous airspace and predicts acceptance of high-levels of acceptance will not occur until 2035 or beyond[7].

Challenges

A number of challenges must be addressed to ensure autonomy at scale in air transportation, including:

- Fully certifying and trusting autonomous systems within the NAS, especially in a mixed environment of both autonomous and human-piloted aircrafts.

We believe that increased autonomy, coupled with a rigorous safety and certification regime, will be a central component to addressing the ever more populated and diverse NAS.

- Managing the long tail of existing infrastructure. Re-equipping the entire fleet of existing aircraft would take decades (with the economic life of commercial aircraft extending past 30 years[8]). What considerations need to be in place for heterogeneous fleets with various levels of equipment?
- Understanding human capital and long-term staffing implications for the workforce. What changes in the size of workforce, required skills, and responsibilities will result?
- Defining the boundaries and intersections between existing and emerging modalities. For instance, does traffic management for low flying UAM more closely resemble existing, human-based control in the NAS, or a fully autonomous system similar to what is envisioned for surface modalities?

All new technologies have the potential to create disruptive change within the NAS, so many of the challenges defined above are not limited to just autonomy applications within air transportation.

Conclusion

Though it contributes to certain air transportation challenges, we believe that increased autonomy, coupled with a rigorous safety and certification regime, will be a central component to addressing the ever more populated and diverse NAS. Maintaining human control functions throughout the application of autonomous systems—initially, in the loop and eventually over the loop—will promote trust in the new technology across both the human controllers and the general population. While many advancements in adjacent technologies and domains need to take place before a high degree of automation can be safely and reliably implemented, we have already begun to scratch the surface of the potential benefits to efficiency and cost that autonomy at scale in the NAS can yield.

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