Certifiable Autonomous Flight Management for Unmanned Aircraft Systems

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The next generation air transportation system (NextGen) will achieve unprecedented levels of throughput and safety by judiciously integrating human supervisors with automation aids. NextGen designers have focused their attention on commercial transport operations, with few standards proposed to accommodate the burgeoning unmanned aircraft system (UAS) user community. This presentation introduces challenges associated with safely and efficiently integrating UAS into the National Airspace System (NAS). For UAS, safe operations translate to maintaining acceptable levels of risk to other aircraft and to people and property on the ground. With this definition, a UAS may fly "safely" during and after a crash into unimproved terrain provided no harm comes to people or property. While existing autopilots can fly from takeoff through landing, the greatest impediment to fully-autonomous flight is proving safety in the presence of anomalies such as unexpected traffic, onboard failures, or conflicting data.

This presentation will introduce an expanded definition of "flight envelope" that accounts for evolving physical, computational, perceptual, and environmental constraints. This envelope is traditionally defined by baseline physical constraints then contracted as a function of estimated risk of loss-of-control. The autonomous flight manager can minimize this risk with flight plans that maximize safety margins first and traditional efficiency metrics secondarily. For UAS, such plans may involve diverting away from populated regions on the ground or densely-occupied airspace then deciding whether to continue a degraded flight plan or to terminate the mission through intentional flight termination over a safe (unpopulated) area. The key to certification is guaranteeing acceptable risk levels are maintained, both real and perceived.

Below, we first position this work in the context of current flight and air traffic management. Current and anticipated roles for automation and human operators are discussed. Next, emerging UAS missions are characterized motivating the need for fully-autonomous flight management and integration in the NAS. With loss-of-control as a major concern, an enhanced definition of flight envelope is introduced, and then certification challenges for UAS are summarized in the context of metrics and procedures that will ultimately enable UAS to fly, autonomously, in integrated airspace over populated as well as rural areas.

Flight and Air Traffic Management: A System-of-Systems

In the current and NextGen NAS, systems onboard aircraft will be comprised of a complex network of processing, sensing, actuation, and communication elements. Aircraft, manned and unmanned, will in turn be networked through datalink to air traffic management (ATM) centers responsible for coordinating routes and arrival/departure times. Each aircraft will ultimately be equipped with an onboard flight management system (FMS) that replicates current functionality (i.e., precise flight plan following, system monitoring, communication and pilot interfaces) [LID94][FIS95] plus Automatic Dependent Surveillance – Broadcast (ADS-B) and potentially broadcast of [near-term] intent to aid in collision avoidance. Without such equipage it will be difficult to guarantee traffic remains separated throughout flight, especially when manned and unmanned aircraft must remain separated. Small operators from general and sport aviation to UAS will require low-cost options to the current FMS. Advanced miniaturized electronics make low-cost FMS possible, but it will require a concerted effort to produce and market them given potentially slim profit margins and formidable certification requirements.

Today’s FMS can devise and follow flight plans from origin to destination airport. Future levels of automation are expected to increase in manned and unmanned aircraft, including making and coordinating dynamic routing decisions based on real-time observations (e.g., weather), other traffic, or even mission goals (e.g., target-tracking). Quite simply, we are rapidly moving toward collaborative human-machine decision making or fully-autonomous decision-making rather than human supervision of the automation, particularly when the operator is not onboard. Today’s UAS are flown by remote pilots/operators that designate a set of waypoints or a waypoint sequence as well as a rendezvous location. Communication link failure is one of the most common and challenging issues for UAS. The level of autonomy is increasing to the extent that UAS could operate “unattended” for extended periods, potentially weeks or months, collecting and disseminating data without supervision unless the mission changes or in cases of traffic coordination. “Sense-and-avoid” has become a top priority for integrating UAS in the NAS since pilots cannot easily “see” the smaller UAS; a certified sense-and-avoid technology will provide another step toward autonomous flight management.

Emerging UAS Missions

Traditional transport aircraft have a single goal: safely fly a human or cargo payload from an origin to a destination airport with minimal cost to the airline. The “best” routes are therefore direct, with vectors around traffic or weather as needed. Schedules can be negotiated before flight. Passengers and cargo carriers expect on-time delivery; cost increases with delay. Unlike traditional transport aircraft, the goal of the surveillance UAS is to search a geographical region, to loiter over one or more critical ground sites, or to follow a surveillance target that may take an unpredictable route. Potential commercial applications that complement the myriad of Department of Defense (DoD) uses are shown in Figure 1 [ATK09]. UAS will cooperate as formations that can be viewed as a single entity for deconfliction. UAS teams more typically negotiate tasks but fly independent routes. Persistent long-term coverage may be critical, and cooperative coverage from multiple viewing angles may be required to ensure a critical ground target is not lost in urban environments. Some activities may be scheduled in advance and prioritized through equity considerations (e.g., traffic monitoring), but other activities related to homeland security or disaster response will be unscheduled operations that may take top priority even over airline operations. Although high-altitude UAS must be considered in an overall NAS solution, the low-altitude craft operating over populated regions or in proximity to major airports will be most challenging to accommodate in the next-generation NAS.

Flight Envelope: Minimizing Loss-of-Control Risk

Loss-of-control, the largest cause of aviation accidents across all vehicle classes, is induced when an aircraft exits its nominal flight envelope resulting in an inability to follow a desired flight trajectory [KWA09]. Today's autopilot systems rely on linearized steady flight models [MCC10]. These intuitive models show that aerodynamic stall and thrust constrain the flight envelope, as shown in Figure 2. Researchers are beginning to develop nonlinear system identification and feedback control algorithms that offer stable controlled flight some distance outside this nominal "steady flight" envelope [TAN09], offering the potential for an autonomous system to discover this more expansive envelope [ATK09b] and continue stable operation despite anomalies in environment (e.g., wind) or onboard systems (e.g., control surface failures, structural damage) that would induce loss-of-control. To ensure safe operation and to prove autonomous system performance, it is critical to have a UAS with an autonomous FMS capable of *provably* avoiding loss-of-control in all situations where avoidance is possible.

Toward Fully-Autonomous UAS Certification

Each year the FAA is asked to certify an increasingly diverse group of UAS for flight in the NAS. Although most operations are currently conducted over remote regions where risk to people and property is minimal, UAS will ultimately be fully-integrated. Certification is and must remain based on guarantees of correct performance and contingency management. Redundancy will remain a key to acceptable risk of damage to people and property in the event of failures, although for UAS a full triply-redundant architecture as is present in today's commercial transport may not be required given that ditching is a viable option. Safety certification is a difficult process in which some trust is necessarily placed in manufacturer and operator claims regarding design and usage. Automation algorithms can ultimately be validated through rigorous mathematical and simulation-based verification processes, providing quantitative measures of robustness at least for envisioned anomalies in weather, onboard systems, and traffic.

The remaining vulnerability of a fully-autonomous FMS is its potential for rigidity resulting in the possibility of improper response when faced with truly unanticipated situations. The default method to manage this vulnerability has been to insert a pilot into or onto the aircraft control loop. Particularly when operators are remote with limited engagement, it is unclear whether the human will remain the best mitigation for automation rigidity. Certification of fully-autonomous UAS FMS must then be based on meeting or exceeding human capabilities. Assessing the human capacity for response is challenging; in the context of remote UAS we can characterize bounds on user commands as a start. Formal methods to validate and verify automation plus assessing the flexibility (rigidity) imposed by algorithms as well as the bounded set of remote user commands will be keys to proper safety certification. Simulation and flight testing will of course also be required to gain trust, but we propose that simulation is secondary to formal proof of correctness when assessing robustness.

References

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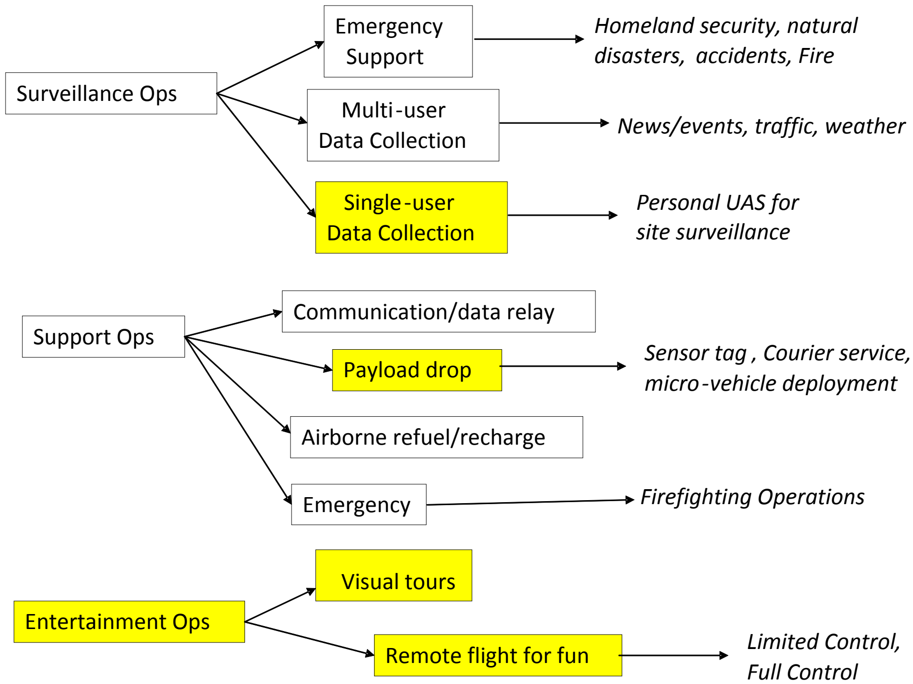

Figure 1: Emerging UAS Applications with focus on Commercial Operations [ATK09].

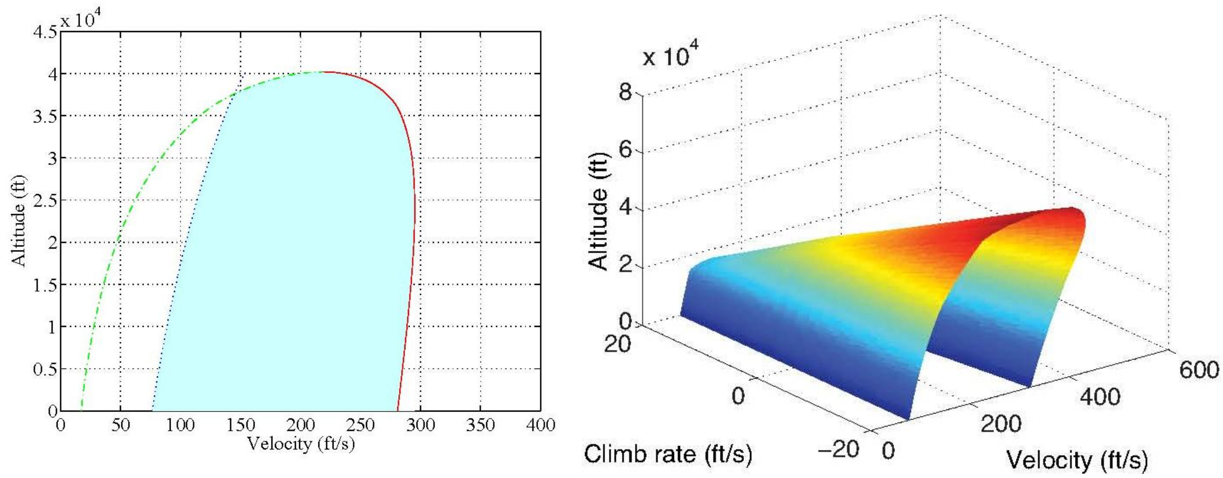

Figure 2: Steady Level (left) and 3-D (right) Traditional Flight Envelope Example [MCC10].