



Architectural Considerations for Assured Autonomy

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Complex System Design



- System flavors
 - Systems
 - Systems of Systems
 - Complex Systems
 - Complex Adaptive Systems
 - Etc.
- Approaches to architecture of operation and control: highly structured
 - System analysis and design
 - Systems engineering
 - Enterprise architecture
 - Etc.
- Autonomous traffic is a complex adaptive system
 - CAS have never been actively designed; they evolved in response to disturbances & demands (e.g., to accidents, in the case of transportation)
 - The current system has a high degree of assurance and trust by virtue of severe bound on complexity and long experience



Autonomy assurance-relevant setting/futures

- Perspective O(optimistic)
 - “Let’s face it: In 2035+ the airspace operations will be pretty much like today, only with some drones, separated from traditional operations.”
Comfortable $\Rightarrow$ popular
- Perspective R(ealistic?)
 - “Let’s face it: In 2035+, and likely much sooner, the airspace will have to accommodate a massive influx of uncontrolled, unmanned aircraft, impossible to restrict to a specific volume, in general.”
 - Cause: UA progressively cheaper, available, no specialized knowledge, longer range, higher altitude, heavier, difficult to detect in time
 - Uncomfortable $\Rightarrow$ unpopular
 - Salient factor: large subset of non-cooperative participants
- Conjectures/claims
 - Ask not “how do we make autonomy happen?” (because it already has), but “how do we assure reasonably safe and efficient access to airspace in the presence of dense autonomy?”
 - O is a special case of R; focus on R



Air Traffic Control with Autonomy

- Traditional view: controlled participants and THE SYSTEM
- Autonomy view: observers, controllers, and controlled (humans or machines, any origin of control, self or other)
- Basic facts of control
 - **Case 1:** The controlled agrees to be controlled
 - Air traffic has always operated in this mode
 - Technically: cooperative/collaborative case
 - E.g., rules of the road rely on everyone agreeing to follow them
 - Some unresolved problems: e.g., diverse equipage; density; efficiency
 - Main problem: with high density and diversity, a significant percent of traffic is likely to be non-cooperative, especially when the pilot's life is no longer endangered
 - **Case 2:** The controller has means to enforce control (e.g., Star Trek universe)
 - Non-existent in civil aviation (geofencing solutions unlikely to suffice)
 - Alternative solution: benign participants must be agile and survivable



- Claim: in autonomous systems “architecture” requires two explicit notions
 - Control architecture for cooperative participants
 - Must bound complexity
 - Design for controllability, robustness, resilience, and adaptability at all scales of the system
 - Management of contingencies: non-cooperative (for any reason, some with no ill intent) participants and malicious participants
 - Overarching need: detection of and protection from cyber interference
 - “Architectural” responsibility must rest with the cooperative/benign aircraft

What's needed for assured control (regardless of architecture)



- **Situational awareness in time to make a decision**
 - Components: sensors, communication, perception, evaluation of sensory input, prediction of contingencies
- **Decision making capability**
 - Components: detection of approach to phase transition from controllable to uncontrollable; multiobjective, real-time constrained optimization under uncertainty
 - Adaptive design/decision making
 - Algorithms for handling unpredicted events
- **Ability to execute decision**
 - Components: vehicle properties (maneuverability, speed, self-preservation, impact resistance, self-protection, self-healing, etc.)
- **Resources for continual updating/re-computation**

Notes on Architecture for Cooperative Participants



- Fundamental “Laws” of Complexity:
 - Requisite Variety (Ashby, 1956): Any control system must have number of states $\geq$ than the number of states in the system to be controlled
 - Conant Thm (Conant & Ashby, 1970): Can’t influence a system effectively w/o thorough understanding of scope, connections or development algorithm
 - Scale: Addressing complex systems requires greater degrees of freedom at the local scale where adaptability is maximized (Bar-Yam, 2004)
- Density of traffic, situational awareness, tractability, and objectives (C/R/R/A) dictate local and semi-local control
 - Given perfect situational awareness, decision making, etc., it doesn’t matter who exercises control
 - Given reality, need to address control and resilience at local level (vehicle and groups of vehicles) via self-organization and self-optimization
 - “Assurance” demands bounding acceptable states
 - Good news: interconnectivity of vehicles raises awareness for the group and offers shared resources for decision making

Notes on Architecture for Managing Contingencies



- Same laws of complexity apply
- Same needs for situational awareness apply
- **Autonomy of non-cooperative disturbances is at the level of aircraft $\Rightarrow$ control for managing contingencies must be at the level of cooperative/benign aircraft**
- The trend is to impose regulatory constraints on unmanned vehicles; this does not address non-cooperative vehicles
- Can only influence cooperative vehicles
- Therefore, shift emphasis on explicit vehicle design for survivability and self-preservation
- May impose new requirements on large passenger-carrying aircraft to operate in a dense environment with autonomy (e.g., structures, maneuverability)

Concluding Remarks



- Claim:

(Relatively) assured control architecture for 2035+

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Complexity-bound multi-scale self-organized
decision making

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Survivable vehicles

- Work in progress
 - Ab initio (clean slate) design of the system architecture
 - Surviving autonomy in a cooperative vehicle
 - While the human is still in the system, human-machine teaming
- Ad: Come to a special session on Clean Slate Design for Autonomy in Vehicles and Airspace at Aviation 2016 for details