



Verification and Validation Challenges for Adaptive Flight Control of Complex Autonomous Systems

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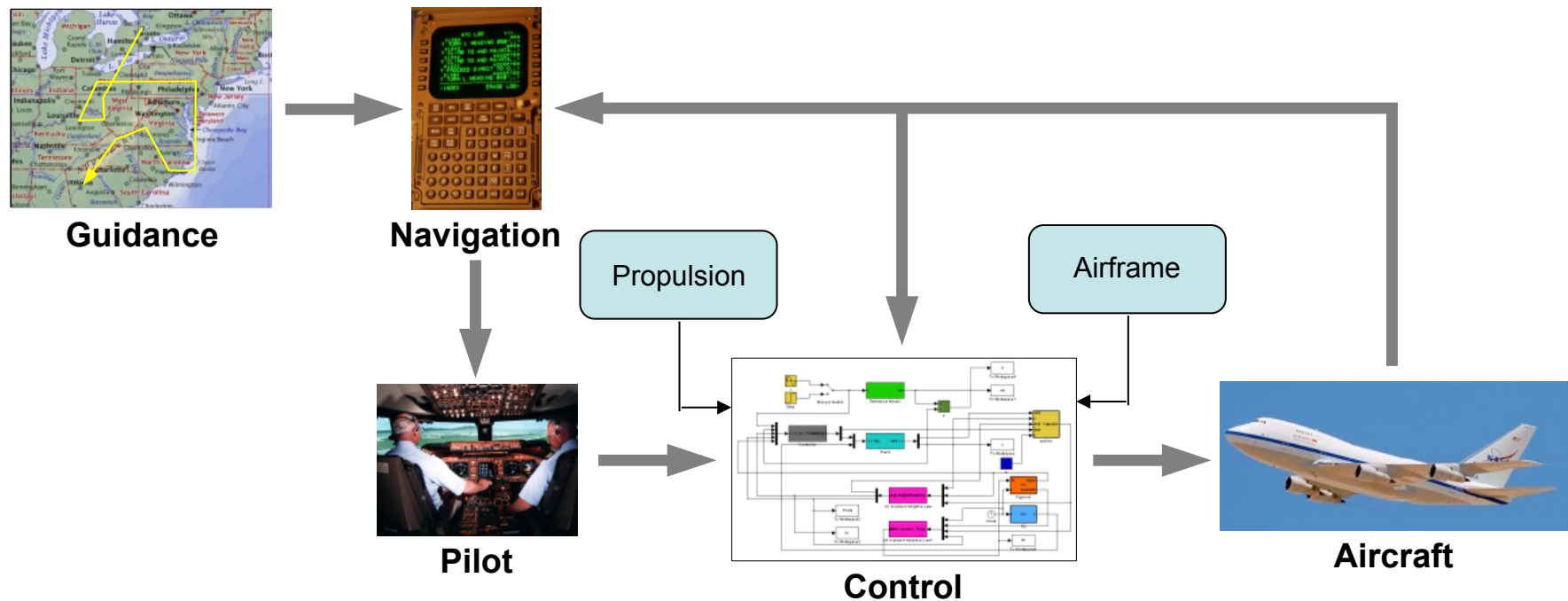


Outline

- **Adaptive Control Role in Complex Autonomous Systems**
- **Technical Challenges**
- **Certification Gaps**
- **Recommendations**
- **Concluding Remarks**

Flight Control Technology

- **Flight critical technology for enabling safe and efficient operation of aerospace systems – Fundamental system requirement**

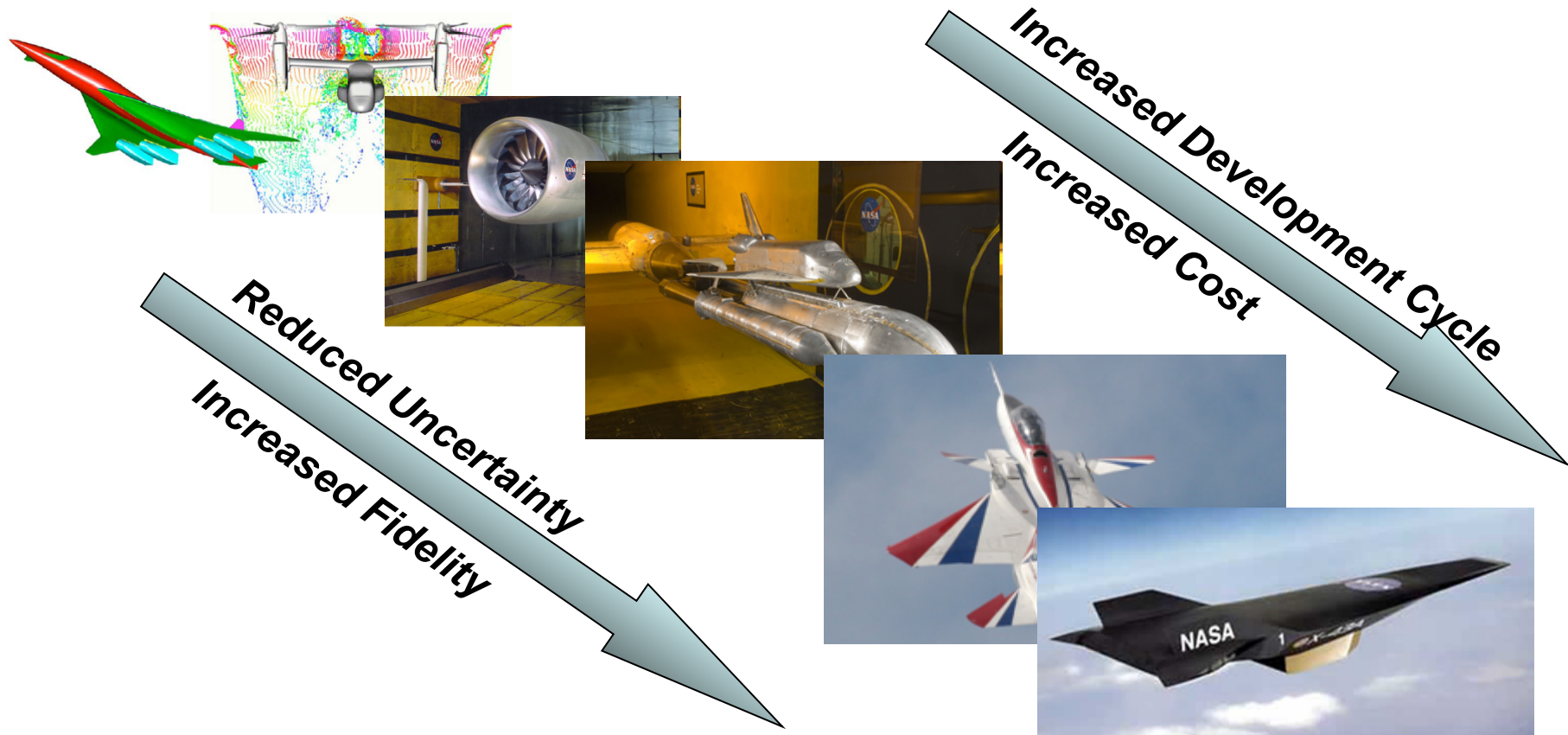


- **Advanced flight control plays an important role in modern aircraft**
 - ▶ Gust load alleviation control "Smoother Ride" technology in Boeing 787 Dreamliner



Traditional Role of Modeling and Simulations

- Modeling is an important part of risk reduction in control design in aerospace

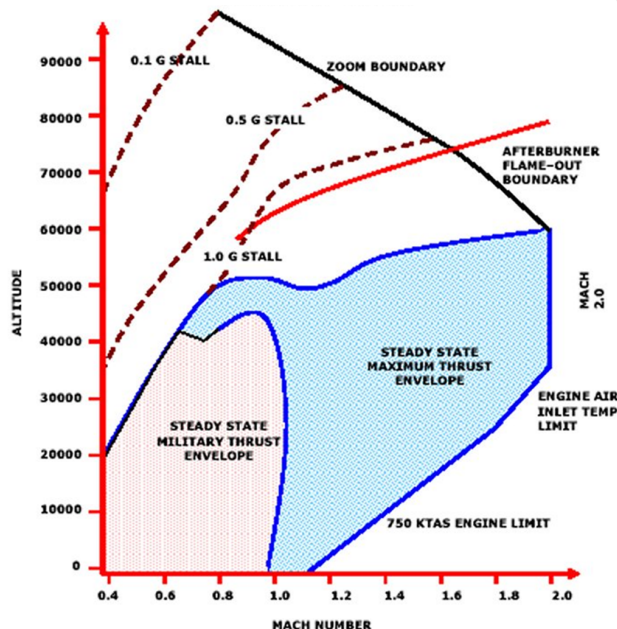
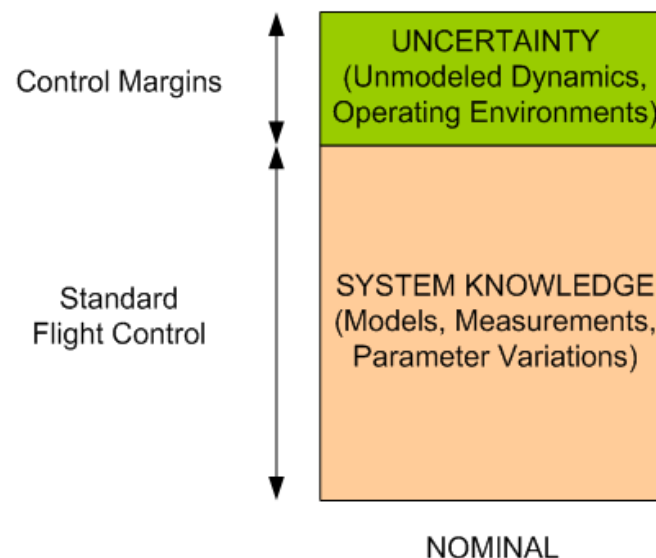


- Reduced uncertainty → increased confidence in control design



Traditional View of System Uncertainty in Control

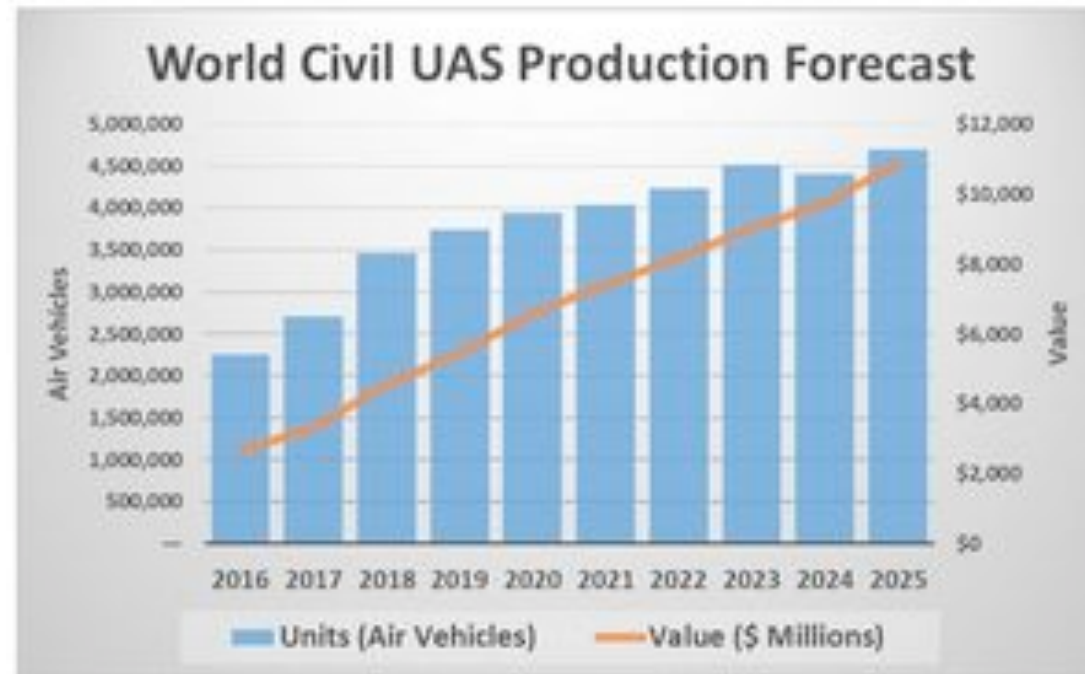
- **Stability is a fundamental property of control systems**
- **System uncertainty can degrade stability property**
 - ▶ Cannot be eliminated but can be managed
- **Risk management of uncertainty**
 - ▶ Modeling
 - ▶ Built-in margins
 - ▶ Operational restriction





Emerging Air Vehicle Platforms

- **UAS and Urban Air Mobility (UAM) platforms are poised for rapid growth opportunities in the aerospace market**



UAS Magazine, September 29, 2016

- **Increasingly, these platforms play more critical roles in all sectors of the society**

Increased Complex Autonomous Capabilities



- Operation beyond line of sight and in high-density airspace calls for increased complex autonomous capabilities
- Many manufacturers develop proprietary avionics without following traditional aerospace practice of risk reduction through system modeling and V&V
- UAS sometimes mistakenly perceived as non-safety critical assets – certification not high on priority list
- This view is proven false – increasingly UAS are view as safety-critical systems which must demonstrate to be highly reliable and safe



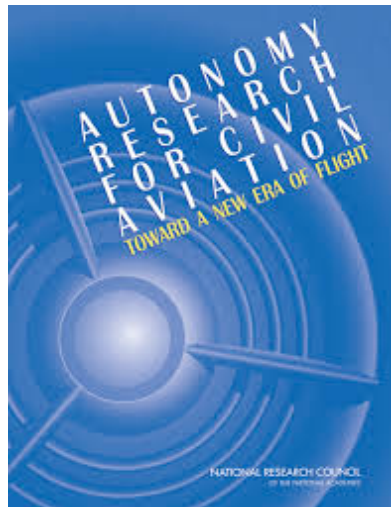
Amazon Prime Air UAS

- Gaps in aerospace practice exists in UAS manufacturers – systems complexities not well-understood through first-principle modeling (e.g., complex vehicle dynamics with novel fixed-wing / rotary wing design) – increased risks and difficult to certify



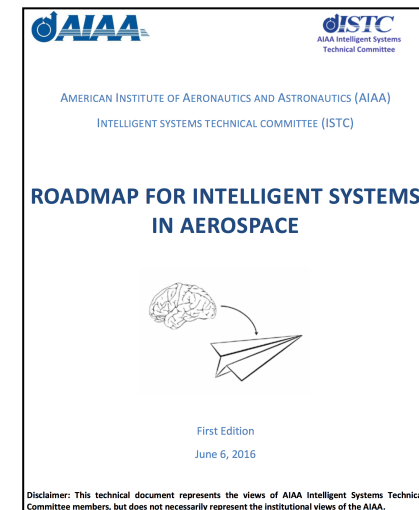
Why Adaptive Control?

- Future aerospace systems tend towards increased complex design and autonomy which can impose greater demand on reliability and safety through risk management
- Adaptive control can revolutionize traditional control technology to better manage significant uncertainty in increasingly complex autonomous systems



Systems that are adaptive and nondeterministic demonstrate the performance enhancements ... Many advanced IA systems are expected to be adaptive and/or nondeterministic ...

NRC Autonomy Research for Civil Aviation – Toward a New Era of Flight, 2014



Adaptability is a fundamental requirement of autonomous systems that enable a wide range of capabilities

AIAA Roadmap for Intelligent Systems in Aerospace, 2016

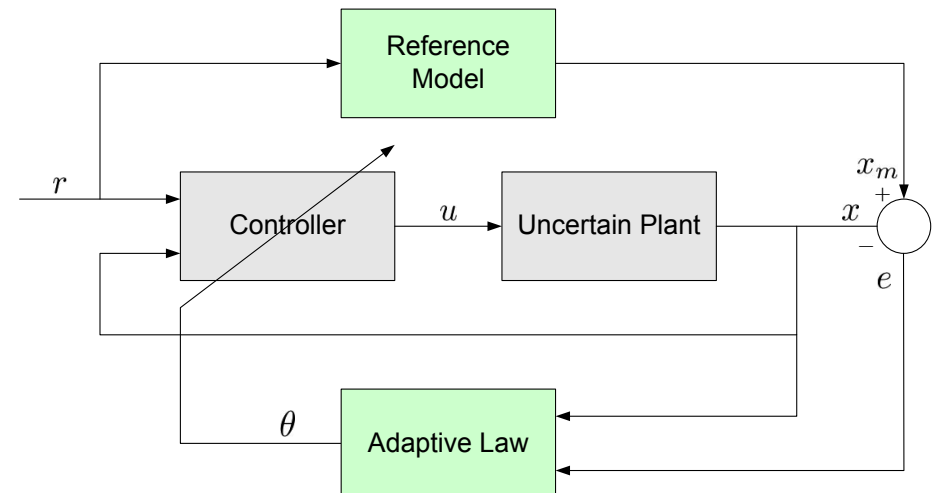


What is an Adaptive System?

Adaptation - the ability to adjust to changing environment through ***learning*** and adopting new behaviors to cope with changes

- **Essential elements of an adaptive system**

- ▶ Reference model
- ▶ Learning mechanism – adaptive law or machine learning

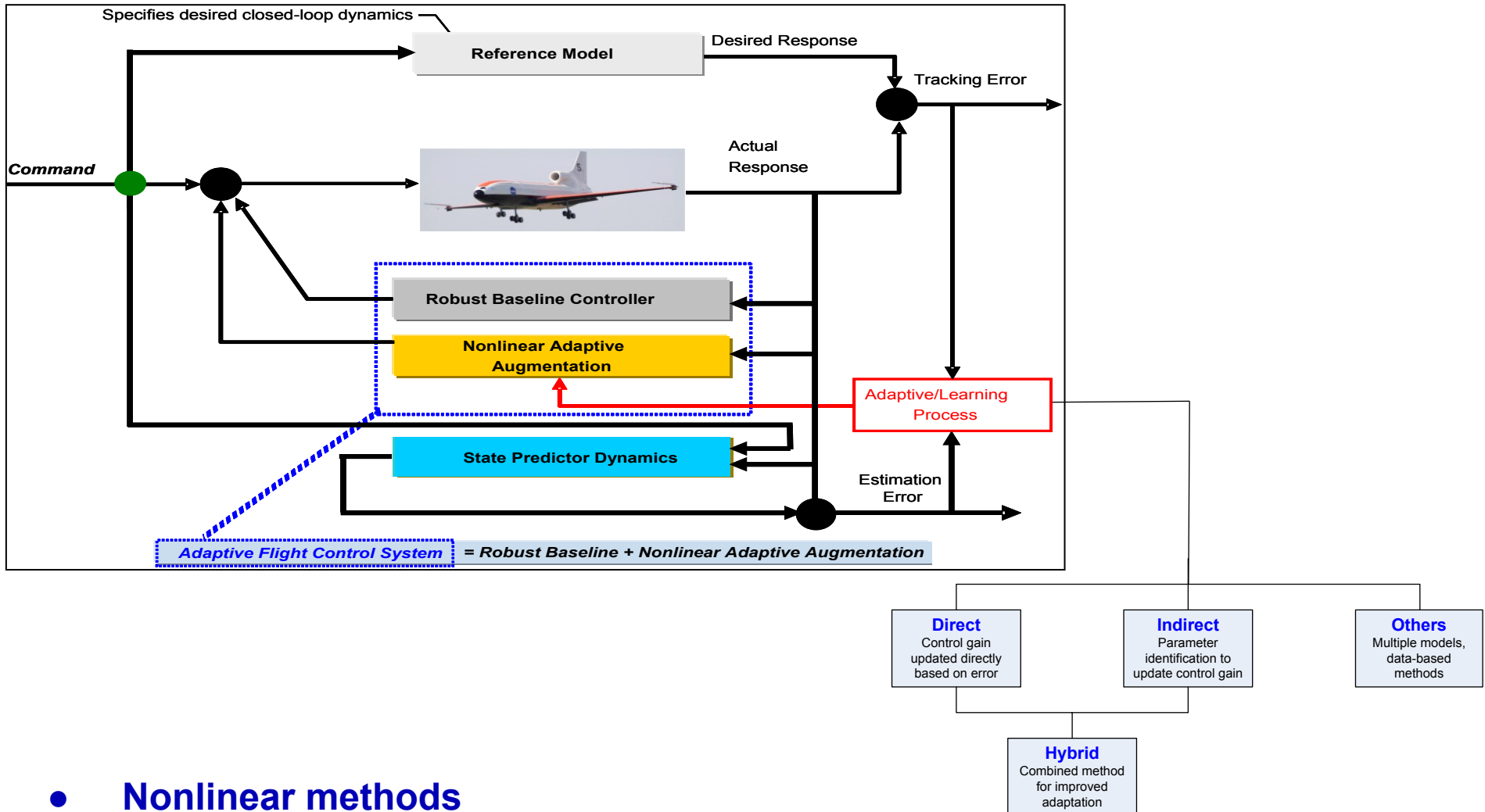


- **Mimics biological concept of learning that enables systems to adapt to changing environment optimally over time – machine learning**
- **Adaptive law provides a learning mechanism to internally adjust system parameters so as**
 - ▶ To suppress undesired response to uncertainty
 - ▶ To seek optimal behaviors over long time horizon



Adaptive Flight Control

Adaptive Flight Control System Architecture



- **Nonlinear methods**

- ▶ Powerful and can handle variety of sources of uncertainty
- ▶ Adaptation leads to increased complex behaviors
- ▶ Fundamentally more difficult to V&V



Basic Elements of Adaptive Control

- Adaptive law

$$\epsilon = B [\Theta^\top \Phi(x) - y(x)]$$

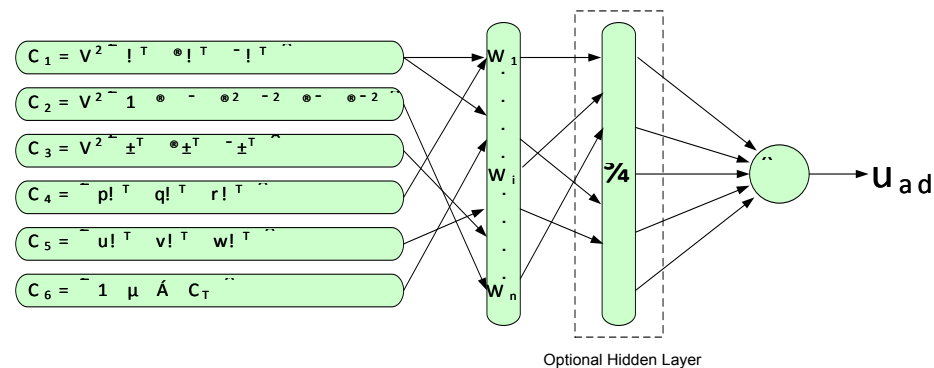
model of uncertainty ——— uncertainty

$$\dot{\Theta} = -\Gamma \Phi(x) e^\top P B$$

adaptive parameter ——— input function
 ——— adaptive gain or learning rate

- Inputs can range from simple functions to complex neural networks

- ▶ Intelligent flight control (IFC)



Single Hidden Layer Neural Network



Adaptive Control Challenges

- **Adaptive systems use machine learning algorithms to provide enhanced performance of complex systems under a wide variety of operating conditions**
- **Learning algorithms can also cause problems**
 - ▶ Incorrect learning is worse than no learning at all
 - ▶ Trust issue
- **Learning process may converge to some local optimum rather than the true global optimum or may not converge at all**
- **Currently, no analytical or formal method exists for verification of parameter convergence to the correct solution within a given time**
- **Stability of adaptive systems remains a difficult problem**



Non-Determinism

- **Non-determinism denotes the ability to predict the action of an adaptive system based on some initial inputs – e.g., neural network initialization with random weights**
- **In theory, adaptive control systems can be designed to be deterministic – e.g., avoid use of neural network and initialization with pre-determined weights**
- **In practice, “*stochastic processes such as atmospheric turbulence, process noise, and reasoning processes such as due to diagnostics/prognostics can also be sources of non-determinism*” (AIAA Roadmap for Intelligent Systems in Aerospace, 2016)**

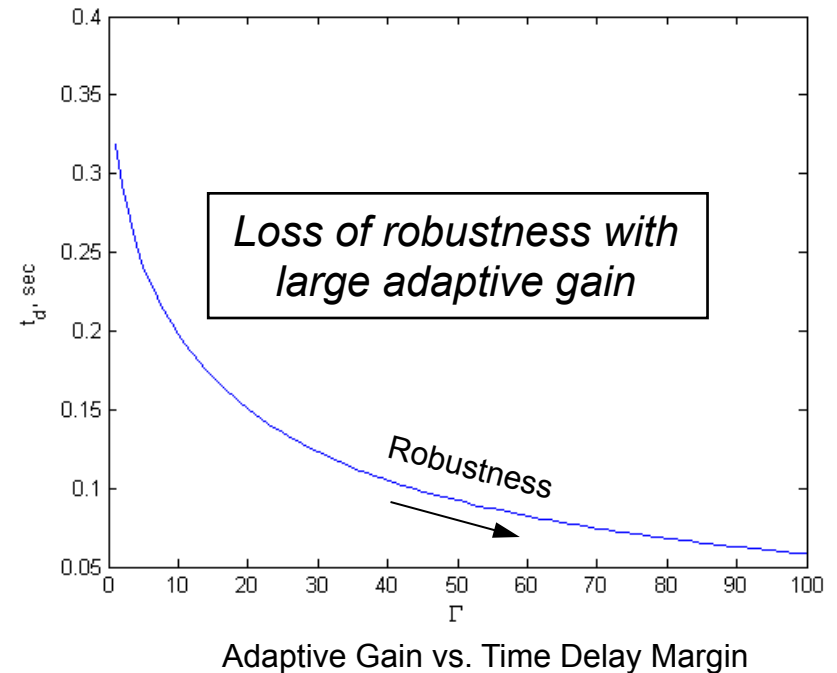


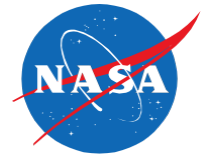
Robustness Issues

- Robustness is the ability to tolerate physical effects not included in design (disturbances, unmodeled dynamics, pilot interaction, etc)
- Fundamental stability requirement can be degraded by lack of robustness
 - ▶ Crash of NASA X-15



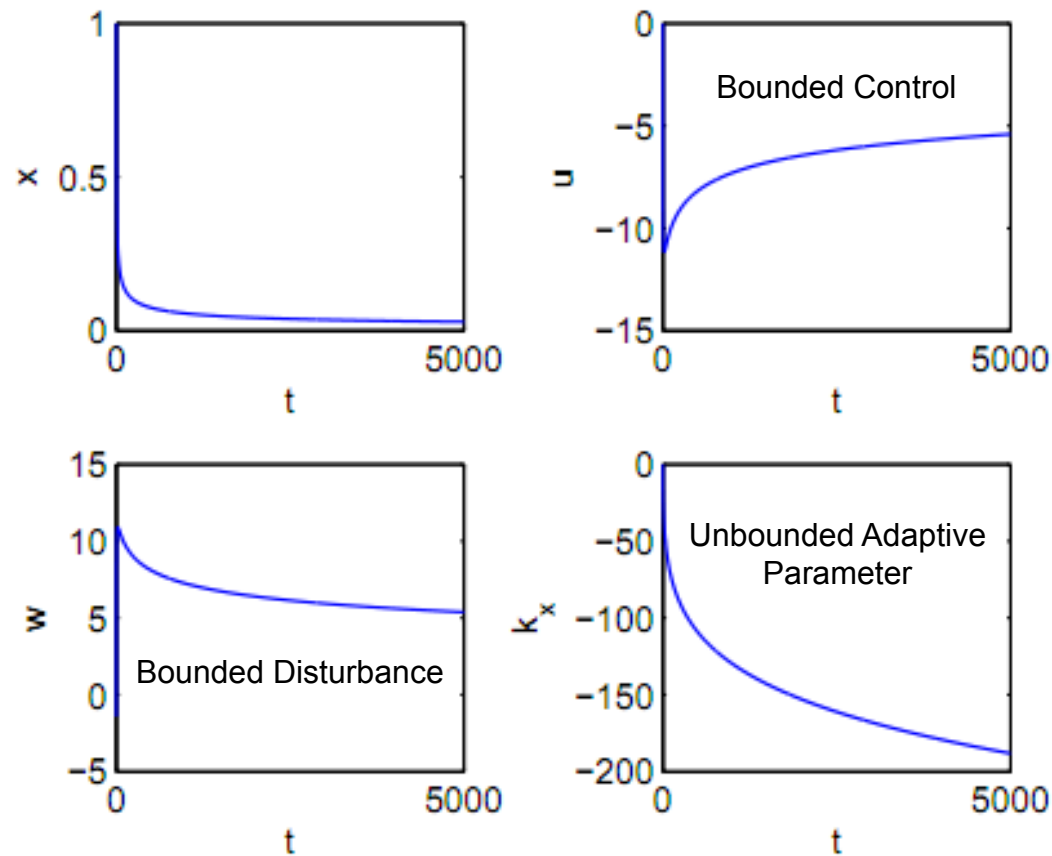
- Adaptive control is inherently non-robust
 - ▶ Parameters can grow unbounded





Parameter Drift

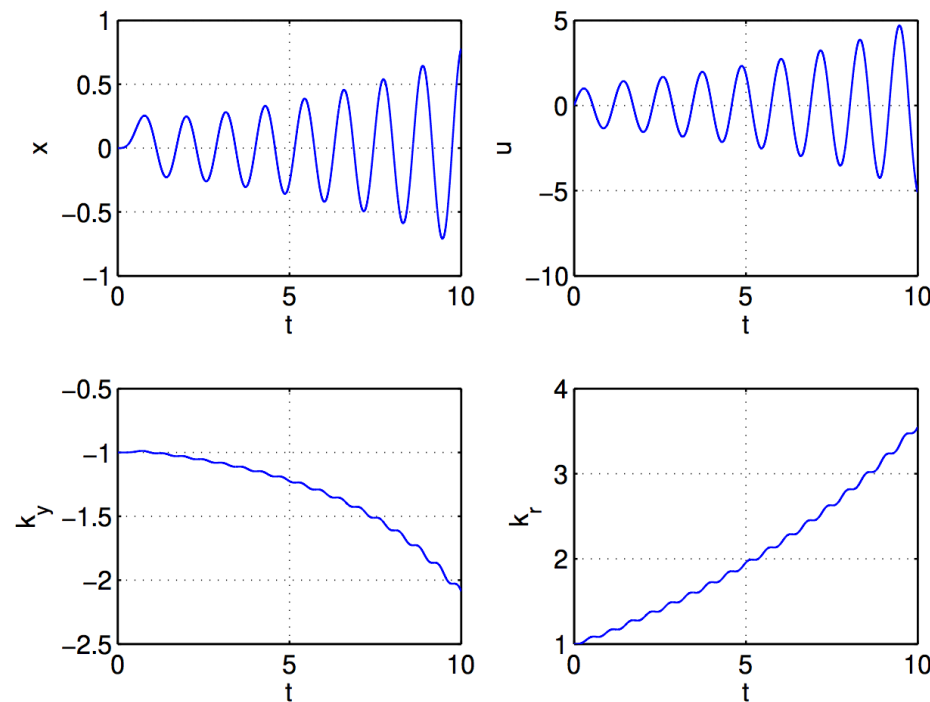
- The ideal asymptotic tracking property of adaptive control is highly desirable for performance, but at the same time creates robustness issue with parameter drift in the presence of exogenous disturbances





Interaction with System Dynamics

- Unmodeled / uncertain dynamics destroys ideal property of adaptive control in model following, thereby potentially leading to instability
- Systems can diverge in myriad ways in the presence of unmodeled dynamics

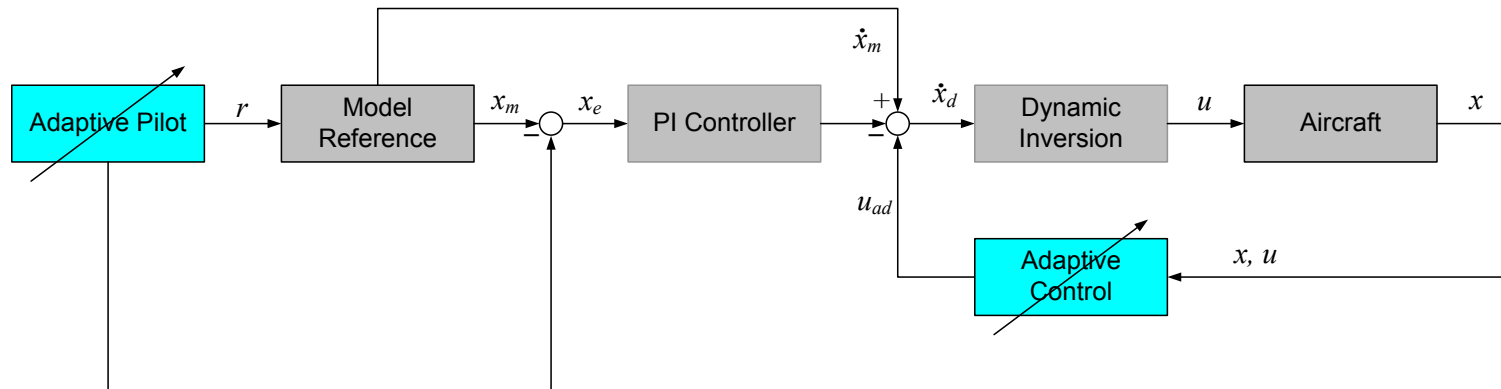


Instability Due to Command at Zero Phase-Margin Frequency



Human Interactions

- **Human interactions with adaptive systems can cause unpredictable and undesirable behaviors due to response latency and lack of situational awareness**
 - ▶ Predator B mishaps during landing (*Human Factors of UAVs: "Manning the Unmanned"*)
 - ▶ Pilot-induced oscillations during NASA IFCS program in mid 2000's

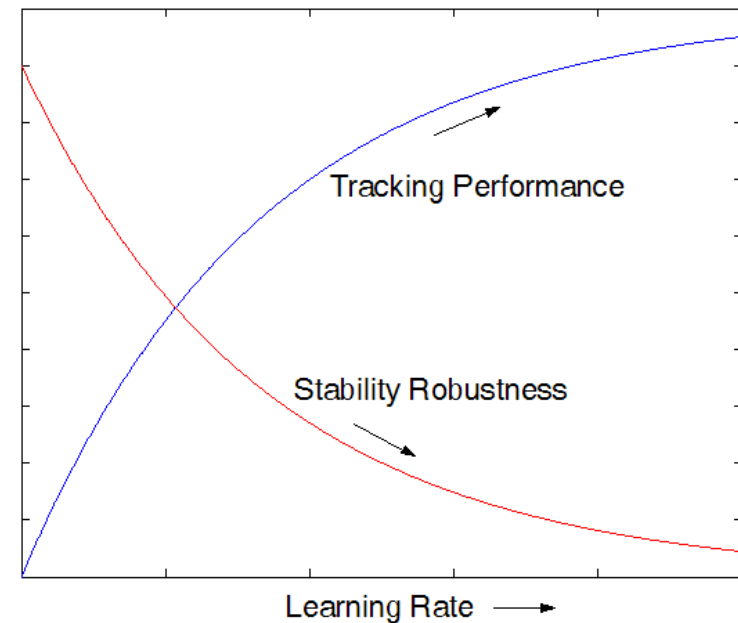


- **Adaptive control technology cannot be fully matured without consideration of closed-loop dynamics of the human**
 - Effects of interaction on system behaviors can be unpredictable
 - Closed-loop human interactions can reveal important features that need to be factored into design



Bounding Mechanisms

- **Adaptive parameter bounding mechanisms**
 - ▶ Robust modification to provide damping mechanisms
 - ▶ Projection method to enforce explicit a priori known bounds on adaptive parameters
- **Increased robustness, but command following degrades - fundamental design trade-off**
- **Stability can still be an issue if system dynamics change substantially in off-nominal operation**





Certification Gaps

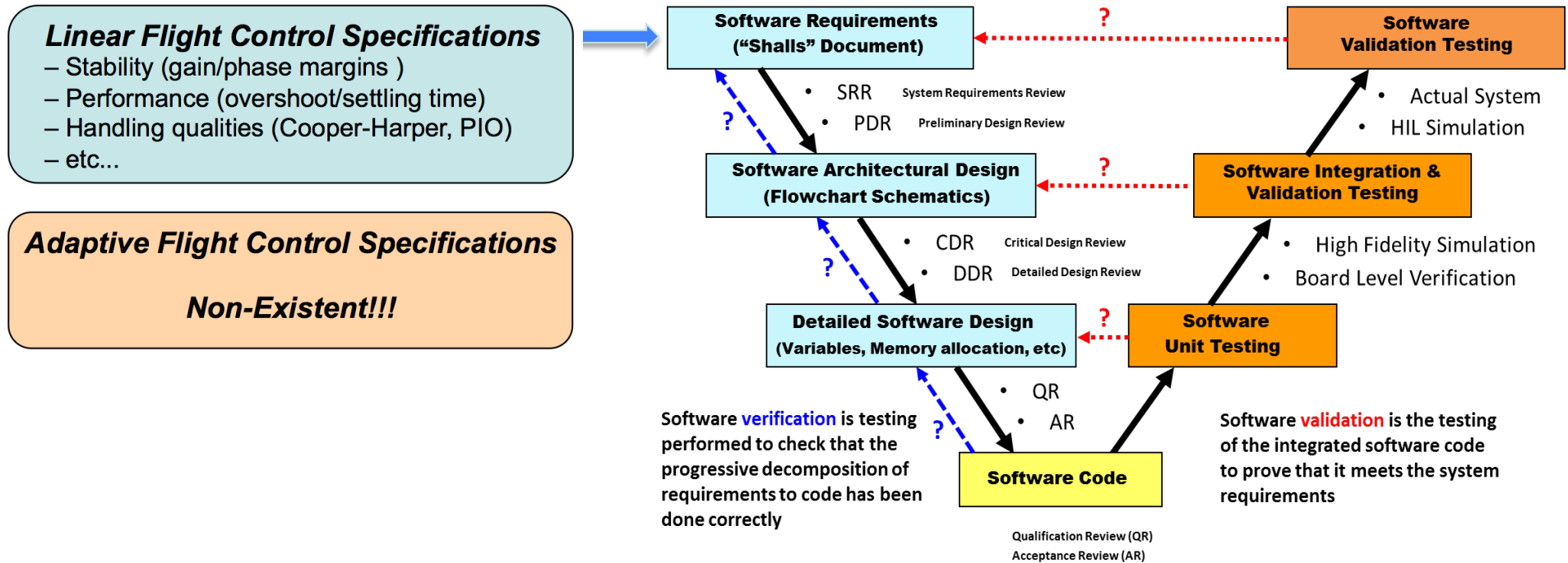
- **In spite of potential benefits of adaptive control, no adaptive flight control software has been certified for use in commercial airspace**
- **Software approval process defined by FAA requires flight critical software to meet RTCA DO-178C guidelines or other methods accepted by FAA**
 - ▶ Does not address adaptive flight control which is fundamentally different from traditional gain-scheduled control
- **Certification gaps**

- ▶ Gap 1 - Lack of adaptive control design requirements
- ▶ Gap 2 - Difficulty in proving adaptive control stability
- ▶ Gap 3 - High-fidelity benchmark simulations
- ▶ Gap 4 - On-line assurance monitoring tools
- ▶ Gap 5 - Development of certification plan for adaptive control

Jacklin, S., "Closing the Certification Gaps in Adaptive Flight Control Software,"
AIAA Guidance, Navigation, and Control Conference, AIAA-2008-6988, 2008

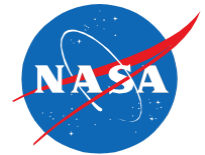


Gap 1 - Adaptive Control Requirements



Jacklin, S. A., “Small Satellite Software Architecture, Verification, and Validation,” NASA TM TBD

Verifiable metrics for specification of adaptive control design requirements must be developed in order to enable the introduction of this technology into future flight systems



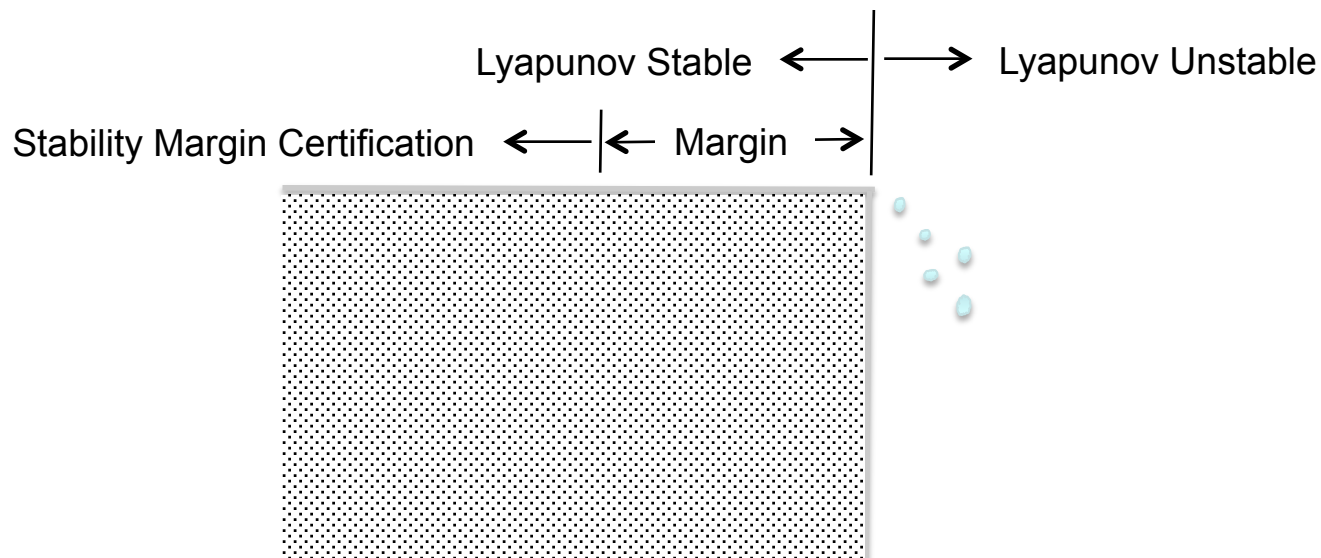
Development of Metrics

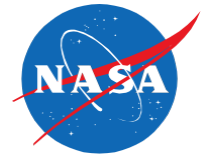
- **Metrics are set of criteria which can be used for establish trust certificates**
 - **NASA developed some initial metric definitions for adaptive control in 2009**
 - ▶ Stability margin
 - ▶ Transient performance
 - ▶ Steady-state error
 - ▶ Control limiting
- Stepanyan, V., Krishnakumar, K., Nguyen, N., Van Eykeren, L., "Stability and Performance Metrics for Adaptive Flight Control," AIAA Guidance, Navigation, and Control Conference, AIAA-2009-5965, 2009
- **Metrics need to be validated by simulations and flight tests**
 - **Metrics must be well-accepted by community of practitioners and theoretically rigorous but yet easy to implement by engineers**
 - ***“Develop performance criteria, such as stability, robustness, and resilience, for the analysis and synthesis of adaptive/nondeterministic behaviors” (Autonomy Research for Civil Aviation – Toward a New Era of Flight, 2014)***



Gap 2 - Stability Analysis

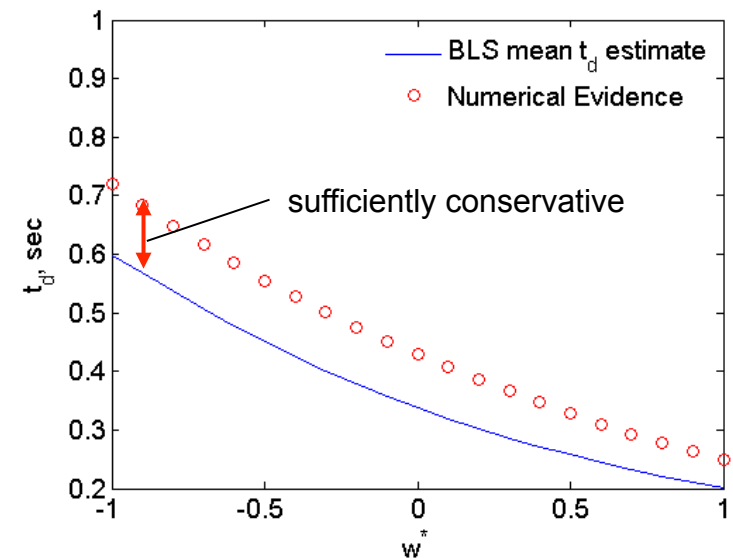
- **Stability of adaptive systems under wide ranging situations is difficult to assess**
- **Factors that can affect stability**
 - ▶ Inputs to adaptive law
 - ▶ Pilot commands
 - ▶ Initial conditions of vehicle states
 - ▶ Parameter convergence
 - ▶ Human interactions
- **Standard Lyapunov theory cannot predict how close a system is away from instability – notion of stability margin is missing**





Development of Analytical Tools

- **Analytical tools for stability analysis is not well matured**
 - ▶ Divergent interest between academia and flight control practitioners
- **Some analytical predictions based on Lyapunov theory can be too conservative, hence not practical**
- **Some techniques for adaptive systems**
 - ▶ Gap metric
 - ▶ Bounded linear stability analysis
- **Fundamentally difficult to apply in practical control setting**
- **This is viewed perhaps as one of the biggest barriers in adaptive systems**



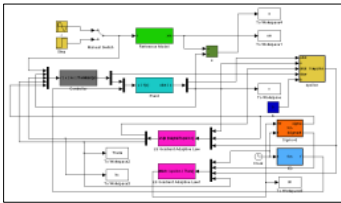
Nguyen, N., Bakhtiari-Nejad, M., Huang, Y., "Hybrid Adaptive Flight Control with Bounded Linear Stability Analysis," AIAA Guidance, Navigation, and Control Conference, AIAA-2007-6422, 2007

Need to develop practical analytical tools for adaptive control that can gain wide acceptance by community



Gap 3 - Benchmark Simulations

- **DO-178C allows certification credit for high-fidelity simulations as well as flight validation**



Model Fidelity	Simulation Type & Test Bed
Low	Desk Top Computer (Matlab-Simulink)
Low-Medium	Work Station (nonlinear models)
Medium	Simulation with Target Flight Computer
Medium	Sub-Scale Aircraft (UAV, RPV)
Medium-High	Hardware-in-the-Loop (cockpit + FC)
Medium-High	Aircraft-in-the-Loop Simulator (Iron Bird)
Medium-High	Motion-Based Flight Simulator
High	Full-Scale Aircraft

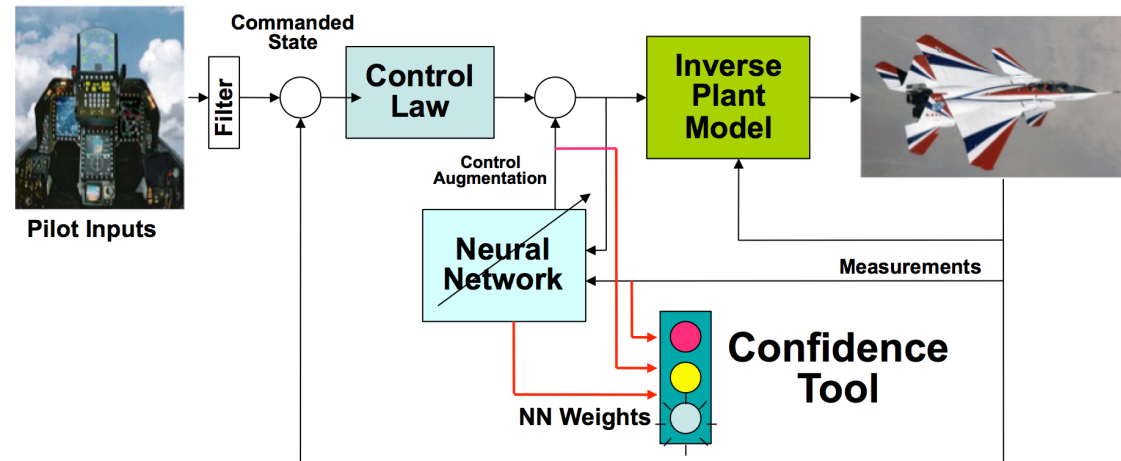


- **There is no standardization of benchmark simulations**
 - ▶ Difficult to assess relative merits of different adaptive control technologies
 - ▶ Difficult for certification authorities to assess which simulations are adequate references or benchmarks



Gap 4 – On-Line Assurance Monitoring Tools

- Simulations may discover problems, but they can never prove the absence of all problems
- State space explosion can result in order to cover all possible scenarios in Monte Carlo simulations to find hidden faults
- On-line monitoring tools can provide prognostics of potential problems, but the challenges are to know what to monitor and how to make meaningful inference



The Confidence Tool, based on a Bayesian approach, provides a measure of how well the neural network is performing at the moment



What Requirements Form a Complete Set?

- **Flight Environment**
 - ▶ Turbulence / wind gust
 - ▶ Buffet
 - ▶ Air data
- **Vehicle**
 - ▶ Unmodeled / uncertain dynamics
 - ▶ Actuator / sensor dynamics
 - ▶ Changes in vehicle dynamics
 - ▶ Structural load limits
 - ▶ Pilot coupling
- **Control architecture**
 - ▶ Redundancy management – ensure that adaptation does no harm
 - ▶ Adaptation to off-nominal flight events
 - ▶ Adaptation to bad data such as sensor noise, electrical glitches
 - ▶ Control authority degradation
 - ▶ Communication / computational latency

Requirements are required to be correct and complete in DO-178C which can be difficult for adaptive systems



How to Validate?

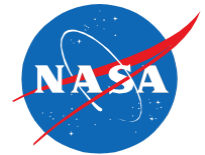
- **Rely on proven methods and simplify design**
 - ▶ Leverage existing certification tools and methods for certifiable systems to maximum extent possible
 - ▶ Simplify adaptive system design with as few adaptive parameters as possible and reduce or eliminate sources of non-determinism
- **Use established V&V methods**
 - ▶ Safety case (review assumptions)
 - ▶ Formal / analytic methods
- **Establish metrics for certification**
 - ▶ Stability
 - ▶ Performance
 - ▶ Robustness / sensitivity
- **Establish interdisciplinary control-theoretic, system modeling, and software V&V approaches**



Recommendations

- **NRC Autonomy Research for Civil Aviation – Toward a New Era of Flight**
 - ▶ *Develop Methodologies to Characterize and Bound the Behavior of Adaptive/Nondeterministic Systems over Their Complete Life Cycle*
 - *Develop mathematical models for describing adaptive/nondeterministic processes as applied to humans and machines*
 - *Develop performance criteria, such as stability, robustness, and resilience, for the analysis and synthesis of adaptive/nondeterministic behaviors*
 - *Develop methodologies beyond input-output testing for characterizing the behavior of IA systems*
 - *Determine the roles that humans play in limiting the behavior of adaptive/nondeterministic systems and how IA systems can take over those roles*

- **AIAA Roadmap for Intelligent Systems in Aerospace**
 - ▶ *Research investment areas*
 - *Multidisciplinary Modeling & Simulation Technologies*
 - *Vehicle Performance-Driven Adaptive Systems*
 - *Resilient Multidisciplinary Control System Technologies*
 - *Safety Monitoring, Assessment, & Management*
 - *Validation Technologies for Complex Integrated Deterministic and Stochastic Systems*



Concluding Remarks

- **Adaptive control is a promising revolutionary technology with cross-cutting applications in many different facets of aerospace industry including UAS and UAM**
- **Adaptive systems are widely recognized as critical capabilities for complex autonomous systems**
- **In spite of potential benefits, implementation challenges exist**
- **V&V challenges are numerous due to the complex learning algorithms for adaptive systems**
- **Recognizing adaptive systems as a R&D priority is important in development of certification process for future applications of adaptive control in safety-critical systems**