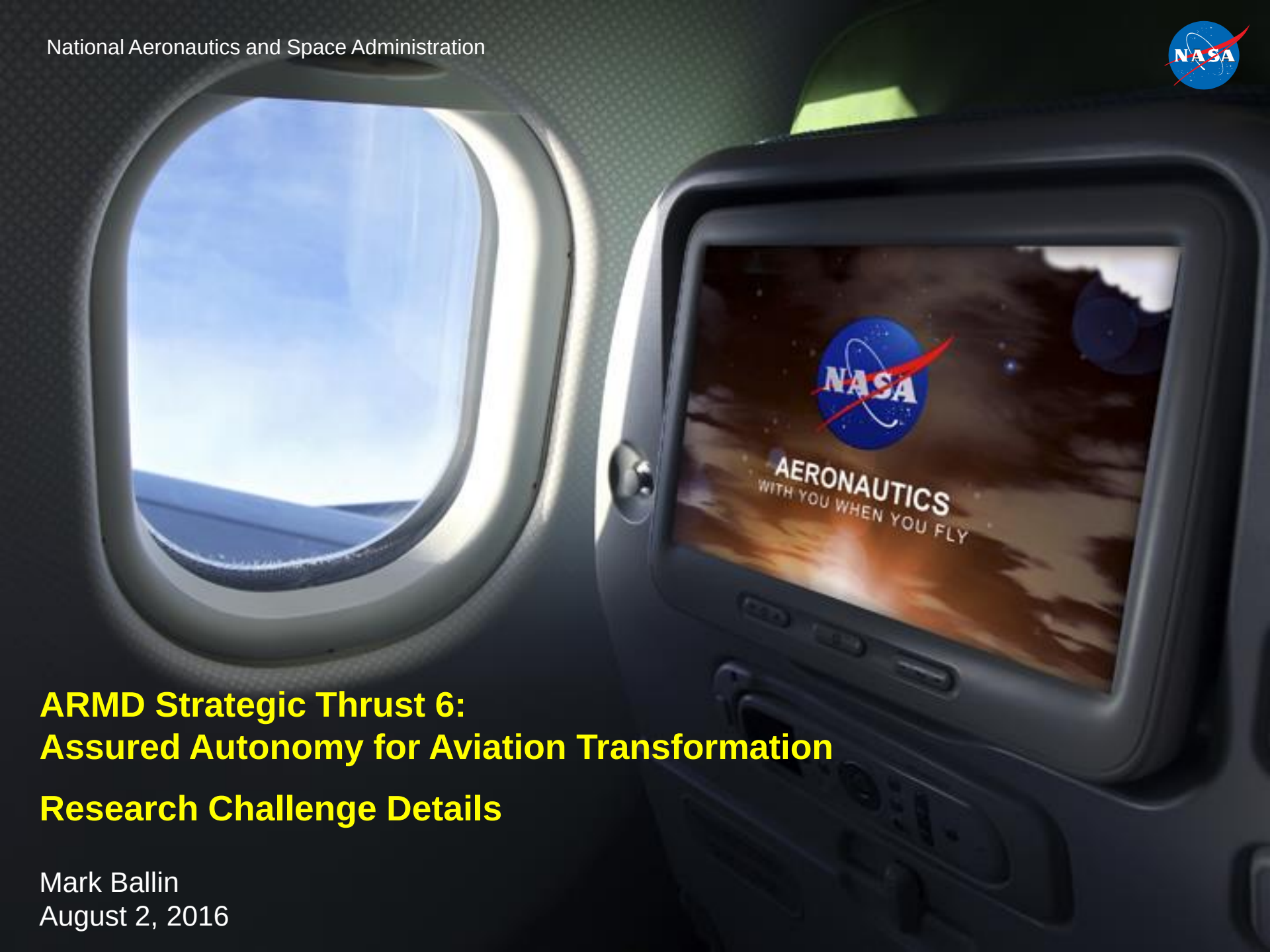
National Aeronautics and Space Administration



ARMD Strategic Thrust 6: Assured Autonomy for Aviation Transformation

Research Challenge Details

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Strategic Thrust 6 Research Challenges

Research Themes	2015	2025	2035
	Introduction of aviation systems with bounded autonomy, capable of carrying out function-level goals	Introduction of aviation systems with flexible autonomy based on earned levels of trust, capable of carrying out mission-level goals	Introduction of distributed collaborative aviation systems with assured autonomy, capable of carrying out policy-level goals
Technologies and Methods for Design of Complex Autonomous Systems	1A. Develop machine intelligence design methods that are robust to system failures and system integrity threats		1F. Develop design methods for adaptive/non-deterministic machine intelligence
	1C. Develop machine intelligence design methods for unforeseen events in complex environments		
	1B. Develop technologies to support machine sensation, perception, and low-level cognition	1E. Develop technologies to support machine reasoning and decision making	
	1D. Develop technologies to support system-state management and optimization		1G. Develop technologies for self-healing systems
	1H. Develop technologies to support collaboration between autonomous systems		
Assurance, Verification, and Validation of Autonomous Systems	2A. Develop methods for characterizing the behavior of increasingly autonomous and collaborative systems	2D. Develop methods and standards for maintaining real-time trustworthiness of increasingly autonomous systems in complex environments	
	2B. Develop methods and standards for assuring trustworthiness of increasingly autonomous systems		2E. Develop methods and standards for maintaining real-time trustworthiness of adaptive/non-deterministic collaborative systems
	2C. Develop certification methods for safe deployment of increasingly autonomous systems		
Human-Autonomy Teaming in Complex Aviation Systems	3A. Develop methods and guidelines for assigning roles to humans and increasingly autonomous systems in realistic operating conditions		3E. Develop methods to determine which human capabilities remain necessary / add value to the aviation system
	3D. Develop methods and technologies to support teaming between humans and increasingly autonomous systems in normal and non-normal operations		
	3B. Develop framework for introducing increasingly autonomous systems that matches role and authority with earned levels of trust		
	3C. Develop technologies to enable real-time situation understanding between human operators and increasingly autonomous systems		
Implementation and Integration of Autonomous Airspace and Vehicle Systems	4A. Develop methods to evaluate the viability & impacts (e.g., societal, economic, technological) of increasingly autonomous aerospace vehicles & operations	4E. Identify infrastructure to support flexible, large-scale, cooperative autonomous systems	4G. Identify infrastructure to support adaptive, system-wide collaborative autonomous systems
	4B. Select, develop, and implement applications of autonomy that are compatible with existing systems	4F. Select, develop, and implement applications of autonomy that enable flexible, large-scale aerospace vehicle cooperation	4H. Select, develop, and implement applications of autonomy that enable adaptive, collaborative aerospace operations on a system-wide scale
	4C. Develop framework for co-development of policies, standards, and regulations with development and deployment of increasingly autonomous systems		
	4D. Assess candidate technology development and transition paths for the future of aviation autonomy		
Testing and Evaluation of Autonomous Systems	5A. Develop metrics, methods and capabilities to assess feasibility, safety, resilience, robustness, trust, performance, and human interactions with increasingly autonomous systems		
	5B. Test, evaluate & demonstrate selected small-scale applications of autonomy	5C. Test, evaluate and demonstrate selected flexible, cooperative applications of autonomy to support large-scale operations	5D. Test, evaluate and demonstrate selected adaptive, collaborative applications of autonomy to support system-wide operations

Research Challenge Details

- The following charts provide sub-challenges for each overarching technical research challenge
- Notes sections of each chart show applicable statements from reference documents

1A. Develop machine intelligence design methods that are robust to system failures and system integrity threats

- Develop methods for design of autonomous systems that
  - Monitor for and detecting system degradation
  - Define recovery paths in degraded modes of operation
  - Define prerequisites for the human role in recovery from system degradation
  - Assess the abilities of human operators to participate in recovery from system degradation, and execute mitigation strategies if humans cannot participate
- Develop design methods for intelligent systems to ensure restoration of unsafe system behavior to a safe operating state
- Develop design methods for increasingly autonomous systems that respond safely to the degradation or failure of aircraft systems
- Develop design methods for intelligent aviation systems to detect and mitigate external adversarial threats, including threats from cyber attacks that either degrade functionality or assume control

1B. Develop technologies to support machine sensation, perception, and low-level cognition

- Develop new sensor systems and mechanisms applicable to aviation environments to generate data to be used by autonomous systems
- Develop the capability to generate accurate predictive models of the surrounding world by conducting multisensory data fusion and converting these data into meaningful information that supports decision-making processes applicable to aviation autonomy functions
- Develop machine-based capabilities that create and maintain situational awareness to support requirements of aviation autonomy functions
- Develop machine-based low-level cognitive functions, such as conflict detection, prioritization, and mitigation, so they do not need continuous human oversight

1C. Develop machine intelligence design methods for unforeseen events in complex environments

- Develop and validate intelligent systems for application to aviation autonomy that
  - Identify and mitigate high-risk situations induced by the mission, the environment, or other elements of the NAS
  - Handle rare and un-modeled events with the goal of ensuring safety, and if possible, accomplishing the mission
  - Mitigate or adapt to emergent system states due to airspace system complexity
  - Are robust to dynamic changes in the environment, mission expectations, or the systems themselves
  - Handle failure modes that have not been identified or considered by system designers
- Develop and validate technologies that augment human operators in adapting to unforeseen dynamic changes

1D. Develop technologies to support system-state management and optimization

- Develop and validate intelligent systems for application to aviation autonomy that
  - Perform autonomous detection and isolation of system faults
  - Respond safely to the degradation or failure of aircraft systems
  - Restore unsafe intelligent system behavior to a safe state
  - Define prerequisites for the human role in recovery from system degradation
  - Assess the abilities of human operators to participate in recovery from system degradation, and execute mitigation strategies if humans cannot participate
- Develop and validate technologies that enable the ability to provide adaptability to dynamically changing operating environments to improve performance and operational efficiency of advanced aerospace vehicles

1E. Develop technologies to support machine reasoning and decision making

- Apply computational intelligence techniques that efficiently explore large solution spaces to provide real-time decision-making for intelligent aerospace systems
- Develop methods and technologies for calculating, negotiating and accepting bounds on risk for different systems, platforms and scenarios involving autonomous systems
- Develop and validate intelligent systems for aerospace autonomy that enable capture of multi-dimensional knowledge representations and knowledge engineering to improve decision options
- Develop and apply machine architectures that achieve safety-critical computations in real-time by resource-constrained autonomous agents
- Determine methods and technologies for multi-objective decision-making and optimization that do not require, and are not limited by, human decision-making

1F. Develop design methods for adaptive/non-deterministic machine intelligence

- Develop design methods to ensure autonomous systems maintain behavioral predictability as they change in response to learning
- Develop mathematical models for describing adaptive/nondeterministic processes as applied to autonomous systems, including combined human/machine systems
- Develop theories and methodologies that will enable modeling and simulation to serve as embedded components within adaptive/nondeterministic systems

1G. Develop technologies for self-healing systems

- Through direct research and application of external research for analogous systems, establish a technical foundation for self-configuring and self-optimizing aviation systems
- Through direct research and application of external research for analogous systems, establish a technical foundation for self-protecting and self-healing aviation systems
- Develop technologies to enable self-configuring and self-optimizing large-scale distributed aviation systems and system elements
- Develop technologies to enable self-protecting and self-healing large-scale distributed aviation systems and system elements

1H. Develop technologies to support collaboration between autonomous systems

- Develop methods and technologies for autonomous negotiation between multiple stakeholders within distributed collaborative aviation systems
- Develop and validate intelligent systems for aerospace autonomy that enable ability to handle heterogeneous, multi-agent cooperation so each agent can achieve its objectives
- Develop and validate intelligent systems for aerospace autonomy that enable ability to handle heterogeneous, multi-agent collaboration to achieve common objectives
- Develop methods and design tools that enable the efficient and effective creation of joint human-machine cognitive systems
  - Humans and machines collaborate to achieve objectives
  - Autonomous systems act in ways that are seen as logical by human agents
  - Autonomous systems are capable of predicting human intent as required for effective teaming and achievement of objectives
- Develop technologies to support real-time assessment of confidence levels to maintain trust between agents

Assurance, Verification, and Validation of Autonomous Systems

2A. Develop methods for characterizing the behavior of increasingly autonomous and collaborative systems

- Develop methodologies beyond input-output testing for characterizing the behavior of increasingly autonomous systems
  - Develop and demonstrate applications of runtime assurance methods that detect and avert unsafe results
  - Establish methods and metrics to infer when an intelligent system can be relied on for safety critical function
  - Establish systems that incorporate probabilistic or uncertain models into verification and validation
  - Define test cases and expected results that overcome the difficulty of enumerating all conditions and non-deterministic responses that autonomous systems will generate in response to complex environments
  - Develop methods to move from hardware-oriented verification, validation, and certification processes to ones that address the primacy of software in creating autonomous systems
- Identify the possible consequences of unmanaged autonomy, such as
  - Unmanaged Complexity – concern that the exceedingly large, complex and coupled decision state space makes behavior prediction, verification and validation all but impossible
  - Unintended Consequences – concern that unpredicted emergent behavior will negatively impact the system or human operators

Assurance, Verification, and Validation of Autonomous Systems

2B. Develop methods and standards for assuring trustworthiness of increasingly autonomous systems

- Develop verification and validation methods for autonomous systems to assure trustworthiness given non-repeatable results or large system complexity
- Characterize and define requirements for intelligent software and systems
- Develop automatic and robust techniques to specify and manage integrity levels in requirements specification
- Develop standards and methodologies for accrediting increasingly autonomous models and simulations

Assurance, Verification, and Validation of Autonomous Systems

2C. Develop certification methods for safe deployment of increasingly autonomous systems

- Develop, assess, and propose new certification standards for autonomous systems operating under uncertain, unexpected, and hazardous conditions
  - Develop approaches for maintaining certification of adaptive systems throughout the system's lifecycle
- Develop certification methods for autonomous systems created using nontraditional methodologies and technologies
- Develop certification standards for effective operation of human-machine teams
  - E.g., in response to failures in communication or failures in capability of an agent
- Develop approaches to certification that allow flexibility while controlling costs

Assurance, Verification, and Validation of Autonomous Systems

2D. Develop methods and standards for maintaining real-time trustworthiness of increasingly autonomous systems in complex environments

- Develop and validate advanced formal methods for highly non-deterministic systems operating in complex environments
- Identify and address the impact that airspace system complexity has on verification, validation, and certification
- Develop and validate methods to ensure autonomous systems do not create unintended consequences due to emergent behavior

Assurance, Verification, and Validation of Autonomous Systems

2E. Develop methods and standards for maintaining real-time trustworthiness of adaptive/non-deterministic collaborative systems

- Develop verification and validation methods for autonomous systems that interact with dynamic environments in a non-deterministic manner
  - Determine if existing methods can be adapted or if new methods for V&V of autonomous systems are needed
- Identify issues and solutions to address vulnerability of distributed autonomous systems to all forms of cyber attacks

3A. Develop methods and guidelines for assigning roles to humans and increasingly autonomous systems in realistic operating conditions

- Define the rationale and criteria for assigning roles to key personnel and increasingly autonomous systems
- Identify how roles and responsibilities of the human and autonomy should change in the future
  - Determine how roles should change as a function of the mission, capabilities, and limitations of autonomous systems
  - Determine what the human operator's temporal requirements should be for supervision of autonomous systems
  - Determine whether (or how) autonomous systems should be designed in a way that preserves the human operator's flexibility to intervene to "save the day" when necessary
  - Determine how characteristics of autonomous systems impact operator situational awareness, attention, workload, fatigue, and boredom
- Identify methods to assess the abilities of humans and autonomous systems to perform assigned roles under realistic operating conditions
- Determine where increasingly autonomous systems could prevent or mitigate the severity of specific accidents or classes of accidents

3B. Develop framework for introducing autonomy that matches role and authority with earned levels of trust

- Develop approaches for establishing trust in increasingly autonomous systems
  - Determine the ways in which trust-related information is communicated between humans and autonomous systems
  - Identify methods to ensure that autonomous systems act and communicate in a manner that is compatible with the operator's calibration of the system's capabilities
- Identify methods to ensure transitions of authority from autonomy-to-human (and vice versa) are unsurprising, informative, and safe
  - Develop mechanisms for transfer of control and delegation between humans and autonomous systems that support shared situational awareness
  - Identify methods to ensure graceful degradation of capability when the work performed by the autonomous system must be transferred back to a human counterpart
- Develop human factors standards to address part-time monitoring of safety-critical functions

3C. Develop technologies to enable real-time situation understanding between human operators and increasingly autonomous systems

- Develop and validate new paradigms, technologies, displays, and interfaces that
  - Ensure effective bidirectional communication between autonomous systems and human operators
  - Enable communication of intent between autonomous systems and human operators
  - Enable human operators to query an autonomous system to understand the basis for an action
  - Enable autonomous systems to correctly predict human intent
  - Enable natural language understanding by autonomous systems

3D. Develop methods and technologies to support teaming between humans and increasingly autonomous systems in normal and non-normal operations

- Develop and validate human-machine interfaces that are
  - Designed for effectively managing uncertainty and failure in communication
  - Designed to support real-time decision making, particularly in high-stress, dynamic situations
  - Designed to support operation of advanced increasingly autonomous systems during normal and atypical operations
  - Designed for management of multiple mission-oriented intelligent aerospace systems that can learn and adapt from human-decision-making
  - Designed to take advantage of natural modes of human communication and interaction
- Develop and validate operational training techniques for
  - Operators chosen to work with new autonomous systems or subsystems
  - Explicitly building trust in autonomous systems
  - For using modeling and simulation to coach human operators and adaptive autonomous systems

3E. Develop methods to determine which human capabilities remain necessary / add value to the aviation system

- Develop methods to determine, across the range of civil aviation missions and autonomous system capabilities, which human capabilities remain necessary and add value
- Determine the roles that humans play in limiting the behavior of adaptive/nondeterministic systems and how increasingly autonomous systems can take over those roles when appropriate

Implementation and Integration of Autonomous Airspace and Vehicle Systems

4A. Develop methods to evaluate the viability & impacts (e.g., societal, economic, technological) of increasingly autonomous aerospace vehicles & operations

- Develop methods to evaluate component-level, vehicle-level and system-level risks for autonomous systems with new interdependencies and new relationships among the various operational elements
- Develop methods to define and evaluate system-level impacts of autonomous systems on civil aviation, including equitability, agility, adaptability, scalability, and resilience, along with possible tradeoffs across those system characteristics
- Evaluate concerns with public acceptance of civil aviation autonomy, including privacy and safety concerns
- Identify areas within civil aviation where autonomy in operations is desired and desirable

4B. Select, develop, and implement applications of autonomy that are compatible with existing systems

- Develop approaches to ensure that autonomous systems are backward-compatible with legacy airframes, ATM systems, and other elements of the civil airspace
- Develop approaches to support integration of information within and across platforms
  - Sensor integration within a single platform
  - Information integration across vehicles with varying levels of advancement in communication, navigation, and surveillance systems
  - Information integration between ground-based and airborne systems
  - Communication and coordination across complex distributed networks that include both machines and humans
- Develop approaches for maintaining data integrity across integrated autonomous systems

4C. Develop framework for co-development of policies, standards, and regulations with development and deployment of increasingly autonomous systems

- Conduct research to address moral, legal, and regulatory issues/barriers associated with introduction and operation of autonomous systems in civil airspace
- Develop safety standards for autonomous aerial systems that specifically address the safety of personnel in other aircraft and on the ground
- Develop data exchange standards for distributed autonomous systems to facilitate system-wide stability and resilience
- Develop autonomous system interface standards for modularization (e.g., along the lines of “plug and play”)
- Develop autonomous system software standards focused on affordability

4D. Assess candidate technology development and transition paths for the future of aviation autonomy

- Conduct trade studies, alternative concept/algorithm/technology analysis, and algorithm/technology development for various candidate futures and airspace uses
- Identify and assess transition paths from current operations to a future that incorporates increasingly autonomous systems
- Develop understanding of the design space and tradeoffs for incorporating autonomy into a mission
- Examine the use of open-source products for non-safety-critical and safety-critical applications
  - Develop paths for migrating open-source, intelligent software to non-safety critical and safety-critical applications
- Develop and mature nontraditional software languages for increasingly autonomous applications

4E. Identify infrastructure to support flexible, large-scale, cooperative autonomous systems

- Investigate airspace structures that could support UAS operations in confined or preapproved operating areas using methods such as geofencing
- Investigate airspace structures and operating procedures to ensure safe and efficient operations of legacy and increasingly autonomous systems in the NAS
- Develop an open architecture software structure to facilitate adaptation to evolving requirements and addition of new capabilities after deployment
- Develop strategies and technologies to address the increased demand for wireless communications that will accompany increased use of unmanned aircraft in civil airspace
- Develop sensor technologies that
    1. Are extremely low energy or energy harvested sensors
    2. Have highly efficient sensor communication
    3. Have high availability
    4. Are highly secure
    5. Are globally spectrum compliant
- Develop a common design tool/language base that applies to complex safety-critical autonomous systems

Implementation and Integration of Autonomous Airspace and Vehicle Systems

4F. Select, develop, and implement applications of autonomy that enable flexible, large-scale aerospace vehicle cooperation

- Identify nominal and off-nominal scenarios that autonomous systems must satisfy
- Develop and validate autonomous systems that enable the ability to handle heterogeneous, multi-vehicle cooperation
- Identify services that should be provided by autonomous systems

4G. Identify infrastructure to support adaptive, system-wide collaborative autonomous systems

- Investigate airspace structures and operating procedures to ensure safe and efficient operations of legacy and increasingly autonomous systems in the NAS
- Develop an open architecture software structure to facilitate adaptation to evolving requirements and addition of new capabilities after deployment
- Develop strategies and technologies to address the increased demand for wireless communications that will accompany increased use of unmanned aircraft in civil airspace
- Develop a common design tool/language base that applies to complex safety-critical autonomous systems

Implementation and Integration of Autonomous Airspace and Vehicle Systems

4H. Select, develop, and implement applications of autonomy that enable adaptive, collaborative aerospace operations on a system-wide scale

- Identify nominal and off-nominal scenarios that autonomous systems must satisfy
- Develop and validate autonomous systems that enable adaptation to dynamic changes in the environment, mission and platform
- Identify services that should be provided by autonomous systems

Testing and Evaluation of Autonomous Systems

5A. Develop metrics, methods and capabilities to assess feasibility, safety, resilience, robustness, trust, performance, and human interactions with increasingly autonomous systems

- Develop techniques and strategies to enable or accelerate experimentation, flight testing, and deployment of nontraditional technologies
- Develop metrics and methods for measuring the following properties of autonomous systems:
  - Feasibility
  - Resilience
  - Stability
  - Robustness
  - Effect on overall system safety
  - Effect on overall system efficiency
  - Effect on human performance
  - Ability to adapt in dynamic conditions
  - Ability to coordinate with other human and machine systems
  - User's trust in the system
  - Viability
- Develop and enhance modeling and simulation capabilities to predict and demonstrate
  - Performance impacts of autonomous system concepts
  - Possible unintended consequences associated with autonomous system concepts
- Establish and maintain relevant testbeds for developing and testing autonomous system concepts
  - Develop and regularly update standardized modules for common testbed components

Testing and Evaluation of Autonomous Systems

5B, 5C, & 5D. Test, evaluate & demonstrate selected applications of autonomy

- Develop modeling and simulation capabilities that can generate performance data and demonstrate the behavior of autonomous systems over a wide range of operational scenarios
- Utilize small unmanned aerospace systems to demonstrate the reliability and safety of autonomous operations
- Identify operational insertion opportunities to generate performance data and demonstrate the behavior of autonomous components and systems in actual operations, beginning with non-safety critical applications of autonomy