National Aeronautics and Space Administration

ARMD Strategic Thrust 6: Assured Autonomy for Aviation Transformation

Roadmap, Part 1: Vision and Research Challenges

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Strategic Thrust 6
Assured Autonomy for Aviation Transformation

Autonomy is the ability to achieve goals while operating independently from external control. (adapted from 2015 NASA OCT Roadmap)

- Supervision Level
- Goal Specification Level
- World View
- Collaboration Level

- **Deliberative Layer**
  - Risk Awareness
- **Habitual Layer**
  - Adaptivity
- **Reflexive Layer**
  - Quick responsiveness

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The objective of Strategic Thrust 6 is to enable autonomous systems that employ highly intelligent machines to maximize the benefits of aviation to society.

- NASA Aeronautics Strategic Implementation Plan, 2015

- Emphasis on human/machine continuum over self-governance continuum
- Emphasis on societal benefits

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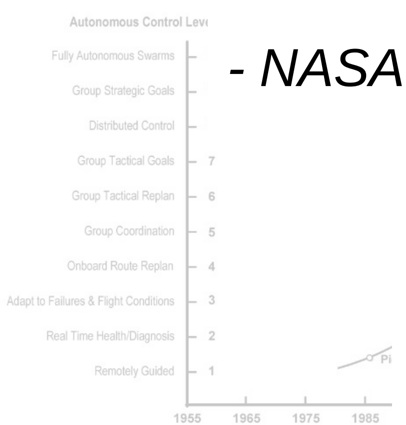


(from DoD Unmanned Aircraft Systems Roadmap, 2005)

Why Autonomy?

2014 NRC Report*

"The burgeoning industrial sector devoted to the design, manufacture, and sales of increasing autonomy systems is indicative of the perceived economic opportunities that will arise."

"Civil aviation is on the threshold of potentially revolutionary changes in aviation capabilities and operations associated with increasing autonomy systems."

- Identified *Barriers to Implementation*
  - Technology Barriers
  - Regulation and Certification Barriers
  - Legal and Social Barriers
- Identified eight *High-Priority Research Projects*
- Identified NASA's Role:

  "NASA supports basic and applied research in civil aviation technologies, including ATM technologies of interest to the FAA. Its interests and research capabilities also encompass the scope of all eight research projects, particularly *modeling and simulation, nontraditional methodologies and technologies, and safety and efficiency*."

* Committee on Autonomy Research for Civil Aviation; Aeronautics and Space Engineering Board; Division on Engineering and Physical Sciences; National Research Council: **Autonomy Research for Civil Aviation: Toward a New Era of Flight.** National Academies Press, 2014.

Unique Autonomy Challenges (1 of 2)

- Differing expectations regarding technical feasibility of advanced autonomy

*

*Embedded cartoon comment: In the 60s, Marvin Minsky assigned a couple of undergrads to spend the summer programming a computer to use a camera to identify objects in a scene. He figured they'd have the problem solved by the end of the summer. Half a century later, we're still working on it.**

NRC Report: "As happens with any other rapidly evolving technology, early adapters sometimes get caught up in the excitement of the moment, producing a form of intellectual hyperinflation that greatly exaggerates the promise of things to come and greatly underestimates costs in terms of money, time, and—in many cases—unintended consequences or complications. While there is little doubt that over the long run the potential benefits of IA in civil aviation will indeed be great, there should be equally little doubt that getting there, *while maintaining or improving the safety and efficiency of U.S. civil aviation,* will be no easy matter."

*http://xkcd.com

Unique Autonomy Challenges (2 of 2)

- Autonomy might not be a candidate for traditional aerospace approaches for research and development

  - and -

  Autonomy is appearing in the non-aviation world in ways that cannot or should not be used for aviation

  NRC Report: “These systems, however, pose serious unanswered questions about how to safely integrate these revolutionary technological advances into a well-established, safe, and efficiently functioning NAS…”

- Autonomy may create new markets and value networks, eventually disrupting existing ones and displacing earlier technologies

- Many non-technical barriers (economic, socio-cultural, potential for adverse consequences)

Autonomy is Required to Enable a Long-Term Aviation Vision

- *Anyone can safely fly any time and anywhere…*
- *with high confidence…*
- *in a fraction of the time it takes today…*
- *while sharing the sky with 1,000 times more vehicles than today…*
- *as some of those vehicles accomplish new missions…*
- *in close proximity to people and property…*
- *without harming the environment.*

- Autonomy will foster a radical increase in aviation efficiency, reliability, and dependability through system-wide operational planning and highly responsive replanning to changes
- The aviation system will be so large and complex that it would be unmanageable without machine intelligence
- Autonomous machines will achieve unprecedented agility through high-bandwidth sensing, replanning, reconfiguration, and control
- Networked multi-vehicle systems will collaborate to achieve new goals
- Machine intelligence will enable new types of vehicles and missions, unconstrained by the requirements of today's conventional vehicles
- Autonomy will augment human abilities and make some tasks easier for humans, allowing machines to assist us and safely work among us
- Configured by autonomous systems, vehicles will continuously operate at peak performance and efficiency

Outcomes, Benefits, and Capabilities

	2015	2025	2035
Outcomes	**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**
Benefits	• Efficiency and NAS capacity • Increased robustness and resilience in operations • Enhanced vehicle performance • Initial UAS applications benefits	• Increased NASA system flexibility, efficiency and capacity • Prognostic safety • New vehicles designed to leverage autonomy • Reduced costs at all levels • Multi-vehicle UAS applications benefits	• Extreme flexibility and adaptability for large-scale systems, with extreme levels of reliability and recovery from disturbances • Advanced prognostic safety • Further reduced costs at all levels
Capabilities/ NASA Outputs	• Advanced prescribed automation and initial goal-directed and adaptive automation • Initial world views from local sensors and limited data exchange • Applied to aviation system components and small-scale systems. • Predominantly human-supervised; higher levels of machine independence under carefully controlled conditions	• Mission-level goal-directed adaptive automation • Large-scale detailed world views using advanced sensors and networks • Applied to large-scale integrated systems • Human/machine teams with many levels of control, depending on specific situations; extensive machine-based learning	• Campaign-level goal-directed adaptive automation, embedded within all system elements • Adaptive collaboration based on extensive shared world views • Highly distributed large-scale collaborative systems that constitute integral parts of larger systems they support • Human/machine teams, with humans primarily specifying strategic goals; many systems self-protect and self-heal

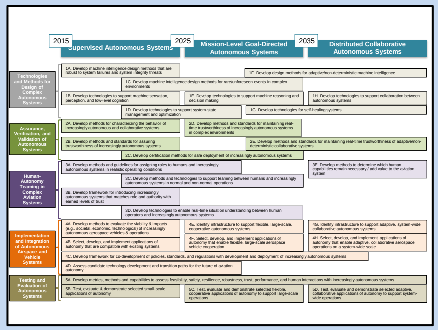
10-Year Vision for the Future of Civil Aviation

2025 capabilities provide early payoffs and vital steps toward the 2035+ future

- Based on earned levels of trust, intelligent systems perform many tasks previously performed by human operators, in the air and on the ground
- Natural language processing facilitates communication between humans and machines
- Reliable high-bandwidth low-latency communications enable vehicle-to-vehicle and vehicle-to-ground coordination
- UAS can act autonomously to avoid collisions with other air vehicles, terrain, and structures
- Semi-autonomous UAS traffic management services assure safety of low-altitude UAS operations
- Teams of UAS, managed by a small number of human operators, operate over large geographical areas
- Onboard systems autonomously monitor, assess, and predict vehicle states and vehicle needs
- Sensing, decision making, and execution systems are capable of assuming control of vehicles to prevent accidents
- Advanced learning and data analytics systems balance air traffic demand and airspace system capacity
- Operators and service providers collaborate using intelligent networked systems to continually optimize flight trajectories
- Optimized vehicle design and manufacturing processes reduce certification time and cost

Roadmap Elements

Three parallel and interdependent elements to achieve the Vision

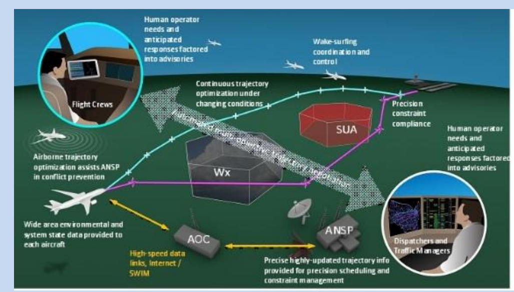


Research Challenges

Technical activities to achieve knowledge breakthroughs and advance aviation autonomy capabilities

Advancement Strategies

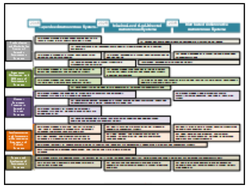
Approaches employed by NASA to achieve aviation autonomy objectives



Mission Products

Targeted NASA and community capabilities that facilitate a viable path toward mature and widespread aviation autonomy

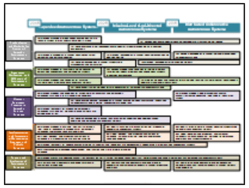
Vision



Previous Efforts Provide Firm Foundation for Research Challenges

Key Reference Documents

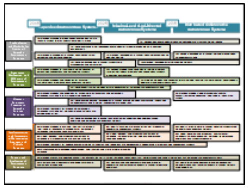
1. National Research Council: Autonomy Research for Civil Aviation: Toward a New Era of Flight
2. ICAST: Recommendations on NASA's Civil Aviation Autonomy Research Strategy
3. AIAA Intelligent Systems Technical Committee: Roadmap for Intelligent Systems in Aerospace (2015 Draft)
4. Automax Workshops Proceedings (Draft TM)
5. LaRC Autonomous Systems Brief to ARMD - Updated
6. Defense Science Board: The Role of Autonomy in DoD Systems
7. MITRE: Anticipating the Onset of Autonomy: A Survey of the DoD, Armed Service, and other Federal Agencies' Outlook on Autonomy



Research Challenges

Research is organized into five research themes

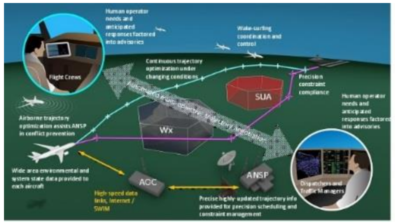
1. Technologies and Methods for Design of Complex Autonomous Systems
   - Methods and technologies for design of intelligent machine systems capable of operating and collaborating in complex environments
2. Assurance, Verification, and Validation of Autonomous Systems
   - Methods for certification and assuring trustworthiness in the design and operation of autonomous systems
3. Human-Autonomy Teaming in Complex Aviation Systems
   - Optimal human-machine role assignments and teaming strategies for increasing machine autonomy and earned levels of trust
4. Implementation and Integration of Autonomous Airspace and Vehicle Systems
   - Novel real-world autonomy applications and transition paths toward higher levels of autonomy
5. Testing and Evaluation of Autonomous Systems
   - Metrics, models, simulation capabilities, and testbeds for assessment of autonomous systems in laboratory and operational settings.



NRC Recommendations for "Particular" NASA Focus

NRC Project:

- Modeling and Simulation
- Nontraditional Methodologies and Technologies
- Safety and Efficiency



Mission Products

- Technologies and Methods for Design of Complex Autonomous Systems
- Assurance, Verification, and Validation of Autonomous Systems
- Human-Autonomy Teaming in Complex Aviation Systems
- Implementation and Integration of Autonomous Airspace and Vehicle Systems
- Testing and Evaluation of Autonomous Systems

Strategic Thrust 6 Research Challenges

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

Research Themes

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

Each Research Challenge Contains a Set of Sub-Challenges

Example:

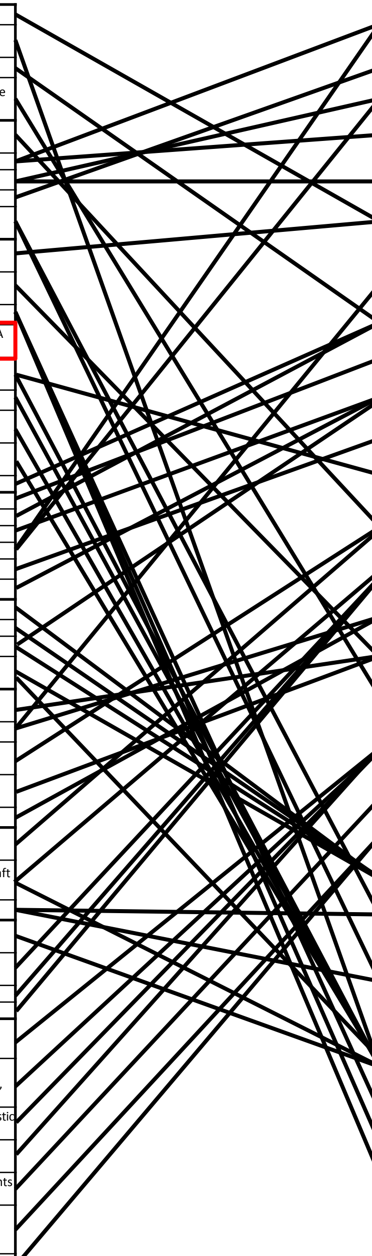
Research Challenge 1H: Develop technologies to support collaboration between autonomous systems

- 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

Mapping of NRC Research Projects to Research Challenges

NRC Research Projects

Behavior of Adaptive/Nondeterministic Systems	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.
Operation Without Continuous Human Oversight	Investigate human roles, including temporal requirements for supervision, as a function of the mission, capabilities, and limitations of IA systems.
	Develop IA systems that respond safely to the degradation or failure of aircraft systems.
	Develop IA systems to identify and mitigate high-risk situations induced by the mission, the environment, or other elements of the NAS.
	Develop detect-and-avoid IA systems that do not need continuous human oversight.
	Investigate airspace structures that could support UAS operations in confined or preapproved operating areas using methods such as geofencing.
Modeling and Simulation	Develop theories and methodologies that will enable modeling and simulation to serve as embedded components within adaptive/nondeterministic systems.
	Develop theories and methodologies for using modeling and simulation to coach adaptive IA systems and human operators during training exercises.
	Develop theories and methodologies for using modeling and simulation to create trust and confidence in the performance of IA systems.
	Develop theories and methodologies for using modeling and simulation to assist with accident and incident investigations associated with IA systems.
	Develop theories and methodologies for using modeling and simulation to assess the robustness and resiliency and of IA systems to intentional and unintentional cybersecurity vulnerabilities.
	Develop theories and methodologies for using modeling and simulation to perform comparative safety risk analyses of IA systems.
	Create and regularly update standardized interfaces and processes for developing modeling and simulation components for eventual integration.
	Develop standardized modules for common elements of the future system, such as aircraft performance, airspace, environmental circumstances, and human performance.
	Develop standards and methodologies for accrediting IA models and simulations.
Verification, Validation, and Certification	Characterize and define requirements for intelligent software and systems.
	Improve the fidelity of the VV&C test environment.
	Develop, assess, and propose new certification standards.
	Define new design requirements and methodologies for IA systems.
	Understand the impact that airspace system complexity has on IA system design and on VV&C.
	Develop VV&C methods for products created using nontraditional methodologies and technologies.
Nontraditional Methodologies and Technologies	Develop modular architectures and protocols that support the use of open-source products for non-safety-critical applications.
	Develop and mature nontraditional software languages for IA applications.
	Develop paths for migrating open-source, intelligent software to safety-critical applications and unrestricted flight operations.
	Define new operational categories that would enable or accelerate experimentation, flight testing, and deployment of nontraditional technologies.
Roles of Personnel and Systems	Develop human–machine interface tools and methodologies to support operation of advanced IA systems during normal and atypical operations.
	Develop tools and methodologies to ensure effective communication among IA systems and other elements of the NAS.
	Define the rationale and criteria for assigning roles to key personnel and IA systems and assessing their ability to perform those roles under realistic operating conditions.
	Develop intuitive human–machine integration technologies to support real-time decision making, particularly in high-stress, dynamic situations.
	Develop methods and technologies to enable situational awareness that supports the integration of IA systems.
Safety and Efficiency	Analyze accident and incident records to determine where IA systems may have prevented or mitigated the severity of specific accidents or classes of accidents.
	Develop and analytically test methodologies to determine how the introduction of IA systems in flight operations, ramp operations by aircraft and ground support equipment, ATM systems, airline operation control centers, and so on might improve safety and efficiency.
	Investigate airspace structures and operating procedures to ensure safe and efficient operations of legacy and IA systems in the NAS.
Stakeholder Trust	Identify the objective attributes of trustworthiness and development of measures of trust that can be tailored to a range of applications, circumstances, and relevant stakeholders.
	Develop a systematic methodology for introducing IA system functionality that matches authority and responsibility with earned levels of trust.
	Determine the way in which trust-related information is communicated.
	Develop approaches for establishing trust in IA systems.
Other Research Needs Identified from NRC Report	The use of increasingly interconnected networks and increasingly complex software embedded throughout IA airand ground-based system elements, as well as the increasing sophistication of potential cyberphysical attacks, threaten the safety and reliability of IA systems.
	IA capabilities create a more complex aviation system, with new interdependencies and new relationships among various operational elements. This will likely reduce the resilience of the NAS because disturbances in one portion of the system could, in certain circumstances, cause the performance of the entire system to degrade precipitously.
	Verification, validation, and certification are necessary but not sufficient to engender stakeholder trust in advanced adaptive/nondeterministic IA systems.
	Social issues, particularly public concerns about privacy and safety, could significantly impede the degree and speed of adoption of IA technology in the NAS.
	It will be difficult to engineer some IA systems so that they are backward-compatible with legacy airframes, ATM systems, and other elements of the NAS.
	Many existing safety standards and requirements, which are focused on assuring the safety of aircraft passengers and crew on a particular aircraft, are not well suited to assure the safety of unmanned aircraft operations, where the primary concern is the safety of personnel in other aircraft and on the ground.
	Public policy, as reflected in law and regulation, could significantly impede the degree and speed of adoption of IA technology in the NAS.



NASA Research Challenges

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

Backup

2025 Vision (1 of 3)

All of the following anticipated capabilities are not envisioned to be in widespread use by 2025; rather we anticipate that there will be varying degrees of advancement and implementation for each. The pace of advancement for each capability will depend on many factors, the most significant of which will likely be market demand and confidence in cost-benefit potential. However, we do believe that by 2025, each of these capabilities can be advanced to demonstrations in a relevant environment, at a minimum.

1. Enabling New Airspace Uses, Users, and Vehicles

- Remotely operated UAS perform a variety of missions with routine access to airspace that is dynamically controlled by air navigation service providers; information networks continually update UAS operators of accessible airspace, as well as any changing conditions that may impact flights (e.g. weather).
- Small UAS operate at low-altitude beyond visual line of sight to conduct missions such as precision agriculture, infrastructure inspection, environmental monitoring, search and rescue, and first-responder assistance. These operations will be organized through semi-autonomous UAS traffic management services that will provide safety assurance and transparency to UAS operators, other stakeholders, and the public.
- Teams of collaborating UAS perform coordinated missions in highly controlled, safety assured contexts. The vehicles are controlled and managed by a single human operator or small team on the ground. Missions have larger-scale geographic coverage for purposes such as environmental monitoring, surveillance, and disaster relief.
- Experimental UAS systems can join to emulate a single-vehicle configuration to exploit range and performance advantages and potentially enable new missions such as modular high altitude extremely long endurance missions, and long-range search and rescue.
- For emergency/rescue operations, unmanned aircraft operate in support of manned aircraft and ground-based first-responders by quickly providing critical information (e.g., locating people in need of rescue, detecting hazards, etc.).
- UAS autonomously re-plan missions or safely end missions in response to changing conditions. Replanning is based on pre-established criteria for conforming to operational flight rules or human operator approval.

2025 Vision (2 of 3)

2. Improving Safety Where Needed for Existing Missions and Assuring Safety for New Missions

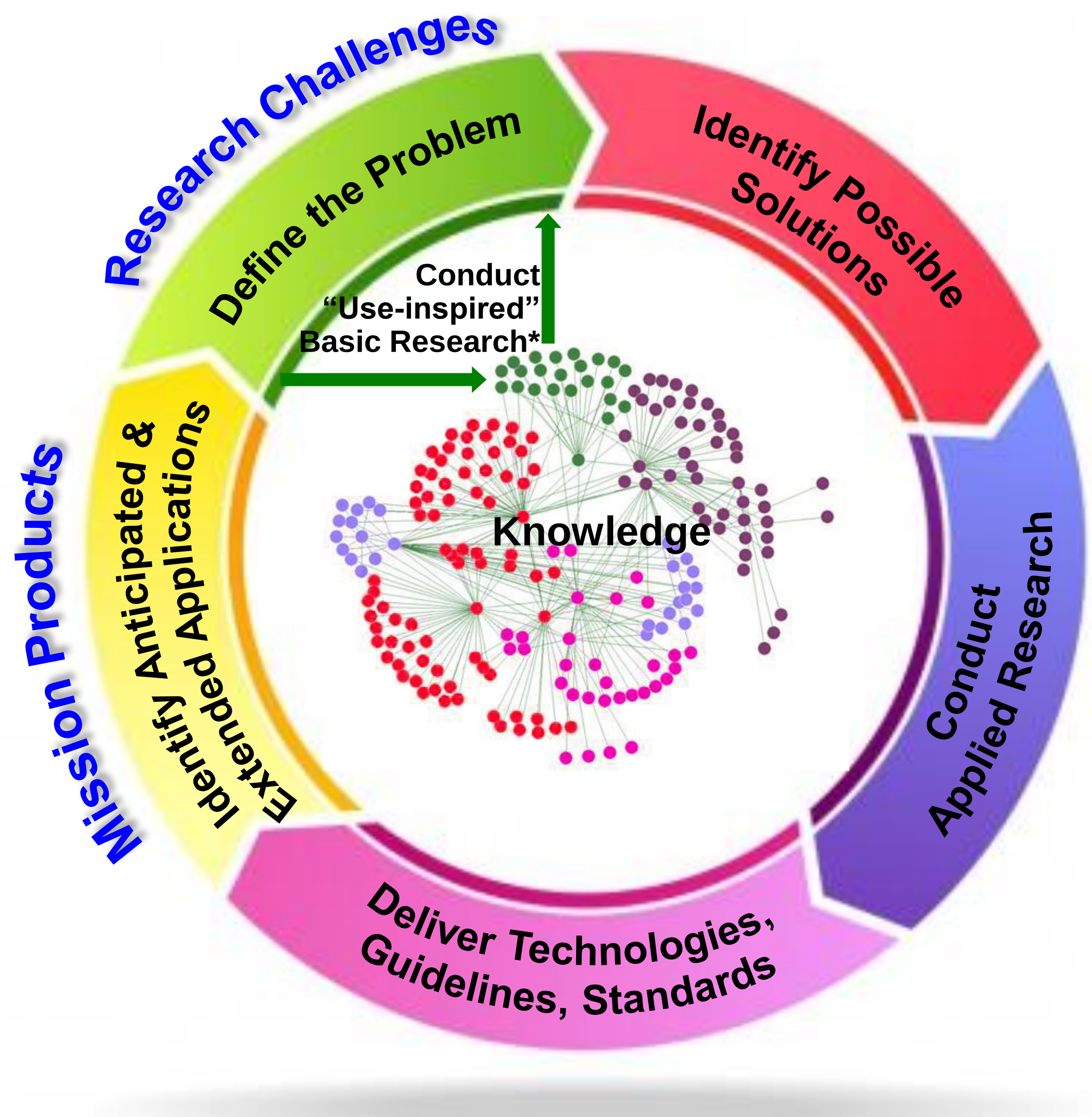
- Missions with elevated risk factors make use of mission-specific, context-relevant decision aids, haptic interfaces, sensors, and guidance systems to continuously evaluate flight risks and advise or assist operators with mission replanning support and appropriate flight guidance. For example, emergency medical evacuation flights operate using systems that assist operators in mission replanning based on risks that may be unknown at takeoff, and provide active guidance during flight into and out of unprepared sites. Similarly, single-pilot air taxi flights into remote areas operate safely by self-mitigating encountered risks that would otherwise be mitigated by air traffic control or airport infrastructure.
- Experimental decision assistance systems in commercial aircraft evaluate flight risks and assist operators to reduce complexity and operator workload during off-nominal flight situations and conditions. Onboard vehicle-state diagnostic and predictive capabilities inform decision-making functions of critical markers trending to unsafe states. Predictions regarding encountering unexpected conditions are assessed in-flight based on information coming from onboard and off-board sources. Systems assure that information can be trusted and actively prioritized based on context. Vehicle system health information is reported to ground-based tracking and archiving systems to build historical databases in support of initial and future system-wide safety assurance systems.
- Onboard systems provide advisories to human operators based on (a) observations from all available sources, (b) learning based on prior similar experiences of the vehicle or other vehicles, and (c) bounded predictions of what may occur if certain decision sequences are acted on in the presence of input and environmental uncertainties. Systems evaluate option spaces within time-varying authority constraints to suggest best course of action that meets both mission and safety objectives.
- Highly-assured context-relevant sensing, decision making, and execution systems are capable of assuming control of vehicles in some circumstances to prevent accidents due to extreme and immediate hazards that are not manageable within human limits. Resilient control architectures support autonomous replanning and reconfiguration. Applications include autonomous landing after pilot incapacitation; reconfiguration of available control surfaces after failures or departure from controlled flight; and maneuvering to avoid terrain and other external hazards.
- Access to low-altitude airspace by UAS is dynamically controlled and continually updated by semi-autonomous UAS traffic management services to ensure that UAS operate in accordance with all rules and regulations, and risks related to rogue and intruder vehicles are safely mitigated.
- Onboard assured containment or conformance systems help to ensure that UAS fly in approved operating areas and pose no threat to public safety, privacy, security, or property.
- Without requiring human intervention, some UAS can avoid collisions with other air vehicles, terrain, and structures for missions requiring close proximity to these potential hazards.
- Without requiring human oversight, onboard systems monitor, assess, and predict vehicle needs for maintenance or upgrades. In experimental systems, sensor networks embedded in vehicle structures monitor critical internal loads and structural health/damage characteristics in real-time and during ground checks for specific subsystems. High-fidelity, physics-based models ascertain structural degradation and repair requirements.

2025 Vision (3 of 3)

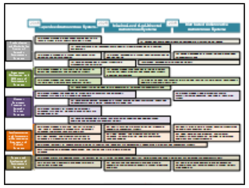
3. Improving Operational Efficiency to Reduce Environmental Impact, Air Traffic Congestion, Passenger Journey Times, and Consumer Costs

- A data sharing infrastructure provides reliable high-bandwidth low-latency two-way communications between aircraft, air navigation service providers, and ground-based organizations such as airline operations centers and fixed base operators. The infrastructure enables vehicle-level and airspace system-level health-monitoring, assessment, and prognostics through use of initial intelligent systems that analyze real-time data streams and historical databases to develop in-time mitigation strategies. The infrastructure enables vehicle-to-vehicle and vehicle-to-ground coordination to realize management of traffic by trajectory (Trajectory-Based Operations), and facilitates the introduction of a diverse set of new business/operating models that leverage network-centric principles, such as resource pooling, to achieve new operating efficiencies.
- Operators and air navigation service providers collaborate using intelligent networked replanning systems to continually optimize flight trajectories in response to evolving conditions. Continuous optimization improves schedule conformance and operational efficiency for individual flights and airline fleets, in addition to increasing overall system resilience in the presence of disruptions. Additional optimization benefits are achieved by early adopters through use of experimental data analytics systems that predict disturbances and anticipate operator responses, as well as through use of automated air/ground trajectory negotiation.
- Advanced machine-based learning and data analytics systems balance air traffic demand and airspace system capacity to improve traffic flow and reduce environmental impact.
- Machine-based learning algorithms provide advisories for integrated arrival, departure, and surface operations, including reconfiguration of airport runways and gates at airports and within metroplexes, enabling system-level throughput optimization and efficiency.
- Autonomous scheduling and routing systems enable new business models for personal air transportation, in which the specifics of a trip, such as origin, destination, and departure time, are highly tailorable by the customer.
- Ground-based air traffic scheduling algorithms generate formation flying opportunities to save fuel during long-range high-altitude flight segments. Onboard systems utilize traffic surveillance data, onboard sensors, and uplinked information to enable rendezvous and maintain spacing.
- Experimental autonomous tugs tow aircraft to and from runways, thereby demonstrating a new means of reducing fuel use and improving the efficiency of surface operations.
- Experimental airborne systems automatically maintain optimal flight configurations, increase engine efficiency, and reduce aircraft structural loads through use of predictive vehicle-specific models, internal and external sensors, and advanced control schemes.
- Intelligent machine systems reliably perform many highly procedural tasks previously performed by human operators and service providers. Allocation of ill-defined, unstructured tasks to intelligent machine systems is limited to non-safety-critical functions, and is based on earned levels of trust. As human operator and service provider roles evolve with the introduction of increasingly capable intelligent machine systems, these systems are used to augment training and retention of new knowledge and skill requirements.
- Vehicle design and manufacturing processes are optimized through use of advanced design tools and model-based testing to reduce certification time and cost for new vehicles, including systems and structures (e.g., advanced composite structures).
- Advances in natural language processing facilitate bi-directional communication between humans and machines, enabling rapid automation support for a wide range of operator and service provider tasks, decreasing communication errors, and reducing workload.

Relationship between Research Challenges and Mission Products



* Stokes, D.E. (1997). *Pasteur's Quadrant – Basic Science and Technology Innovation*. Washington, DC: Brookings Institute Press



NRC Implementation Barriers and ICAST Research Themes

NRC Report* Barriers

- Technology barriers
  - Communications and data acquisition
  - Cyberphysical security
  - Decision making by adaptive/nondeterministic systems
  - Diversity of vehicles
  - Human–machine integration
  - Sensing, perception, and cognition
  - System complexity and resilience
  - Verification and validation (V&V)
- Regulation and certification barriers
  - Airspace access for unmanned aircraft
  - Certification process
  - Equivalent level of safety
  - Trust in adaptive/nondeterministic IA systems
- Other barriers
  - Legal issues
  - Social issues

* Autonomy Research for Civil Aviation, 2014

ICAST* Research Themes

- Autonomous planning, scheduling, and decision making
- Real time multi-vehicle cooperation and interoperability
- Autonomous vehicle control, health management, adaptation, and optimization
- Human-autonomy teaming
- Secure command and control
- System wide status and assessment
- Autonomy infrastructure and information management
- Verification, validation, and certification of autonomous systems
- Test and evaluation capabilities
- Design and analysis of autonomous systems

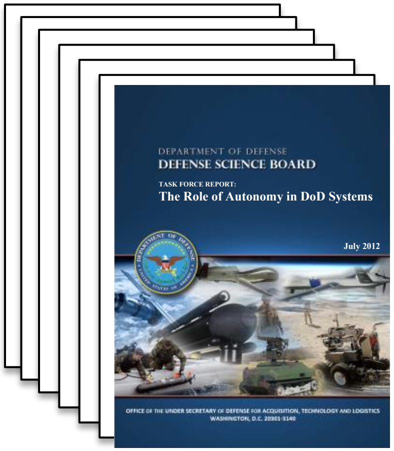
* ARMD Inter-Center Autonomy Study Team briefing, 2014

Major Research Needs Cited in Multiple Documents

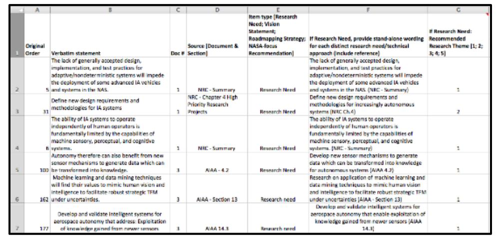
- Need for improved tools, design standards, models, simulations, and architectures, including
  - Common representations and architectures that facilitate interaction between intelligent systems and humans
  - Standards in design and analysis methods
  - Methods and tools assisting in verifiable requirements development and analysis
  - Modeling learning, reasoning, perception, and smart behaviors
  - Models for sensing, perception, cognition, and intelligent decision making
- Understanding of human-agent interactions
  - Human/unmanned systems with scalable and robust distributed collaboration
  - Human-machine communication
- Ensuring robustness, trust, and assurance
  - Unpredictable environments and interactions with other systems can lead to unexpected emergent behaviors
  - Reliance on human operator to compensate for brittleness
  - Developing new approaches to certification
- Test, Evaluation, Verification, and Validation
  - Testing and assessing safety and performance of complex of self-learning autonomous systems

Research Challenges Generation Process (1 of 4)

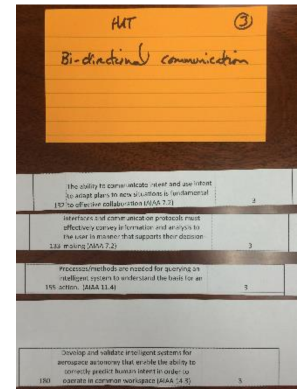
7 Key Reference Documents*



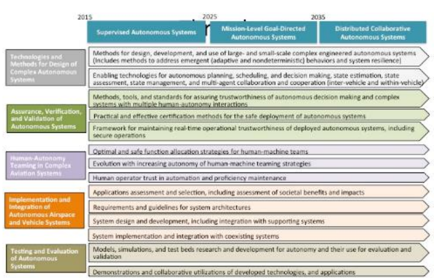
Extracted Research Needs



Categorized Research Needs



Research Subthemes



Research subthemes linked with referenced research needs (RT 3 example)

- Optimal and safe function allocation strategies for human-machine teams
  - Research need categories
    - Roles and responsibilities
    - Transition of authority
- Evolution with increasing autonomy of human-machine teaming strategies
  - Research need categories
    - Human interfaces
    - Training / skill retention
- Human operator trust in automation and proficiency maintenance
  - Research need categories
    - Transparency / situation awareness
    - Bi-directional communication
    - Operator trust

*** Key Reference Documents**

1.National Research Council: Autonomy Research for Civil Aviation: Toward a New Era of Flight
2.ICAST: Recommendations on NASA's Civil Aviation Autonomy Research Strategy
3.AIAA Intelligent Systems Technical Committee: Roadmap for Intelligent Systems in Aerospace (Draft)
4.Automax Workshops Proceedings (Draft TM)
5.LaRC Autonomous Systems Brief to ARMD - Updated
6.Defense Science Board: The Role of Autonomy in DoD Systems
7.MITRE: Anticipating the Onset of Autonomy: A Survey of the DoD, Armed Service, and other Federal Agencies' Outlook on Autonomy

Research Challenges Generation Process (2 of 4)

Thrust 6 Vision

Attributes	2015-2025 Outcome: Supervised Autonomous Systems	2025-2035 Outcome: Mission-Level Goal-Directed Autonomous Systems	>2035 Outcome: Distributed Collaborative Autonomous Systems
Capabilities	Advanced prescribed automation and initial goal-directed and adaptive automation; initial world views from local sensors and limited data exchange	Mission-level goal-directed adaptive automation; extensive machine-based learning; large-scale detailed world views using advanced sensors and networks	Campaign-level goal-directed adaptive automation, embedded within all system elements; adaptive collaboration based on extensive shared world views
System Complexity	Aviation system components and small-scale systems	Large-scale integrated systems	Highly distributed large-scale collaborative systems that constitute integral parts of larger systems they support
Supervision Level	Predominantly human-supervised; higher levels of machine independence under carefully controlled conditions	Human/machine teams with many levels of control, depending on specific applications and situations	Human/machine teams, with humans primarily specifying strategic goals; many systems self-protect and self-heal
Key benefits	Efficiency and NAS capacity; increased robustness and resilience in operations; initial single-vehicle UAS applications benefits	Increased NAS system flexibility, efficiency and capacity; prognostic safety; reduced costs at all levels.	Extreme flexibility and adaptability for large-scale systems, with extreme levels of reliability and recovery from disturbances; advanced prognostic safety; further reduced costs at all levels

<u>Research subthemes linked with referenced research needs (RT 3 example)</u>

- Optimal and safe function allocation strategies for human-machine teams
  - Research need categories
    - Roles and responsibilities
    - Transition of authority
- Evolution with increasing autonomy of human-machine teaming strategies
  - Research need categories
    - Human interfaces
    - Training / skill retention
- Human operator trust in automation and proficiency maintenance
  - Research need categories
    - Transparency / situation awareness
    - Bi-directional communication
    - Operator trust

<u>Epoch differentiation based on system complexity and scope.</u>

- Epoch 1 (Simple) = development of small-scale autonomous systems and autonomous components of larger systems
- Epoch 2 (Complicated) = development of flexible, large-scale, cooperative autonomous systems
- Epoch 3 (Complex) = development of adaptive, large-scale, collaborative autonomous systems

or

<u>Epoch differentiation based on goal specification and collaboration levels.</u>

- Epoch 1 (Simple) = human-specified tactical goals and, under carefully controlled conditions, initial strategic goals
- Epoch 2 (Complicated) = human-specified tactical and strategic goals while operating as coordinated teams
- Epoch 3 (Complex) = high-level human-specified strategic goals while operating as adaptive, collaborative teams

Simplified Model for Research Challenge

Verb indicates what will be done

Indicates the desired capability

Indicates the product or element being affected

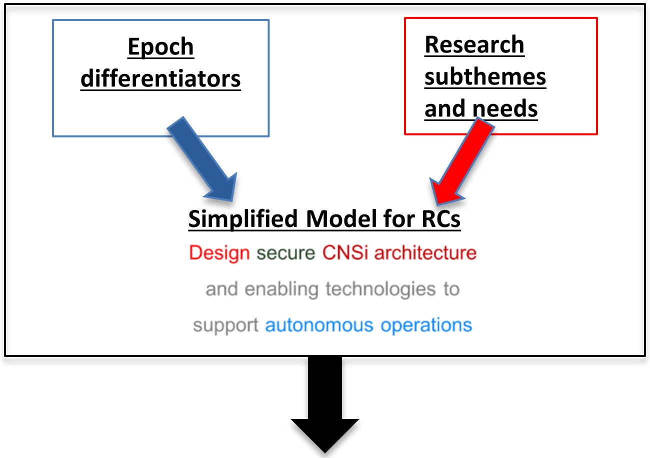
Design secure CNSi architecture

and enabling technologies to

support autonomous operations

Indicates the purpose or benefit of the improvement

Research Challenges Generation Process (3 of 4)



RT 3 Example

Epoch 1:
Develop a framework for dynamic function allocation between humans and autonomous machine systems that execute tactical and initial strategic goals

Develop concepts and guidelines for safely integrating existing human-machine systems and new autonomous systems that execute tactical and initial strategic goals

Develop technologies and interfaces that establish operator trust and bi-directional communication with autonomous machine systems that execute tactical and initial strategic goals

Epoch 2:
Develop a framework for dynamic function allocation between humans and autonomous machine systems that operate as part of a larger coordinated team

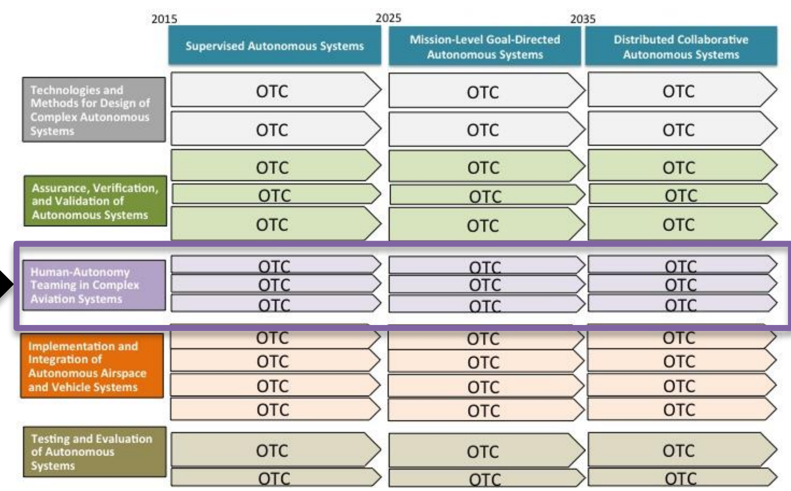
Develop concepts and guidelines for safely integrating existing human-machine systems and new autonomous systems that operate as part of a larger coordinated team

Develop technologies and interfaces that establish operator trust and bi-directional communication with autonomous machine systems that operate as part of a larger coordinated team

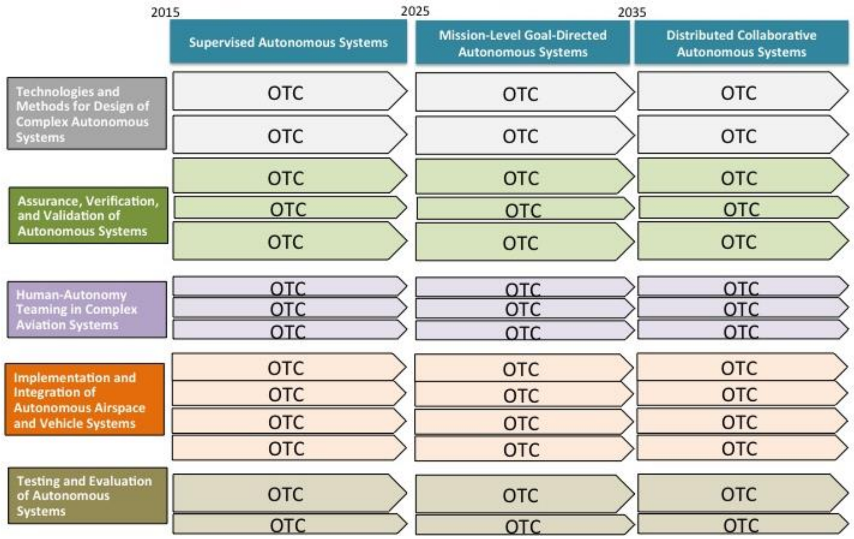
Epoch 3:
Develop a framework for dynamic function allocation between humans and autonomous machine systems that operate as part of a large, adaptive, collaborative team

Develop concepts and guidelines for safely integrating existing human-machine systems and new autonomous systems that operate as part of a large, adaptive, collaborative team

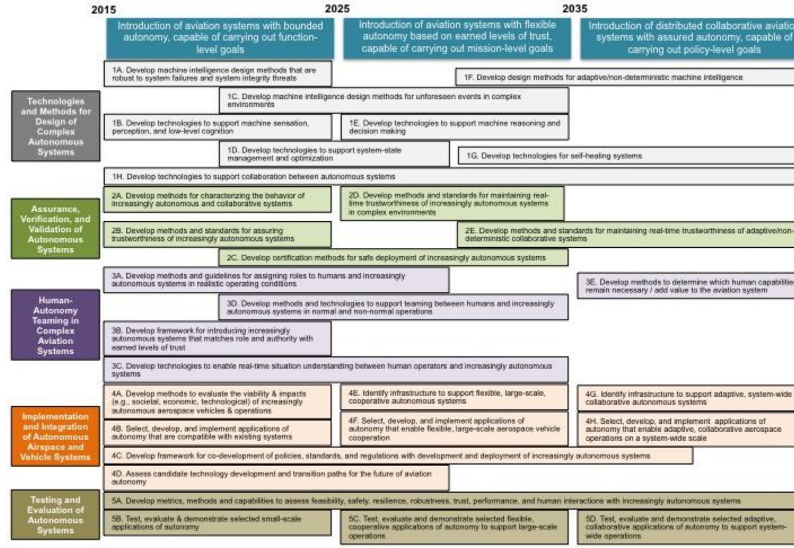
Develop technologies and interfaces that establish operator trust and bi-directional communication with autonomous machine systems that operate as part of a large, adaptive, collaborative team



Research Challenges Generation Process (4 of 4)



"Final" Research Challenges Roadmap



- Interdependencies, relative start/end times, etc., were identified
- This activity shifted RCs across Epoch boundaries.
  - For example, something we've identified as an Epoch 2 RC might need to start in Epoch 1.
  - Something we've identified as an Epoch 1 RC might shift to Epoch 2 if, for example, the completion of several other Epoch 1 RCs would be required before work on that RC could begin.
- The timelining process identified some gaps in our RCs, necessitating modification or creation of new RCs.
- Each RC represents a traceable collection of related research needs identified across a range of sources.