ARMD Strategic Thrust 6: Assured Autonomy for Aviation Transformation

Vision and Roadmap

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Why an Aviation Autonomy Roadmap?

• The world has entered an era where machine intelligence, data analytics, high-speed communications, and ubiquitous low-cost hardware are having wide application across society.
• These capabilities can have large potential payoffs for civil aviation
  – Enabling new aviation uses, users, and mission types
  – Potential to radically transform aviation system capacity, robustness, and flexibility beyond what is possible today

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
Challenges for NASA in Advancing Autonomy

- Extremely high expectations despite extremely high unknowns
  - Divergent opinions regarding technical feasibility of advanced autonomy
  - Unique technical barriers in applying autonomy to aviation (e.g., safety; trust)
  - Many non-technical barriers in aviation (economic, socio-cultural, potential for adverse consequences)

- Traditional approaches to research, development, and implementation in aviation may not apply to autonomy
  - Autonomy may create new markets and value networks, eventually disrupt existing ones and displacing earlier technologies
  - Autonomy may be adopted first by a different set of consumers in a new market, and later adopted by the original market
Outline

• Vision of Autonomy in Civil Aviation
• Mapping of Vision Attributes
• Roadmap Elements
• Research Themes
• Advancement Strategies
• Mission Products
• Summary
Vision for the Future of Civil Aviation
Autonomy is Required to Enable the Vision

Anyone can safely fly…

any time and anywhere, with high confidence…

while sharing the sky with 1000 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 augment human abilities

Radical increase in aviation efficiency, reliability, and dependability through system-wide operational planning and replanning

Monitored by autonomous systems vehicles will operate at peak performance and efficiency

Machine intelligence needed for complex aviation system

Machine intelligence will enable new types of vehicles and missions to be possible

Networked multi-vehicle systems will collaborate to achieve common and novel goals

Unprecedented agility through high-bandwidth sensing, replanning, reconfiguration, and control
Strategic Thrust 6 Outcomes

**Outcomes**

**Supervised Autonomous Systems**
- 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 Autonomous Systems**
- 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 applications and situations; extensive machine-based learning

**Distributed Collaborative Autonomous Systems**
- 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

**Capabilities**

**Benefits**

Increasing efficiency, NAS capacity, resiliency, and robustness

Prognostic Capabilities
Roadmap Elements

Three parallel and interdependent roadmap elements

• Research Themes and Technical 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/community capabilities that facilitate a viable path toward mature and widespread aviation autonomy
Research Themes

Technologies and Methods for Design of Complex Autonomous Systems

Develop methods and technologies for design of intelligent machine systems capable of operating in complex environments.

Assurance, Verification, and Validation of Autonomous Systems

Develop methods for certification and assuring trustworthiness in the design and operation of autonomous systems.

Human-Autonomy Teaming in Complex Aviation Systems

Develop optimal and safe human-machine role assignments and teaming strategies.

Implementation and Integration of Autonomous Airspace & Vehicle Systems

Develop, implement, and integrate novel real-world autonomy applications into existing systems.

Testing and Evaluation of Autonomous Systems

Develop and apply metrics, models, simulation capabilities, and testbeds for assessment and evaluation of autonomous systems.
Roadmap Elements

*Three parallel and interdependent roadmap elements*

- **Research Themes and Technical 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/community capabilities that facilitate a viable path toward mature and widespread aviation autonomy
1. Address critical autonomy barriers that require unique NASA contributions

2. Leverage initial technologies and early adopters to insert autonomy into operational environments, and then build on operational experience (Evolutionary Autonomy)

3. Develop and demonstrate feasibility-driven autonomy concepts, technologies, and mission products to generate breakthrough capabilities (Revolutionary Autonomy)

4. Advance autonomy technologies and overcome barriers by developing mission products that leverage the high demand for Unmanned Aerial Systems and their rapid development cycles

5. Leverage large investments in non-aviation autonomy technologies by developing mission products that repurpose those technologies for aviation where appropriate

6. Establish mechanisms to achieve stakeholder consensus.
Assured Autonomy for Aviation Transformation

Strategies 2 and 3

Parallel Autonomy Advancement Paths

Evolutionary Autonomy

• Offer incremental benefits by inserting advanced technology into existing systems
• Gain confidence and refine capabilities from technology insertion experiences
• Specific Objectives:
  a) Offer early direct benefits to users
  b) Address acknowledged aviation safety issues

Revolutionary Autonomy

• Explore limits of knowledge and capabilities through grand challenges
• Enable future possibilities unconstrained by legacy systems and practices
Strategy 6: Community Coordination and Getting Started

*Establish mechanisms to achieve stakeholder consensus. Provide community coordination to achieve research advances and implement selected applications.*

- Identify community stakeholders, their different needs and objectives, and their potential roles in civil aviation autonomy

- Establish approach for achieving community goals and objectives
  - Set agenda and identify participants for community meetings
  - Establish appropriate partnership agreements with community stakeholders
  - Form and lead workshops on specialized topics within civil aviation autonomy

- Determine technical areas in which NASA will enable collaboration or leverage
  - Develop concepts of operations and project plans
  - Identify workforce, facility, and other resource needs

- Provide strawman research agenda (i.e., Strategic Thrust 6 Roadmap) as precursor to developing a national research agenda
Roadmap Elements

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- Mission Products
  Targeted NASA/community capabilities that facilitate a viable path toward mature and widespread aviation autonomy
Strategic Thrust 6 Mission Products

• Mission Products: targeted capabilities to be achieved in Epoch 1
  – Provide focus for research and technology development
  – Cross-cutting; Research Themes will apply theme-specific R&D to each product

• Mission Product selection
  – Based on NASA/community partnership consensus
  – Mission Products guided by roadmap Advancement Strategies and Research Challenges
**Epoch 1 Mission Product Candidates**

- **Address Increased Demand for Air Transportation**
  - Autonomy-Adapted Knowledge and Skill Set Requirements
  - Autonomous Traffic Flow Management

- **Increase Operational Efficiency in Aviation**
  - Autonomy-Augmented Airborne Medical Services
  - Vehicle Teaming for Increased Efficiency
  - Autonomous Robotic Tugs

- **Enhance Aviation Safety**
  - Autonomy-Augmented Airborne Medical Services
  - Autonomy-Augmented Remote Air Taxi Operations

- **Accommodate New Users/Missions and Develop Autonomy Supporting Capabilities**
  - UAS Traffic Services and Mission Management
  - Architecture to Enable V&V of Autonomous Algorithms
  - Integration Tools for Human/Machine Collaboration

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*We will need to establish processes for engaging with community partners and selecting specific mission products*
The NASA Advanced Air Vehicle Program has funded three small multi-Center efforts in vehicle-centric autonomy, one led by each GRC, LaRC, and AFRC.

The Glenn-led, Langley-supported project is: **Intelligent Propulsion System Control Architecture to Enable More Autonomous Vehicle Operation**

- **Autonomous Vehicle**
  - Dynamic flight management
  - NAS weather and traffic information

- **Intelligent Propulsion System**
  - Real-time sharing of sensed environmental conditions
  - Preferred flight path request
  - Emergency/status info

- **Air Traffic Management System**

**Robust to Hazards and Off-Nominal Conditions**
- Weather
- Air traffic/congestion
- Malicious threats

**Intelligent, Mission-Adaptive Propulsion Control**
- Optimal trajectory planning and execution
- Enhanced engine performance to help mitigate vehicle safety hazards
- Minimize fuel burn
- Extend component life

**Reduced Pilot Workload**
- Automated checklists & advisories
- Automated fault detection & mitigation
Summary

• Developed a set of research themes for the roadmap and associated technical challenges across three epochs

• In the process of defining advancement strategies and mission products

• Soliciting feedback from the community to continue developing the roadmap and specific target areas
Thrust 6 Roadmap Development Team

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Backup Material
How Do We Define Autonomy

• “Freedom from external control or influence; independence” – Oxford Dictionary

• Autonomy = a capability (or a set of capabilities) that enables a particular action of a system to be automatic or, within programmed boundaries, “self-governing.” All autonomous systems are supervised by human operators at some level, and autonomous systems’ software embodies the designed limits on the actions and decisions delegated to the computer.*

• The question of automation vs. autonomous is essentially irrelevant to an autonomy capability
  – As machine capability increases, ability to deal with more complex and dynamic environments increases, thus allowing increased autonomy of systems.

  Dealing with the dynamic and complex environments and reacting to the unpredicted causes the system to adapt to the current environment

  NASA Langley Research Center - Dr. Irene M. Gregory
Strategic Thrust 6 Overview

Objective

Community Vision and Outcomes

Roadmap
- Research Themes & OTCs
- Advancement Strategies
- Mission Products

Technical Challenges
(Determined by Programs and Projects)
### Strategic Thrust 6 Outcomes

<table>
<thead>
<tr>
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### Outcomes

- **Capabilities**
  - Increased efficiency and NAS capacity
  - Increased robustness and resilience in operations
  - Enhanced vehicle performance
  - Initial UAS applications benefits
  - Increased NAS system flexibility, efficiency and capacity
  - Prognostic safety
  - New vehicles designed to leverage autonomy
  - Reduced costs at all levels
  - Multi-vehicle UAS applications
  - 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
Research Themes

Technologies and Methods for Design of Complex Autonomous Systems

Develop methods and technologies for design of intelligent machine systems capable of operating and collaborating in complex environments. Technologies include, among others, machine sensing, cognition, and reasoning.

Assurance, Verification, and Validation of Autonomous Systems

Develop methods for certification and assuring trustworthiness in the design and operation of autonomous systems

Human-Autonomy Teaming in Complex Aviation Systems

Develop optimal and safe human-machine role assignments and teaming strategies that can evolve with machine autonomy and earned levels of trust

Implementation and Integration of Autonomous Airspace & Vehicle Systems

Develop, implement, and integrate novel real-world autonomy applications into existing systems, and develop transition paths for future systems with higher levels of autonomy.

Testing and Evaluation of Autonomous Systems

Develop and apply metrics, models, simulation capabilities, and testbeds for assessment and evaluation of autonomous systems in both laboratory and operational settings. Includes demonstrations and field tests of developed technologies and applications.
Strategic Thrust 6 Mission Products

- Mission Products: targeted capabilities to be achieved in Epoch 1
  - Provide focus for research and technology development
  - Cross-cutting; Research Themes will apply theme-specific R&D to each product

- Mission Product selection
  - Based on NASA/community partnership consensus
  - Mission Products guided by roadmap Advancement Strategies and Research Challenges
  - Programs can propose Mission Products

- Six Mission Product categories:
  1. Enhance Aviation Safety
  2. Address Increased Demand for Air Transportation
  3. Increase Operational Efficiency In Aviation
  4. Enhance Aviation Vehicle Performance
  5. Accommodate New Users and Missions
  6. Develop Aviation Autonomy Supporting Capabilities
Epoch 1 Mission Product Candidates (1 of 2)

- **Category 1: Enhance Aviation Safety**
  - a) Autonomy-Augmented Airborne Medical Services
  - b) Autonomy-Augmented Remote Air Taxi Operations

- **Category 2: Address Increased Demand for Air Transportation**
  - a) Reduced Crew for Air Transport Operations
    - Existing ARMD TC: AOSP SASO RCO
  - b) Autonomy-Adapted Knowledge and Skill Set Requirements for Pilots
  - c) Autonomous Traffic Flow Management

- **Category 3: Increase Operational Efficiency In Aviation**
  - a) Adaptive Operations Management
    - Existing ARMD TC: AOSP ATD-3a
  - b) Vehicle Teaming for Increased Efficiency
  - c) Autonomous Robotic Tugs

- **Category 4: Enhance Aviation Vehicle Performance**
  - a) Vehicle Self-Preservation
  - b) Vehicle Health Management
  - c) Active Load Alleviation
    - Existing ARMD TC: Related to AAVP 07
  - d) Autonomy-Augmented Manufacturing
Key Dependencies

- Cybersecurity, including secure comm
  - Further reliance on automation by the aviation community can be achieved only if equal accompanying advances are made in cybersecurity. NASA will rely heavily on the external community to provide this technology.

- Continued advances in autonomy by external community
  - The interest and advances that are occurring in this field go far beyond NASA. This roadmap is predicated on leveraging the vast amount of knowledge being generated.

- Cooperation of FAA in implementing new technologies and concepts of operation
  - The FAA is a critical implementer of many aviation system elements and a critical regulator of aviation operations. Autonomy is currently not within the FAA’s horizon, and will represent a major challenge in developing new standards, procedures, and regulations.

- Cooperation by external community
  - We will need the cooperation of the aviation community to plan, develop, test, and field our technology.

- Continued support by Centers to provide the required resources and oversight
  - To support this growing technology area, new resources and skills will be required. The Centers have been very supportive and their continued support is needed.
Provide strawman community research agenda
Identify stakeholders, their needs, and roles
Establish approach for coordinating community research

Distributed Collaborative Community Research Agenda

Verify, and Implementation of Autonomous and Integration Technologies

Evaluation of Airspace and Autonomous Systems

Testing and Evaluation of Autonomous Systems

NASA Coordination Activities (Epoch 1)

2015 Supervised Autonomous Systems

1. Develop machine intelligence design methods that are robust to system failures and system integrity threats
2. Develop technologies to support machine sensation, perception, and low-level cognition
3. Develop methods for characterizing the behavior of increasingly autonomous and collaborative systems
4. Develop methods for assigning roles to humans and increasingly autonomous systems in realistic operating conditions
5. Develop framework for introducing increasingly autonomous systems that matches role and authority with earned levels of trust
6. Develop framework for ensuring autonomy that are compatible with existing systems
7. Develop methods for enabling real-time situation understanding between human operators and increasingly autonomous systems
8. Develop candidate technology development and transition paths for the future of aviation autonomy
9. Evaluate and demonstrate selected small-scale applications of autonomy

2025 Mission-Level Goal-Directed Autonomous Systems

1. Develop machine intelligence design methods for rare/unforeseen events in complex environments
2. Develop methods for maintaining real-time trustworthiness of increasingly autonomous systems in complex environments
3. Develop methods for maintaining real-time trustworthiness of adaptive/non-deterministic collaborative systems
4. Identify infrastructure to support flexible, large-scale, cooperative autonomous systems
5. Identify infrastructure to support adaptive, system-wide collaborative autonomous systems
6. Develop methods for self-healing systems
7. Develop certification methods for safe deployment of increasingly autonomous systems
8. Develop methods for self-healing systems
9. Establish workforce, tools, & facilities for "lead" areas

2035 Distributed Collaborative Autonomous Systems

1. Develop methods for evaluating the viability & impacts (e.g., societal, economic, technological) of increasingly autonomous aerospace vehicles & operations
2. Select, develop, and implement applications of autonomy that are compatible with existing systems
3. Develop framework for co-development of policies, standards, and regulations with development and deployment of increasingly autonomous systems
4. Assess candidate technology development and transition paths for the future of aviation autonomy
5. Test, evaluate & demonstrate selected small-scale applications of autonomy
6. Test, evaluate and demonstrate selected flexible, cooperative applications of autonomy to support large-scale operations
7. Test, evaluate, and demonstrate selected adaptive, collaborative applications of autonomy to support system-wide operations
8. Lead workshops on specialized topics
9. Establish workforce, tools, & facilities for "lead" areas

Level Goal - Directed Autonomous Systems