National Aeronautics and Space Administration

ARMD Strategic Thrust 6: Assured Autonomy for Aviation Transformation

Candidate Mission Product Descriptions

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1. Autonomy-Enabled Airborne Public Safety Services

Goal and Benefits

- **Product**: Technology prototypes and procedures for improved safety and efficiency across a range of public safety operations
- **Autonomy Goal**: Promote public acceptance of autonomy through integration of autonomy-enabled capabilities that improve safety and effectiveness of airborne public safety operations
- **Benefits**
  - Reduced time to reach emergency sites and victims
    - Increase in victim lives saved
    - Increase in structures/acres saved from fires
    - Decrease in relief delivery times (e.g., water, food, medical supplies)
    - Decreased time spent on airborne and ground-based asset coordination
  - Reduced accident rates for airborne public safety personnel

Current-Day Challenges

- Safety
  - Helicopter Emergency Medical Services (HEMS) is among the highest-risk civilian occupations in the US (Blumen, 2009)
  - 77% of HEMS accidents weather-related or collisions with objects
  - Intruder drones pose a safety risk to EMS crews and delay getting victims to healthcare facilities (AAMS)
- Efficiency
  - For large-scale disaster relief, ensuring coordination of assisting assets dramatically slows relief efforts (FEMA, 2005)

Concept

- Autonomous hazard awareness systems
  - Intelligent on-board hazard awareness capability recognizes and alerts pilots to obstacles, including power lines, trees, intruder vehicles, etc.; assesses and identifies safe landing zones
- Intelligent decision support
  - Pre-flight and real-time in-flight decision support tools facilitate decisions to go/not go, continue, re-plan, or discontinue the mission by obtaining and jointly assessing environmental, mission, aircraft and flight crew parameters
- Small Autonomous Public Safety Vehicles
  - Launch from larger airborne (mother ship) or ground-based assets to provide surveillance and site reconnaissance; and deliver immediate assistance and emergency supplies; while independently coordinating with other vehicles and services to avoid obstacles and assure airspace containment

Deliverables

- Concepts of operation, including policies, standards, regulations, and procedures
- Prototype systems for autonomy functions
- V&V of flight systems and operations within airspace
- Human-autonomy teaming guidelines and technology

Partner Roles

NASA Role

- Identification and resolution of knowledge gaps
- Concepts and prototype technology development
- V&V procedures

Industry Role

- UAS platforms , payload, and nav & control systems
- Sensor and avionics systems for manned aircraft
- Air/air and air/ground communication systems
- Integration of prototype systems

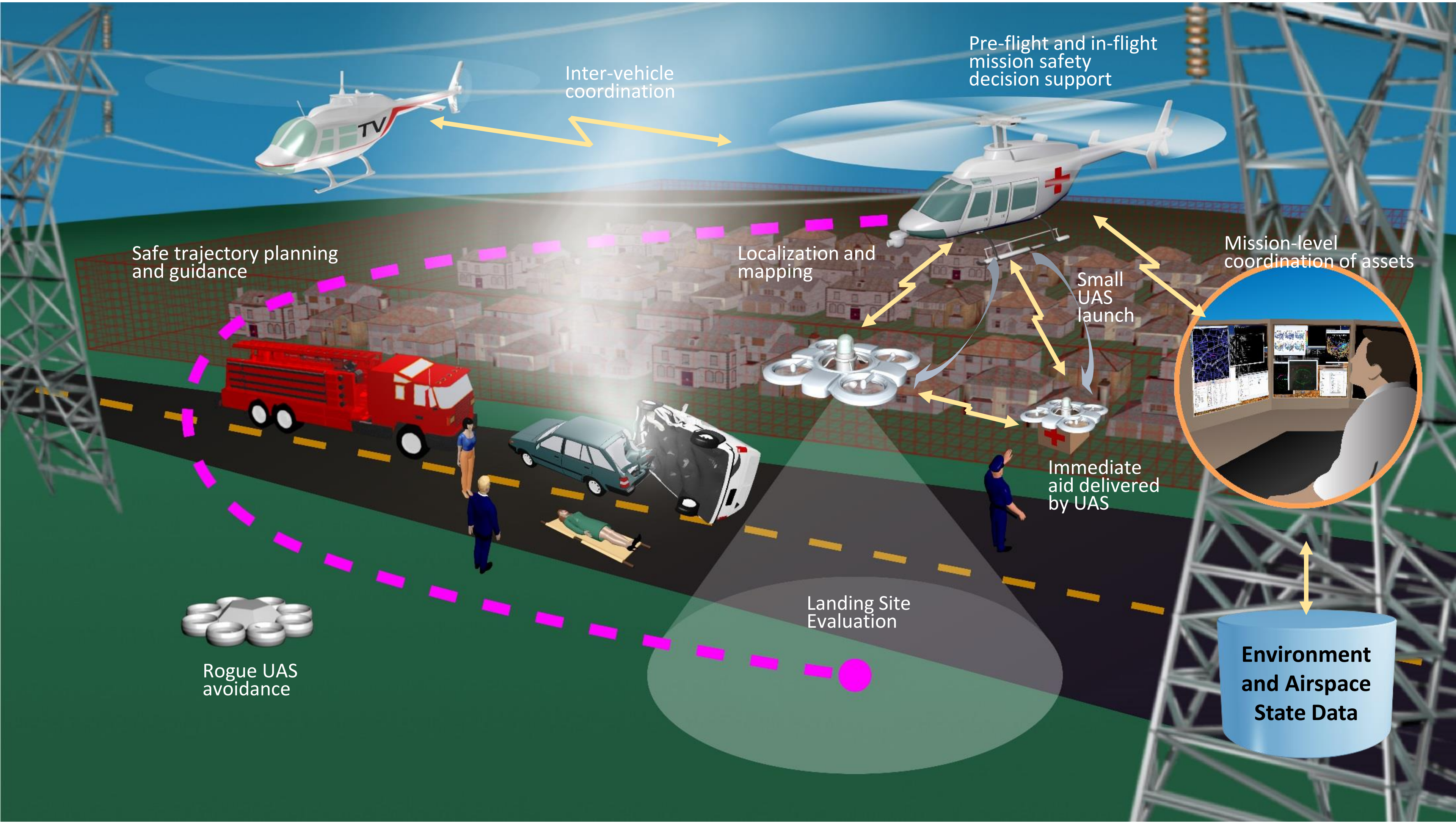
Autonomy-Enabled Airborne Public Safety Services

Advancement Strategies

Strategy	Description
1a	Prototype systems for autonomy functions.
1b	Verification and validation of flight systems and operations within airspace.
1c	Human-autonomy teaming guidelines and technology.
1d	Concepts of operation, including policies, standards, regulations, and procedures for Flight and Operations within airspace
1e	Identify and resolve knowledge gaps through lab and operational evaluations.
2a	Adaptive automation matures through operational experience. Mixed human/machine operational environment supports advancement of machine intelligence that teams with humans.
2b	Direct near-term societal benefit: improved safety and effectiveness for critical public services.
4	Vehicles are providers and users of system state data; supports large-scale prognostic data analytics growth and use.
6	Leverage community UAS platforms, payload systems, nav & control systems Leverage community sensors and avionics for manned systems Leverage existing air/air & air/ground communication systems Coordinate with community for integration of prototype systems

Autonomy-Enabled Airborne Public Safety Services

Operational View



2. Autonomy-Enabled UAS for Earth Science

Goals and Benefits

- Product: Testbed and enabling autonomy technologies for a long-distance, long-duration, pathfinder NASA Earth science mission using a collaborative, multi-vehicle UAS platform
- Autonomy Goal: Establish the technical foundation for many other practical civil applications of large-scale collaborative UAS systems
- Benefits
  - Increase the quantity and quality of scientific measurements through a persistent network of airborne sensor platforms
  - Fill a gap where satellite coverage is inadequate
  - Cost-effective operation of large vehicle swarms over long distances with minimal supervision
  - Momentum of the UAS industry (e.g., atmospheric satellites for internet access) leveraged toward science missions for public good

Current-Day Challenges

- Satellites are expensive and relatively inflexible; observations may have low frequency and inadequate spatial/vertical detail
- UAS require a team of operators (pilot, spotter, mission manager, etc.) for every single vehicle; a logistics train of special handling
- Technologies for unsupervised navigation and hazard avoidance are not ready for wide use
- How to assure safety and reliability for autonomous systems is still an open question
- Building and testing large-scale, multi-vehicle systems in the field is still difficult or impossible; engineering and regulatory methodology is in its infancy

Concept

- Large swarms of vehicles provides a persistent, global platform for continuous scientific measurement
- Vehicle swarm capable of in-situ replanning in response to real-time observations for autonomous discovery
- Vehicle and sensor payload configuration is heterogeneous and rapidly customizable for effective mission performance
- Solar-powered, long-endurance, self-managing vehicles with the ability to land and recharge in the field
- Mission planning and logistics to affordably manage a global network of vehicles and sensors with minimal supervision
- Rigorous engineering methodology applied to ensure that autonomous, unsupervised, over-the-horizon operations are safe and reliable

Deliverables

- Brassboard environment for the development of safe, practical, integrated mission systems in the field
  - Testbed for assured and certifiable, long-range, multi-vehicle autonomous operations in a real-world environment
- Autonomous technologies for collaborative vehicle swarms
  - Vehicle-to-vehicle teaming and adaptive in-flight re-configuration
  - Contingency management in response to failures and hazards
  - Mission planning and logistics

Partner Roles

- NASA: Autonomous swarming technology
- Industry: Advanced vehicle platforms
- Science mission customers: tailored requirements for observation and logistical needs

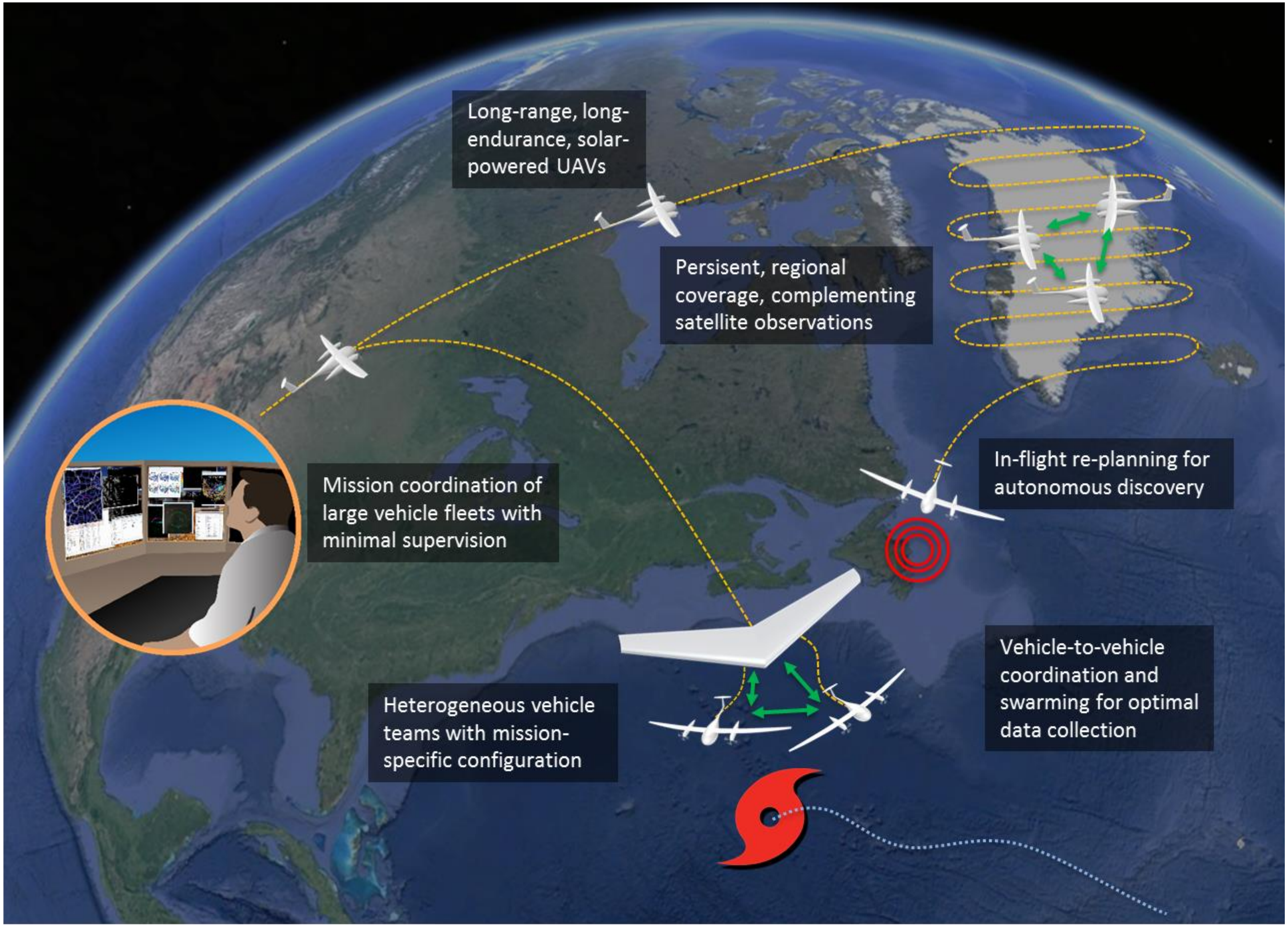
Autonomy-Enabled UAS for Earth Science

Advancement Strategies

Strategy	Description
1a	Prototype vehicle swarm behavior for adaptive science observations
1b	Testbed for development of assured autonomy for long-distance sensing missions
1c	Mission interface and logistics system for long-distance swarm management
1d	Concepts of operation, including policies, standards, regulations, and procedures for Flight and Operations within airspace
1e	Testbed for development of assured autonomy for long-distance sensing missions
3	Grand challenge to develop revolutionary airborne sensor network for continuous, affordable, high-fidelity measurement of the atmosphere and the environment
4	Leverage rapid iteration and momentum of UAS industry toward Earth science missions
6	Leverage community UAS platforms, payload systems, nav & control systems Coordinate with scientific community to target mission applications of greatest impact

Autonomy-Enabled UAS for Earth Science

Operational View



3. UAS Traffic Management and Operations

Goals and Benefits

- Product: Autonomy technologies for UAS traffic management, support services and operations that routinely manage and perform large-scale visual and autonomous beyond visual line of sight UAS operations across rural, suburban and urban environments
- Autonomy Goal: Safely enable large scale UAS operations (millions), safely introduce autonomy-capable and autonomous systems into airspace operations and provide a blueprint and a path for a complete redesign of the National Airspace System that utilizes autonomous systems to safely and efficiently meet the airspace demand of this decade.
- Benefits
  - Enables UAS operator flexibility and autonomy
  - Safely and securely enables multi-billion dollar UAS industry. An estimated investment of $82B/decade in drone industry. FAA forecast shows 2.6M drones by 2020. Provides global leadership opportunity
  - Provides a pathway and blueprint for highly scalable, safe and efficient autonomy-capable beyond NextGen operations

Current-Day Challenges

- Safe, large-scale visual line of sight and autonomous beyond visual line of sight operations for all types of UAS are not currently possible. There is a global void for concepts, operations requirements, and technologies and path towards safe large-scale coordinated operations.
- There is little acceptance of any autonomous vehicle or airspace operations, but the desired millions of UAS operations can only be managed through appropriate use of autonomous airborne, ground-based and cloud-based systems.
- There is huge potential for early targeted autonomy development and testing in the UAS domain if enabled by adequate airspace integration constructs

Concept

- Application Protocol Interface (API)-based integration of
  (1) Autonomous Air Navigation Services,
  (2) Autonomous UAS Operations and
  (3) Autonomous UAS Support Services (USS)
- Intelligent systems optimize UAS operations utilizing autonomous UAS Support Services and coordinate with autonomous Air Navigation Services as needed
- Principles of flexibility where possible and structure where needed enable industry to utilize state of the art autonomous technologies for UAS operations and UAS support services
- Air Navigation Service Providers utilize secure autonomous information systems (and promote time critical real-time information exchange) for safety and security assurance and risk-based management of airspace operations where airspace operations performance requirements are dependent on geography and use case with geographical needs, application, and performance requirements

Deliverables

- Concepts and architectures for autonomous API based management of millions of small UAS operations
- Autonomy technologies in research platforms for
  - Autonomous ANSP constraint management and airspace integration
  - Autonomous UAS support services that can optimize flight and fleet operations under multiple constraints and degraded conditions
  - Autonomous UAS operations that can meet geography and use case based performance requirements

Partner Roles

- NASA and FAA: Develop primary concepts and architectures
- FAA implements primary ANSP technologies, DoD and DHS and public safety partners utilize them
- UAS industry develops and implements UAS and UAS support service technologies to meet performance requirements

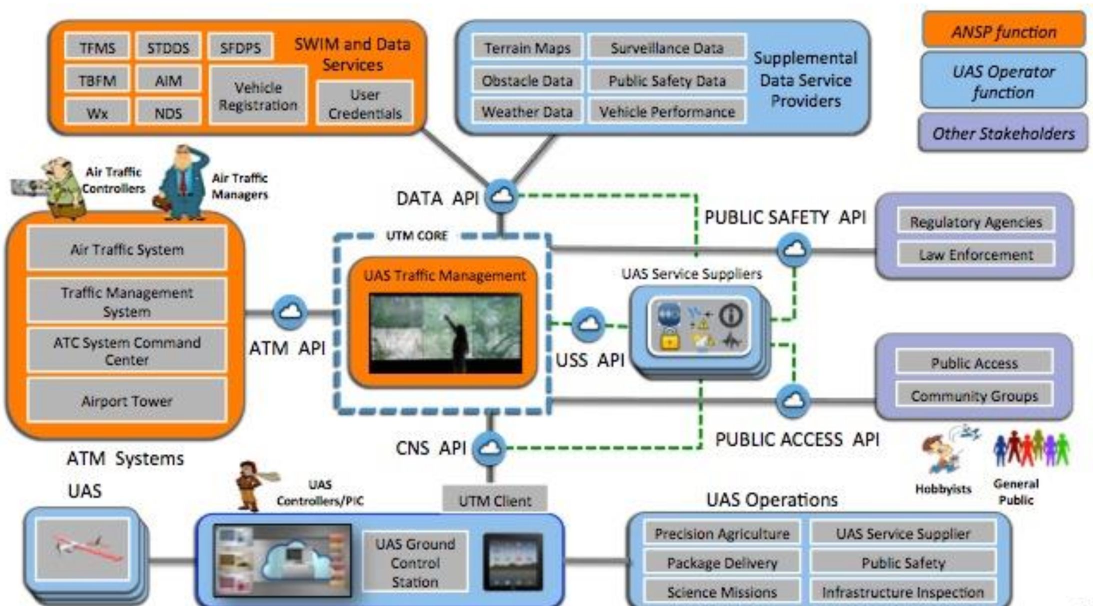
UAS Traffic Management and Operations

Advancement Strategies

Strategy	Description
1	Breaks critical autonomy acceptance barrier by introducing transparent autonomous air, cloud, and ground systems for airspace operations. Defines roles and responsibilities of UAS operator, USS, and ANSPs to maximize scalability
2	Leverages existing and forthcoming UAS technologies developed by industry.
3	Demonstrates autonomous UAS traffic management , services and UAS operations that are not limited in scalability by human performance limitations.
4	Directly advances autonomy technologies and overcomes barriers by developing autonomous UAS management, services and operational constructs that leverage the high demand for Unmanned Aerial Systems and their rapid development cycles – Enables acceptance of autonomous vehicle and operator autonomy
5	Leverages large pool of industry partners that have large investments and experience in targeted or wide-scale autonomy functions from other domains (e.g. internet service providers, road traffic, geospatial services, cellular providers etc.)
6	Directly and openly involves the FAA and other stakeholders in government, industry and academia into the research, development and research transition process . Promotes stakeholder consensus on API and requirements level while leaving flexibility for innovation in individual airborne, ground-based and cloud-based technologies.

UAS Traffic Management and Operations

Operational View



Mantra 1: Flexibility where possible and structure where needed

Mantra 2: Risk based- Geographical needs, application, and performance-based airspace operations

5 Key Principles:

- Authenticated operations only
- UAS stay away from each other
- UAS and manned aircraft stay clear of each other
- UAS operator has awareness of and stays clear of all constraints
- Public safety UAS have priority

API-based integration of increasingly

- Autonomous UAS Operations
- Autonomous UAS Support Services
- Autonomous Air Navigation Services

4. Autonomous Airport Surface Operations

Goal and Benefits

- **Product:** Autonomy technologies for UAS traffic management, support services and operations that routinely manage and perform large-scale visual and autonomous beyond visual line of sight UAS operations across rural, suburban and urban environments
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- **Benefits**
  - Enables UAS operator flexibility and autonomy
  - Safely and securely enables multi-billion dollar UAS industry. An estimated investment of $82B/decade in drone industry. FAA forecast shows 2.7M drones by 2020. Provides global leadership opportunity
  - Provides a pathway and blueprint for highly scalable, safe and efficient autonomy-capable beyond NextGen operations

Current-Day Challenges

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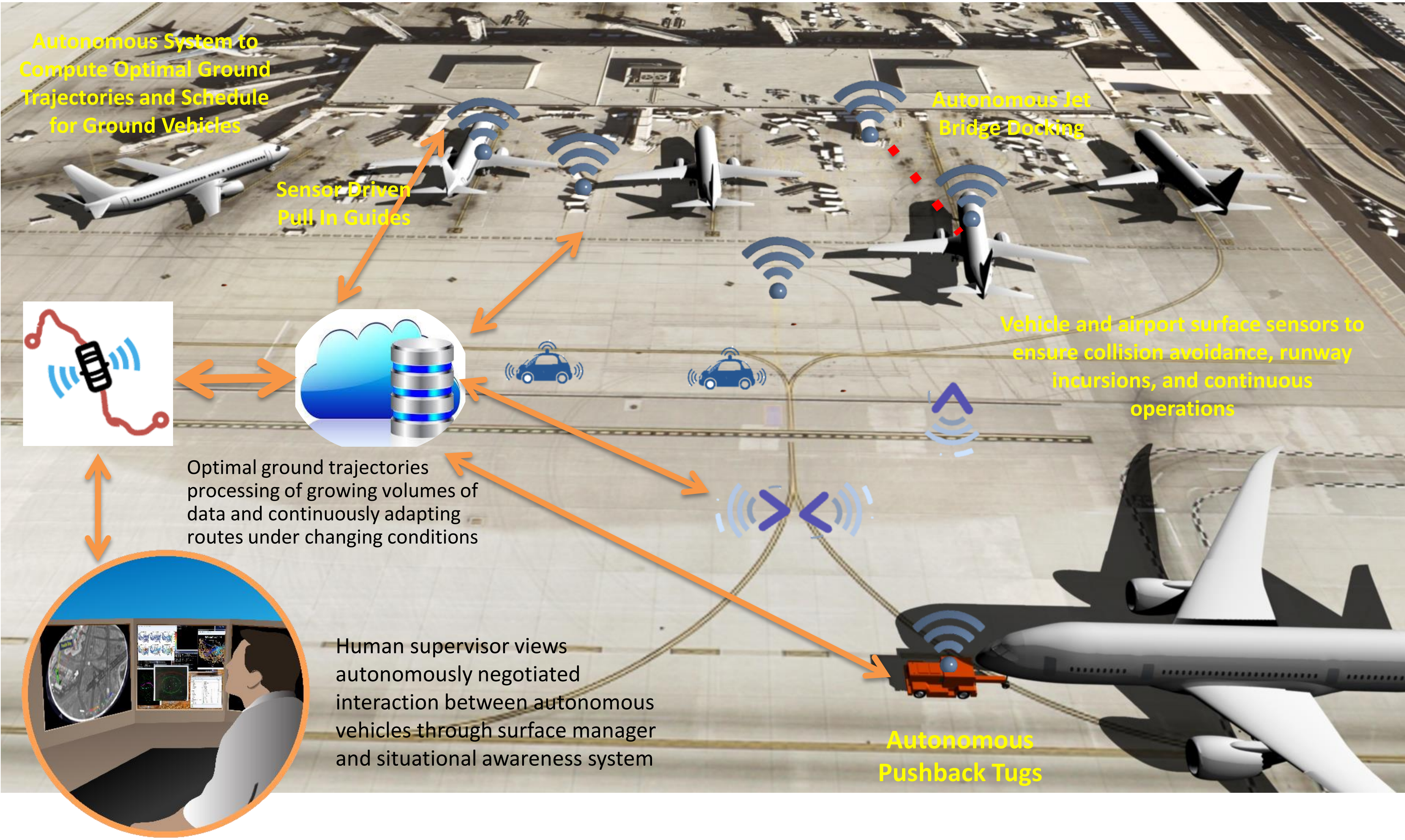
Autonomous Airport Surface Operations

Advancement Strategies

Strategy	Description
1	Address critical autonomy barriers that require unique NASA contributions
	Use operational data to design and test complex multiagent systems on the airport surface and test, system assurance, relationships between humans and machines, and system requirements/standards
	Identifies and resolves knowledge gaps through simulations and demonstrations.
	Provides a viable path toward large-scale prognostic data analytics growth and use
2	Leverage initial technologies and early adopters to insert autonomy into operational environments, and then build on operational experience (Evolutionary Autonomy)
5	Leverage large investments in non-aviation autonomy technologies by developing mission products that repurpose those technologies for aviation where appropriate
	Partnership will play a large role in leveraging autonomous vehicle research for sensor technology, autonomous collaborative algorithms, integrating large quantities of sensor data, and providing diagnostic reporting capabilities to the user
6	Achieves early technology insertion through mutual-benefit partnerships.

Autonomous Airport Surface Operations

Operational View



5. Autonomy-Enabled Air Traffic Management

Goals and Benefits

- Product: Develop initial autonomous TFM advisories using large data systems and analytics for human-supervised management of the air traffic system
- Autonomy Goal: Advance development of autonomous decisions systems and operational concepts using large scale systems requiring integration of complex constraints for coordinated decision advisories through direct operational experience
- Benefits
  - Ability to more rapidly consider comprehensive decisions using large datasets and complex constraints
  - Improved coordinated decision considering all airports regardless of size and operations

Current-Day Challenges

- Capacity and Efficiency
  - FAA forecasts 16.7 million total operations and 769 million enplanements in 2030 (FAA)
  - In FY15 there were 538,690 arrival and departure delays with an average taxi out time of 17.30 min (FAA)
- Need for timely comprehensive multi-objective decisions for this large collaborative system
  - More operations result in complex operations requiring a larger scope of decision making for an efficient and safe system
  - Less frequent strategic decisions in reaction to unexpected situations reduces system efficiency and capacity

Concept

- Autonomous TFM
  - Develop concept and system to develop future autonomous capabilities.
  - Advisories will be developed that can provide timely and comprehensive decisions regarding traffic flow management initiatives and autonomous decision making concepts.
  - Initially, focus on longer range TFM actions that allow for human intervention and approval
- Improved data from all aspects of NAS operations
  - Aircraft, ground assets, current airspace constraints and demand along with airports will be instrumented to provide sufficient information for situational awareness.
  - Data will be rapidly accessible and quality checked from a big data system and made available for supervisory monitoring

Deliverables

- Demonstration of TFM advisories using autonomous algorithms that uses:
  - An autonomy development system that is extensible and scalable for more comprehensive multi-objective autonomous decision making and for certification and approval
  - A supervisory interface that allows diagnostic monitoring and provides a testable human/autonomy teaming approach
  - A rapidly accessible and comprehensive data repository using existing and new systems

Partner Roles

NASA Role
- Concepts and prototype technology development
- V&V procedures

FAA Role
- Develop system requirements, approval, data sharing, and operational concept

Airline Role
- Technology assessment and refinement in collaboration with NASA

Autonomy-Enabled Air Traffic Management

Advancement Strategies

Strategy	Description
1a, b	Operational trials environment provides data/experience for technical advancements in design of complex adaptive systems, system assurance, relationships between humans and machines, and system requirements/standards
1c	Provides continually increasing airspace user immersion in machine-assisted collaborative trajectory management, leading to operator and stakeholder acceptance of new paradigm
1d	Keeps certification and operational approval requirements minimal through a supervised autonomy design approach
1d	Provides a viable path toward large-scale prognostic data analytics growth and use
1e	Identifies and resolves knowledge gaps through operational evaluations.
2a	Designed to provide user business cases to support early adoption and continuing growth
5	Leverages existing air/ground connectivity and data analytics to build increasingly rich shared world view
6	Achieves early technology insertion through mutual-benefit partnerships. Partners: direct benefits NASA: platform for autonomy advancement through operational experience

Autonomy-Enabled Air Traffic Management

Operational View

6. Collaborative In-Flight Optimization for Transport Aircraft

Goals and Benefits

- Product: Operational initial autonomy technologies that achieve high benefits in commercial aviation through in-flight trajectory optimization, trajectory negotiation, and vehicle teaming
- Autonomy Goal: Advance collaborative autonomous air/ground traffic management concepts and technologies through direct operational experience, and provide an autonomy modernization path for existing IFR operations
- Benefits
  - Airspace users fly on business-optimal trajectories, continuously compensating for changing system constraints
  - Increased control authority improves system constraint compliance, leading to increased system predictability
  - Multi-vehicle teams save fuel

Current-Day Challenges

- Air/ground trajectory negotiation is recognized as a key enabler for Trajectory-Based Operations (TBO)
- Missed opportunities for data-driven, safe, dynamic re-planning for efficiency
- For air traffic management applications, autonomy technologies need to be matured through operational use
  - National Airspace System is highly complex; behavior is not predictable a priori
  - Autonomy must be integrated with, and serve the needs of, existing human operators
- Certification and operational approval challenges require a supervised autonomy approach
- Initial autonomy implementations may require minimal changes to existing ATM/ATC processes and procedures

Concept

- Users and airspace resource managers collaborate to achieve highly efficient operations, system predictability, system robustness, and resilience to disturbances
  - Supported by high-bandwidth air/ground data exchange, trajectory management automation continuously optimizes routes under changing conditions
  - Automation negotiates between multiple stakeholders with differing objectives
  - On-board sensors, and off-board information systems enable multi-vehicle rendezvous and teaming for efficiency
- Human operators are supported by increasingly capable automation and data analytics. Current human roles and authority are unchanged.
  - Adaptive automation is used to increase quality of advisories to humans over time
  - Initial human/automation teaming approach employs machine-based anticipation of operators' needs and preferences

Deliverables

- Certified and approved technology and procedures in airborne and ground-based systems for
  - Continuous trajectory optimization based on extensive National Airspace System (NAS) state knowledge
  - Automated negotiation for multi-objective optimization, accounting for flight, fleet, and service provider goals and constraints
  - Adaptive automation that anticipates and accounts for needs and goals of human operators

Partner Roles

- NASA and Private Sector: Concepts and Technology
- Airlines and Service Providers: Technology adoption and refinement in collaboration with NASA

Collaborative In-Flight Optimization for Transport Aircraft

Advancement Strategies

Strategy	Description
1a, b	Operational trials environment provides data/experience for technical advancements in design of complex adaptive systems, system assurance, relationships between humans and machines, and system requirements/standards
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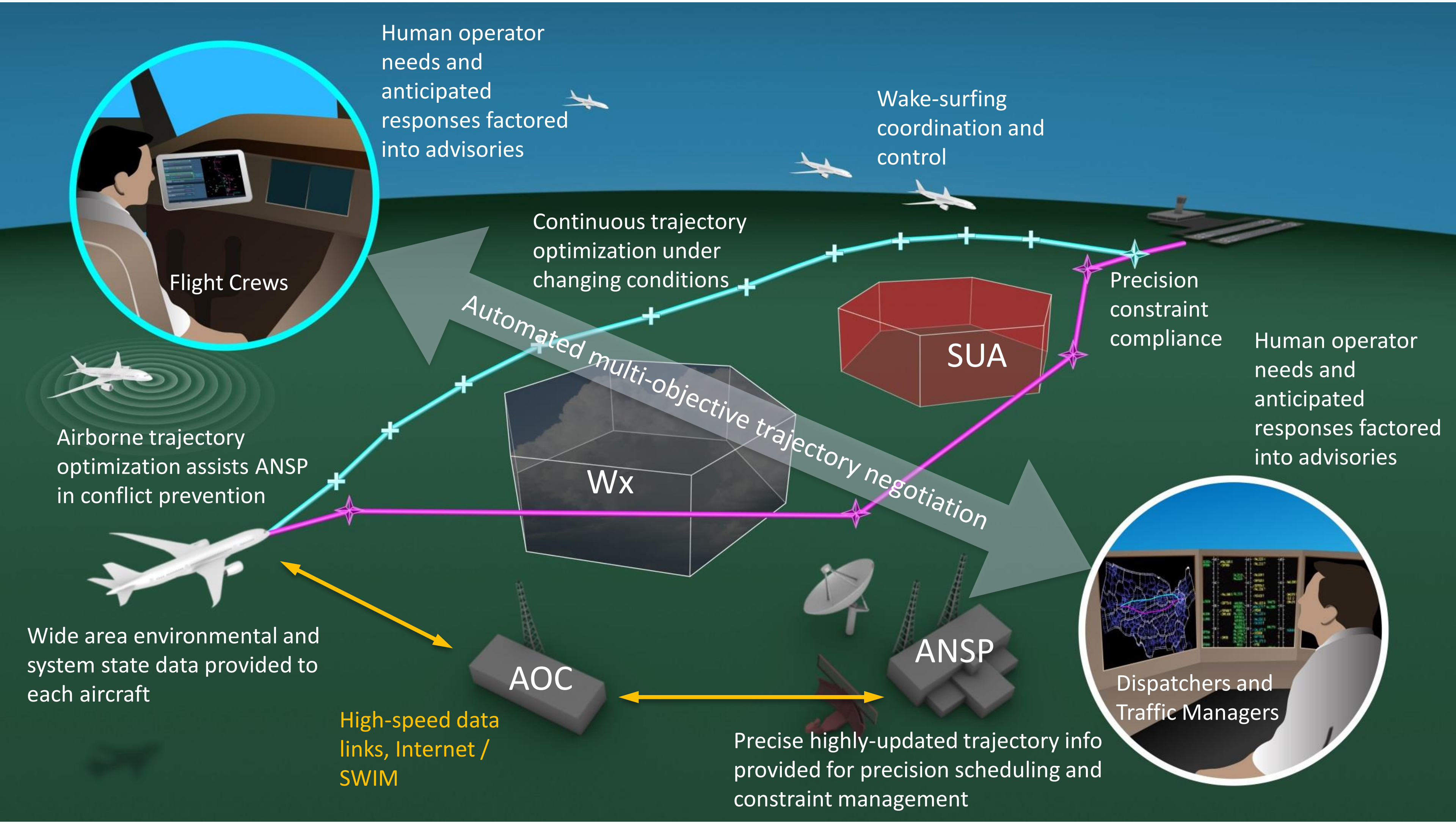
Collaborative In-Flight Optimization for Transport Aircraft

Operational View



7. Autonomy-Enabled Flight Crew Performance in Complex Environments

Goal and Benefits

- **Product**: Revolutionary cockpit technology prototypes and guidelines for autonomy-enhanced flight systems, teamed human/machine decision making, and human/autonomy interfaces to enable advanced, transformational operations and mobility.
- **Autonomy Goal**: Achieve optimal flight performance, pilot training, and operational resilience through human/cockpit systems that employ the specialized skills of operators and machine systems working as an optimized team
- **Benefits**
  - Increased pilot/operator/user capability and performance
  - Increased safety and efficiency through effective, resilient human-autonomy teams
  - Mitigation of growing pilot shortage
  - Enable concepts that improve mobility for people and goods through a distributed network of autonomy-enhanced aircraft

Current-Day Challenges

Incorporating autonomy into aircraft requires humans and machines "to work together in new and different ways" (NRC, 2014)

- Safety
  - Natural human capacities are increasingly mismatched to the data volumes and decision speeds demanded in today's aviation environment.
  - Today's Single Pilot Operations are 4-5X more hazardous than 2-crew operations
- Demand
  - Current flight deck procedures and automation are not scalable to operations in future, higher density NAS (10 to 100x increase in aircraft traffic density)
  - Current systems cannot sustain greater than 3X growth (ODM briefing, NextGEN)
- Mobility
  - Cars and commercial airliners are poorly matched to on-demand regional travel (50-500 miles)

Concept

Enable advanced transformational operations and mobility through

- Integrated, autonomous situational awareness and self-preservation capability in response to changes in crew state/intent, passenger state, weather, traffic, vehicle health, and airspace parameters
- Assessment of variable autonomy to support risk management, decision-making and error mitigation functions
- Approaches to mitigate the pilot as single point of failure due to Incapacitation, impairment, human error, malicious behavior
- Assessment of human roles in diverse operational contexts as a progression from expert crew to operators to users

Deliverables

- Guidelines, standards, prototypes and certification methods for revolutionary cockpits maximizing benefits of crew-autonomy teaming
  - Concept of operations, interface designs, and prototypes for advanced transformational operation and mobility
  - Autonomous crew/vehicle monitoring, fault mitigation, and risk assessment technologies
  - Increasingly autonomous system decision-making and communicate / execute technologies
  - Function allocation analysis to support well-designed pilot-autonomy teams
  - Flight demonstration of technology and concepts in a retrofit aircraft with low-skill pilots

Partner Roles

- NASA: Human-autonomy teaming analysis and design
- Industry: Integration with revolutionary aircraft and cockpit designs
- FAA: help establish certification and regulatory framework for highly autonomous pilot aids

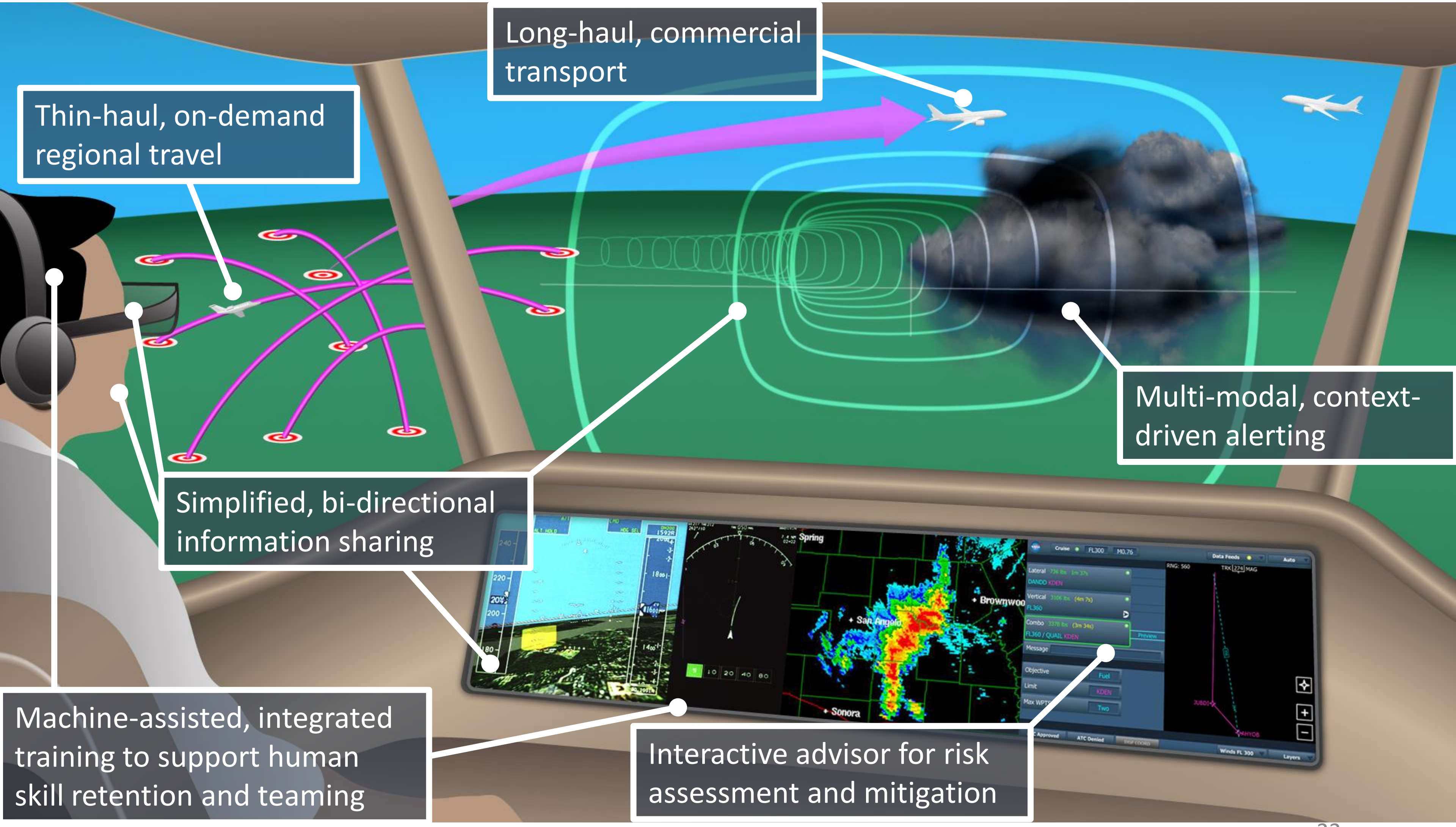
Autonomy-Enabled Flight Crew Performance in Complex Environments

Advancement Strategies

Strategy	Description
1a	Prototype systems for autonomy functions.
1b	Certification methods for collaborative flight systems.
1c	Guidelines & technology for dynamic assignment of human/machine roles; human-machine teaming in normal/non-normal ops.; and for enabling real-time shared understanding between humans and machine systems.
1d	Concepts of operation, including policies, standards, regulations, and procedures for high-density on-demand regional travel.
1e	Identify and resolve knowledge gaps through lab and operational evaluations.
2a	Collaborative human/machine operational environment supports advancement of machine intelligence that teams with humans.
2b	Direct near-term societal benefit: improved safety for existing single-pilot operations.
3	Demonstrate control systems for small aircraft eliminating stick-and-rudder piloting in all normal and non-normal situations
5	Leverage investments in self-driving cars and identify ways to repurpose those advancements for small aircraft to be used for on-demand regional travel
6	Leverage existing and emerging air/air & air/ground communication systems Coordinate with community for integration of prototype systems

Autonomy-Enabled Flight Crew Performance in Complex Environments

Operational View



8. Autonomy-Enhanced Vehicle Safety

Goal and Benefits

- Product: Vehicle intelligence internally assessing safety state, allowing the vehicle to complete the mission, and improving efficiency while preventing incidents with on-demand maintenance, targeting high risk scenarios.
- Autonomy Goal: The vehicle itself is situationally aware of its internal state, able to respond to both nominal and off-nominal conditions, and be able, as appropriate, assume an independent role in safety assurance.
- Benefits
  - Vehicles capabilities to independently assure safety may be the only recourse in some situations, and addresses the recurring issue of inappropriate crew response.
  - Improved situational awareness/response in each vehicle of the NAS yielding enhanced operations across the NAS.
  - Reduced maintenance cost and less vehicle down-time improves vehicle availability and throughput.

Current-Day Challenges

- It is predominately left to pilots (not the vehicle) to interpret current state and infer future states based on experience and expertise.
- CAST, FAA, NTSB, and the NRC have called for research on systems that can predict the state of the aircraft, including the state of autonomous systems, to provide notifications of trending to unsafe states.
- In order for the trust in autonomy, health management/vehicle response needs to be tailored for independent autonomous systems without human intervention.
- There has been development in component health management technology with some adoption; integrated subsystem/vehicle system full-field health management is limited.

Concept

- Future air vehicles, esp. autonomous vehicles, must operate with a high degree of awareness of their own well-being, and possess the internal intelligence to provide warning and potentially take action in response to off-nominal states in order to maintain safety while performing the mission.
- Networked sensors and algorithms to provide necessary vehicle full-field state information, fuse and evaluate that information and take trustworthy real-time or preventive actions.
- Significantly enhance the fidelity and relevance of information provided to ground systems by the vehicle in-flight for use in on-demand maintenance.
- The vehicle level intelligence is built from the bottom up with distributed intelligence and capabilities throughout the vehicle enabling subsystem/vehicle intelligence.
- Vehicle state diagnostics/prognostics that informs decision-making functions of critical markers trending to unsafe states.

Deliverables

- High-priority safety risk cases will define essential state variables requiring estimation and prediction.
- State awareness technologies for identified vehicle subsystems/components for nominal and selected off-nominal operations integrated in a UAS vehicle demonstration.
- Information fusion demonstrated for aircraft subsystems, and an architecture for vehicle information fusion.
- Diagnostic and prognostic identification of simulated faults before on-set as part of an enhanced warning system.
- In–flights demonstrations in simulated fault conditions without pilot intervention.

Partner Roles

- Airframers/Engine Companies: Partnership in technology demonstrations; Feedback on design architecture, technology implementation, and operational considerations.
- FAA: Involvement in advanced technology demonstrations.

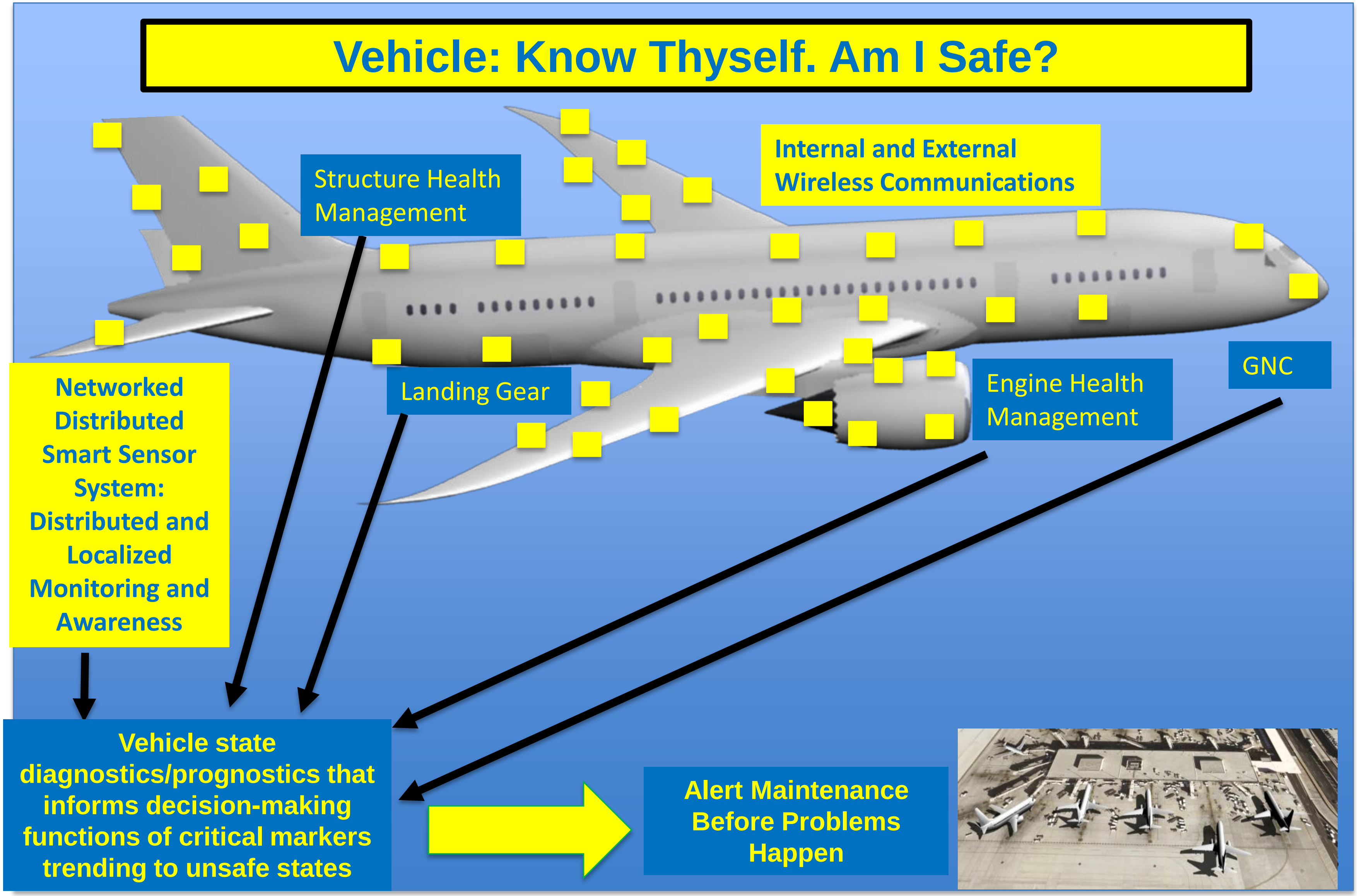
Autonomy-Enhanced Vehicle Safety

Advancement Strategies

Strategy	Description
1a	Design of required state variables for vehicle state awareness for high risk scenarios. Methods for vehicle state awareness, prognostics, and on-demand preventive maintenance.
1b	Demonstration both in simulations and in-flight of vehicle state awareness, diagnostics, and prognostic technologies.
1d	Demonstrates approaches and defines parameters for implementation of vehicle assessment, mission completion, and early warning systems.
1e	Methods to evaluate the capabilities of state awareness and early warning vehicle intelligence through demonstrations and flight test of vehicle safety management.
2a	Provides a range of technologies and approaches that could be implemented for specific vehicle applications
2b	Identifies methods for identification and early warning of a range of high risk safety scenarios.
3	Vehicle independent safety assurance without human intervention demonstrated.
5	Leverages information fusion technologies, internet-of-things intelligent sensor development, data analytics, SA of the environment
6	Industry/FAA to partner in technology demonstrations and evaluations. Provides assessment on vehicle safety response capability independent of pilot.

Autonomy-Enhanced Vehicle Safety

Operational View



9. Resilient, Trusted Autonomous Vehicle Systems

Goal and Benefits

- Product: A prototype scaled vehicle that demonstrates refuse-to-crash operation in selected off-nominal conditions through resilient design approaches, ability to deal with uncertainties, and appropriate response to off-nominal conditions.
- Autonomy Goal: Safe and reliable operations for autonomous aircraft by integration in design of resilient vehicle technologies and approaches enabling trust that if an off-nominal state occurs, the vehicle will assure safety.
- Benefits
  - Trust of autonomy and autonomous vehicle systems in the NAS is enabled by vehicles resilience to off-nominal conditions and operations with safe and predictable behavior.
  - Resilient aircraft systems research has applicability across all vehicle types and mission classes.
  - Semiautonomous aircraft with a high degree of resiliency strongly impact the overall safety of the NAS.

Current-Day Challenges

- Future aircraft and operating concepts will depend on unprecedented levels of autonomy.
- Maintaining current levels of safety for these future vehicles and operations will require resilience under a wide spectrum of uncertain, abnormal, unexpected, & hazardous conditions
- Loss-of-Control (LOC) has been identified as the leading causal factor of aviation accidents (ref: Boeing, NTSB), and is foreseen as such for the future. Contributing to this is the lack of resilience to the unexpected, particularly combinations of hazards whose effects are difficult to understand or mitigate.
- The current status in commercial vehicle operations typically involves the capability to respond to a limited number of simultaneous hazards (e.g., control component failures) and vehicle health management that is applied to specific systems/subsystems/components after vehicles have been built and deployed.

Concept

- Future autonomous air vehicles, flying within new ATM concepts of operation, must be able to withstand a wide spectrum of uncertain, abnormal, unexpected, and hazardous conditions (*be resilient*).
- Autonomous unmanned air vehicles that appropriately respond to unexpected events in an manner that preserves the safe/efficient operation of the NAS, as well safeguards people/property.
- Develop integrated systems technologies that enable the mitigation of multiple hazards, while effectively dealing with uncertainties and unexpected conditions.
- New vehicles types are being developed and new manufacturing processes (e.g., additive manufacturing) are being introduced; Resilient design approaches and built-in intelligence, included in the design phase.
- Methods and tools for the design, integration, and demonstration of resilient systems that will lead to improved, assured safety of operations for new aircraft.

Deliverables

- Defined resilience traits, metrics, architectures, and mitigation approaches will be developed with hazards analysis and test scenarios
- Vehicle level fail-safe response technologies including refuse to crash and mission abort.
- Multi-disciplinary simulations demonstrating required resilient behavior under a representative set of adverse conditions
- Additive manufacturing applied to fabrication of a resilient scaled vehicle with integrated intelligence.
- Flight tests of resilient behavior for selected use-cases using a scaled vehicle.

Partner Roles

- Airframers/Engine Companies: Partnership in technology demonstrations; Feedback on design architecture, technology implementation, and operational considerations
- FAA: Involvement in advanced technology demonstrations.

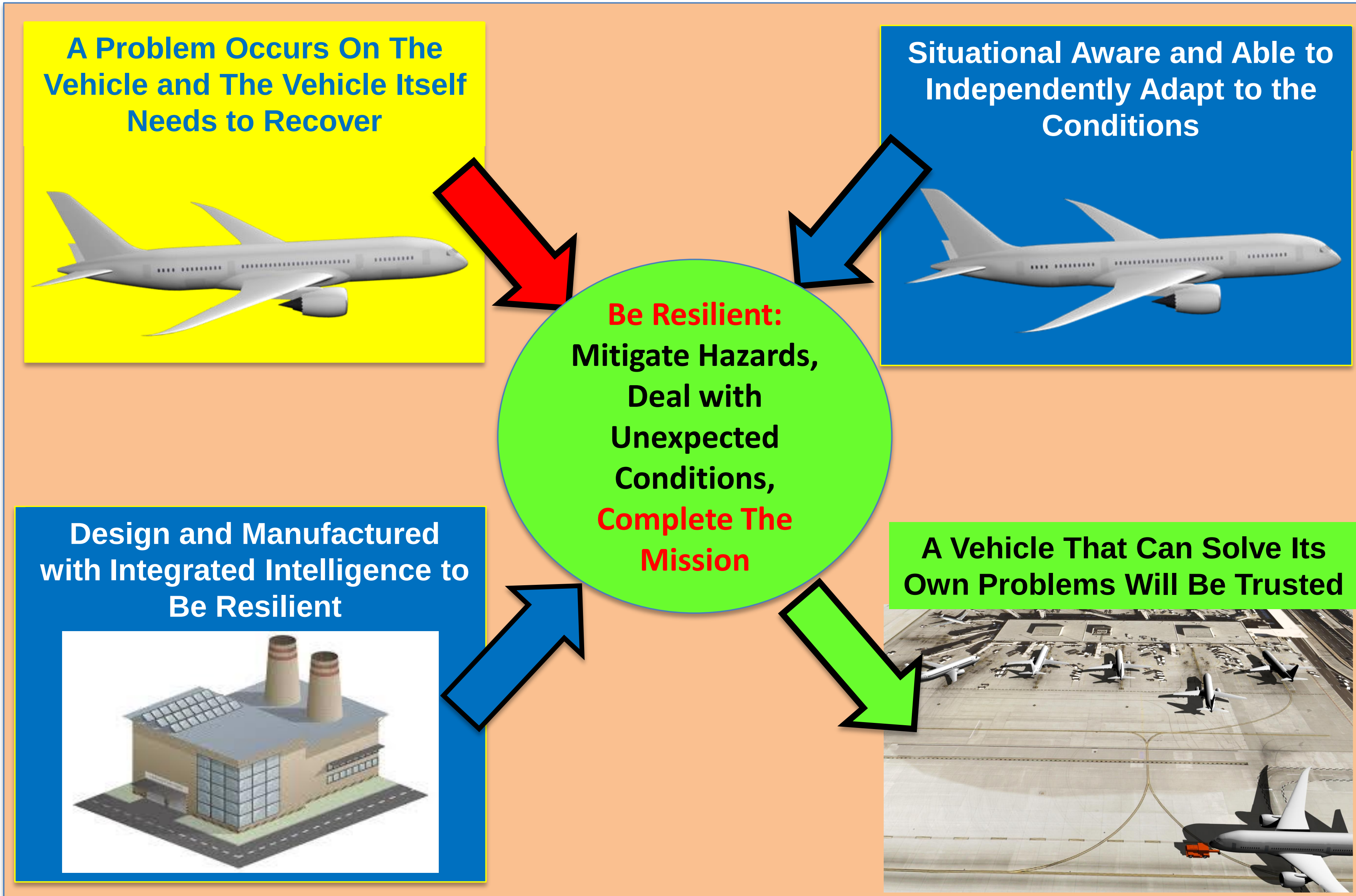
Resilient, Trusted Autonomous Vehicle Systems

Advancement Strategies

Strategy	Description
1a	Methods for resilient vehicle manufacturing, operations, and response design. Definitions of resilient traits, metrics, and architectures.
1b	Demonstration both in simulations and in-flight of resilient behavior for use cases based on what is needed for implementation in the airspace.
1c	The ability to trust autonomous vehicle is core the their implementation in the airspace. A core objective of this work is to enable trusted behavior.
1d	Demonstrates approaches for future implementation of independent vehicle operations that show resiliency to a wide spectrum of operational conditions.
1e	Identifies knowledge gaps and limits in operational capabilities through design, manufacturing, and flight test.
2a	Provides methods to assure vehicle level fail-safe response and mission completion.
2b	Directly address a major issue in safety related to the ability of vehicles to be resilient to off-nominal conditions and still safely complete the mission.
3	Built-in vehicle intelligence and resilience demonstrated with new approaches to manufacturing.
5	Leverages information fusion technologies, data analytics, SA of the environment, and additive manufacturing advances
6	Industry/FAA to partner in technology demonstrations and evaluations. Provides assessment on vehicle resilience and capabilities to independently achieve mission objectives

Resilient, Trusted Autonomous Vehicle Systems

Operational View



10. Inflight Vehicle Performance Optimization

Goal and Benefits

- **Product:** Demonstration of improved vehicle efficiency with less environmental impact through intelligent feedback between internal state monitoring and adjustment of vehicle parameters.
- **Autonomy Goal**: Optimize vehicle performance and efficiency with minimal environmental impact through automated and autonomous systems that determine the vehicle state and adaptively reconfigure.
- **Benefits**
  - Performance and efficiency optimized by an improved understanding of real-time vehicle state combined with the capability optimize operational parameters.
  - Reduced environmental impact through intelligent systems that, e.g., fine-tune operations to decrease emissions or change modes to reduced noise at airports.
  - Independently autonomous vehicles able to not only maintain safety, but also able to efficiently perform missions.

Current-Day Challenges

- Vehicle operations are often constrained by the adaptability and capabilities of the pilot/operator, or by static features of the vehicle design. Some of amount of optimization may take place within limited parameters and in-flight optimization to changing conditions may be limited.
- Improved efficiency, performance, and environmental impact can be enabled by increased autonomy and intelligent systems broadening the parameters responded, to but without overloading the pilot/operator.
- Reduction of environmental impact in other applications, e.g., automotive or pollution control, is often best achieved with adaptive system that modify operational parameters.
- Independently autonomous vehicles need the capability to perform the mission and optimize operations, as well as ensure safety in the NAS.

Concept

- Intelligent systems with in-situ vehicle state awareness and ability to in-flight modify parameters can provide an ability to continuously optimize operations and reduce environmental impact (as well as provide safety and resilience).
- Advanced inflight state awareness combined with adaptive control highly to achieve improved efficiency, performance, and reduced environmental impact.
- Introduction of technologies and approaches from component to vehicle level needed to allow distributed intelligence enabling an intelligent vehicle system.
- Integration of autonomy capabilities into advanced air vehicles early in the design process to enhance or enable improvements in energy consumption, environmental compatibility, maneuverability and/or mobility. Demonstrate capabilities to motivate future upgrades and designs.

Deliverables

- Concept of operations for intelligent in-flight vehicle optimization, including adaptation based on flight mode, stage of mission, and feedback control.
- Demonstrate feedback control technologies for selected emissions using on-board measurements/smart fuel injectors.
- Demonstrate reconfiguration based on the mission stage or vehicle degradation, e.g., adaptive blade tip clearance control or variable camber from trailing surfaces.
- Integrated flight/propulsion/vehicle reconfiguration (e.g. active structural or flow control) to provide optimal mode performance.
- Demonstration of these concepts with flight testing in an integrated vehicle test.

Partner Roles

- Airframers/Engine Companies: Partnership in technology demonstrations; feedback on design architecture, technology implementation, and operational considerations.
- FAA: Involvement in advanced technology demonstrations.

Inflight Vehicle Performance Optimization

Advancement Strategies

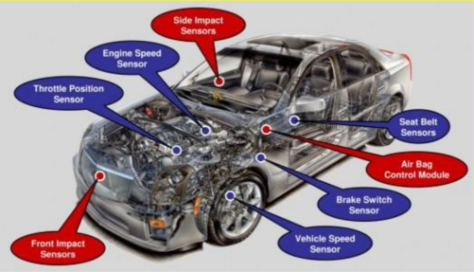
Strategy	Description
1a	Concept of operations for intelligent vehicle optimization appropriate to the various modes and stages of vehicle operations. Methods for new inputs and feedback control responses.
1b	Demonstration of various aspects of the approach in test stand demonstrations as well as the integrated approach with in-flight testing.
1d	Demonstrates approaches for implementation of significant advances in vehicle operations optimization.
1e	Demonstrates methodology and capabilities through ground and flight tests for improved efficiency and decreased emissions.
2a	Provides a range of technologies and approaches that could be implemented for specific vehicle applications
3	Vehicle independent safety assurance without human intervention demonstrated.
5	Leverages a prevalent method for more efficient and greener systems used throughout process control and automotive industries: automated and autonomous state monitoring and feedback control.
6	Industry/FAA to partner in technology demonstrations to evaluate impact of approaches to improve efficiency and reduce emissions.

Inflight Vehicle Performance Optimization

Operational View

A Modern Vehicle's Capabilities, Including Improved Efficiency and Performance with Reduced Emissions, Are Enabled by a Complete Vehicle Approach Including Integrated Intelligence

Ford Model T: https://en.wikipedia.org/wiki/Ford_Model_T

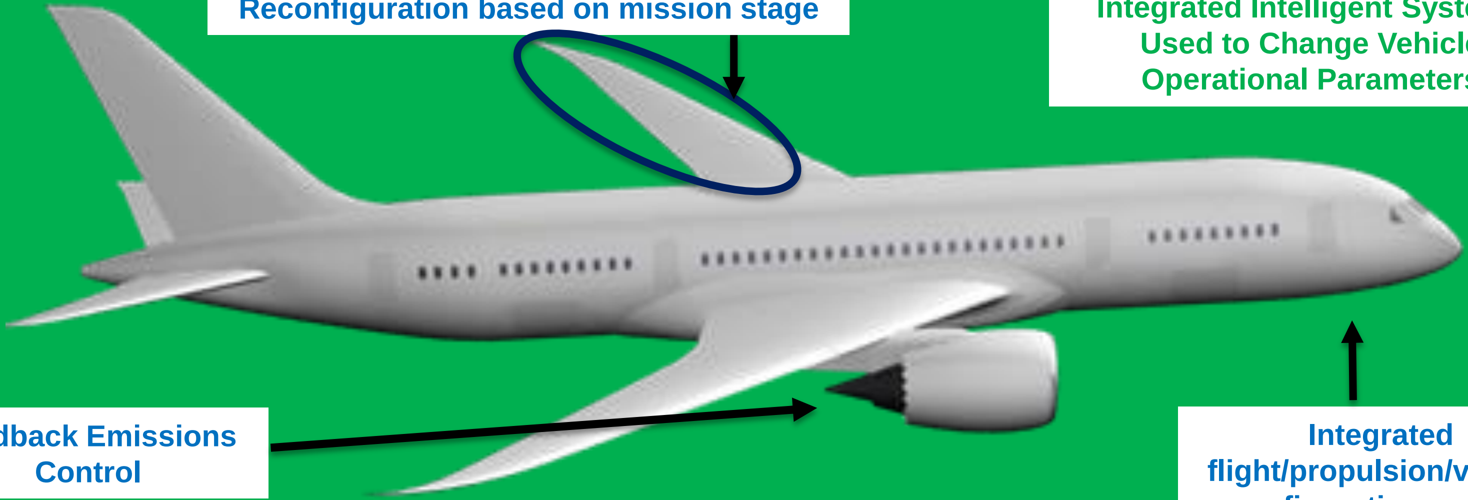


"A modern automobile has over 50 microprocessors." Image and quote at http://www.bu.edu/ece/undergraduate/is-electrical-computer-engineering-right-for-me/automotive-industry/

A Smarter Vehicle is a More Efficient and Higher Performance Vehicle with Less Environmental Impact

Reconfiguration based on mission stage

Integrated Intelligent Systems Used to Change Vehicle Operational Parameters



Feedback Emissions Control

Integrated flight/propulsion/vehicle configuration control

11. Complex Decision-Making UAS

Goal and Benefits

- **Product:** A demonstration UAS that determines loss of control in selected multiple simultaneous simulated faults and makes a decision to crash in a manner that does not impact property/personnel.
- **Goal:** Autonomous and semiautonomous vehicles with reasoning and decision making capabilities to independently and reliably make safety-related decisions in complex, uncertain environments.
- **Benefits**
  - Autonomous decision-making is among the most important properties of a vehicle that has self-governing authority.
  - Reliable decision making is crucial to assuring vehicle directed actions do not result in harm to others.
  - Intelligent vehicle-based decision-making removes constraints to broader use of autonomous vehicles in the NAS.

Current-Day Challenges

- Current vehicle systems make decisions based on very limited authority. When exceeded (as in hazardous situations), these systems disable themselves and it’s often left to pilots to interpret current state and decide how to mitigate the problem
- To date, vehicle system decision-making authority is very limited due to reliance on incomplete sensor information, unanticipated conditions or failure modes, and uncertainty of current and future states.
- The NRC has noted barriers to the introduction of autonomous systems including two depending on vehicle cognition: (1) Decision making by adaptive and nondeterministic systems, and (2) Trust in increasingly autonomous systems.
- Core to expeditiously and safely modernizing flight operations.

Concept

- Autonomous decision-making is core to allowing self-government in the airspace. As vehicles gain more authority, it must be assured that their decisions do not result in harm to others or to the vehicle itself if possible.
- Technologies for vehicle-based intelligent decision-making that enable the core capabilities for vehicles to make independent decisions.
- Option spaces must be evaluated within time-varying authority constraints to suggest best course of action to meet both mission and safety objectives
- Methods for data fusion and information extraction from multiple sources.
- Learning based on prior experiences of the vehicle/other vehicles.

Deliverables

- Metrics for quantifying decision performance documented with a framework for defining constraints.
- Multiple event cases used to evaluate decision making approaches.
- Identification of an information acquisition and delivery architecture to enable decision making.
- Conflict resolution methods in multi-option decision spaces demonstrated.
- Autonomous decision making methods demonstrated on a UAS with a series of simulated faults/unexpected events.

Partner Roles

- Airframers/Engine Companies/New Service Providers based on UAV’s: Partnership in technology demonstrations; Feedback on design architecture, technology implementation, and operational considerations
- FAA: Involvement in advanced technology demonstrations.

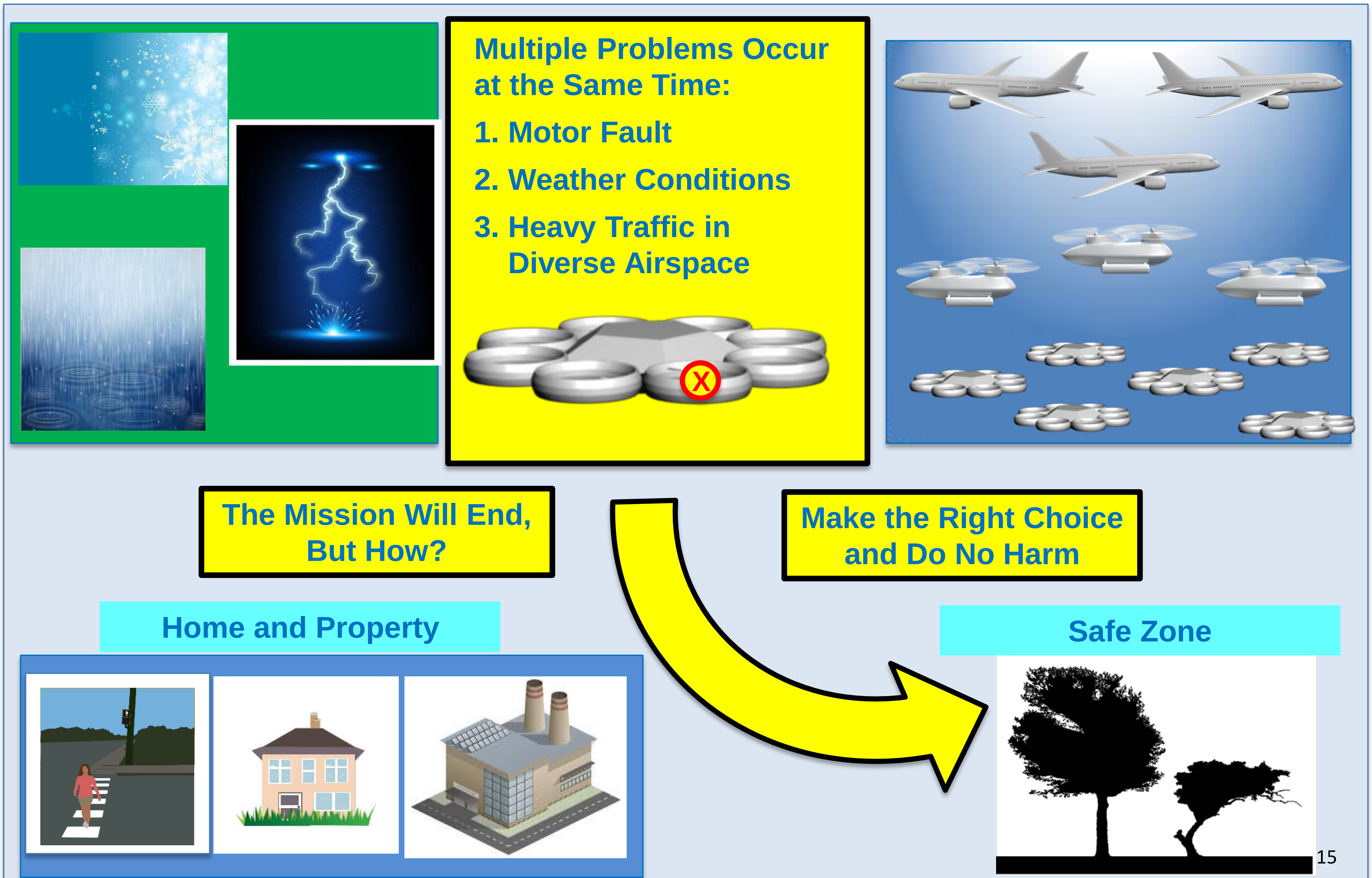
Complex Decision-Making UAS

Advancement Strategies

Strategy	Description
1a	Addresses one of the most crucial aspects of complex adaptive engineered systems, Decision Making, through providing metrics, framework for constraints, information acquisition and delivery architecture, and option spaces.
1b	Demonstration and evaluation of time-varying authority, conflict resolutions in multi-option decision spaces, and in-flight decision making with multiple test cases.
1c	Decision making is core for autonomous operations. This activity emphasizes pushing the limits of decision making to gain confidence in that capability.
1d	Decision making capabilities and approaches are core for future implementation of independent vehicle systems.
1e	Evaluation and testing methodologies of a broad range of core aspects of involved in the use of autonomous systems.
2a	Provides decision making methods that can be applied to earlier stages of autonomous systems
2b	Directly address a major issue in safety related to the implementation of autonomous systems of any class: if allowed in the airspace, how is the safety of persons/property assured
3	Autonomous systems with this level of machine intelligence needed will enable notable paradigm changes in NAS operations.
4	Core to the use of UAS in the airspace is this core capability for decision making.
5	Leverages machine intelligence, information fusion, data analytics, and SA of the environment
6	Industry/FAA to partner in technology demonstrations and evaluations. Provides assessment on boundaries of decision making systems.

Complex Decision-Making UAS

Operational View



12. Fully Autonomous Transport Aircraft

Goal and Benefits

- **Product**: CONOPS, initial technologies and system requirements necessary for fully autonomous transport class civil aircraft design, development and operations in sparse density/infrastructure air space.
- **Autonomy Goal**: Understand the full benefits and costs of on-board autonomous technologies impact on transport class civil aircraft through revolutionary approach of designing a fully autonomous aircraft for a particular operational niche and advance required autonomous technologies to enable this.
- **Benefits**
  - Cost effective and appropriately safe civil aircraft configurations built for a particular mission or market niche.
  - Safe, efficient, cost effective transport aircraft designed to be autonomous from the start drives revolutionary autonomy technology development, changes system design, configurations, architectures, and CONOPS with spinoffs to other vehicle categories e.g. VRLT, ODM, …

Current-Day Challenges

- Aircraft design requires pilot cockpit, associated support systems and CONOPS
- Mission/market specific configuration tailoring is limited → small production numbers not cost effective
- Full impact of autonomous technologies for transport aircraft are impossible to explore on derivative, cockpit containing configurations
- Transport class aircraft cost and geographic access are limited by current ATC infrastructure and skilled pilot availability
- Autonomy related technologies are rapidly advancing but require appropriate aviation application in order to advance across multiple aviation domains
- Evolutionary approach to introducing autonomy is unlikely to take full advantage of autonomous technologies or to produce necessary certification processes

Concept

- Clean design for fully autonomous transport class aircraft operating in sparse density/infrastructure.
- Develop CONOPS, architectures, configurations for new missions or market segments.
- Determine requirements on autonomy technologies for safe and efficient operations under all conditions and autonomy's full impact through cost/benefit analysis.
- Establish requirements and develop systems and architectures necessary for fully autonomous transport aircraft with on-board decision making
- Develop adequate intelligent sensing, perception and internal health monitoring/assessment for required situational awareness (SA).
- Develop on-board intelligent decision-making capability and adaptive mission management to safely execute defined mission under all conditions.
- Design and build a fully autonomous sub-scale aircraft to access CONOPS, autonomous system architecture and technologies, and provide initial data/processes towards certification.

Deliverables

- Initial set of CONOPS and technologies for fully autonomous transport civil aircraft designed for specific mission/market segment
  - CONOPS, autonomous systems architecture and requirements for safe and efficient operations
  - Flight demonstrated enabling autonomy technologies for transport class aircraft
  - Proposed approaches and data for certification for fully autonomous transport aircraft
  - Proof-of-concept configuration design and flight test
  - Technology transfer to and technical support for NASA partners for their mission specific autonomous vehicle applications.

Partner Roles

- NASA, Private Sector, DoD: CONOPS, concepts, technology and flight demonstrator

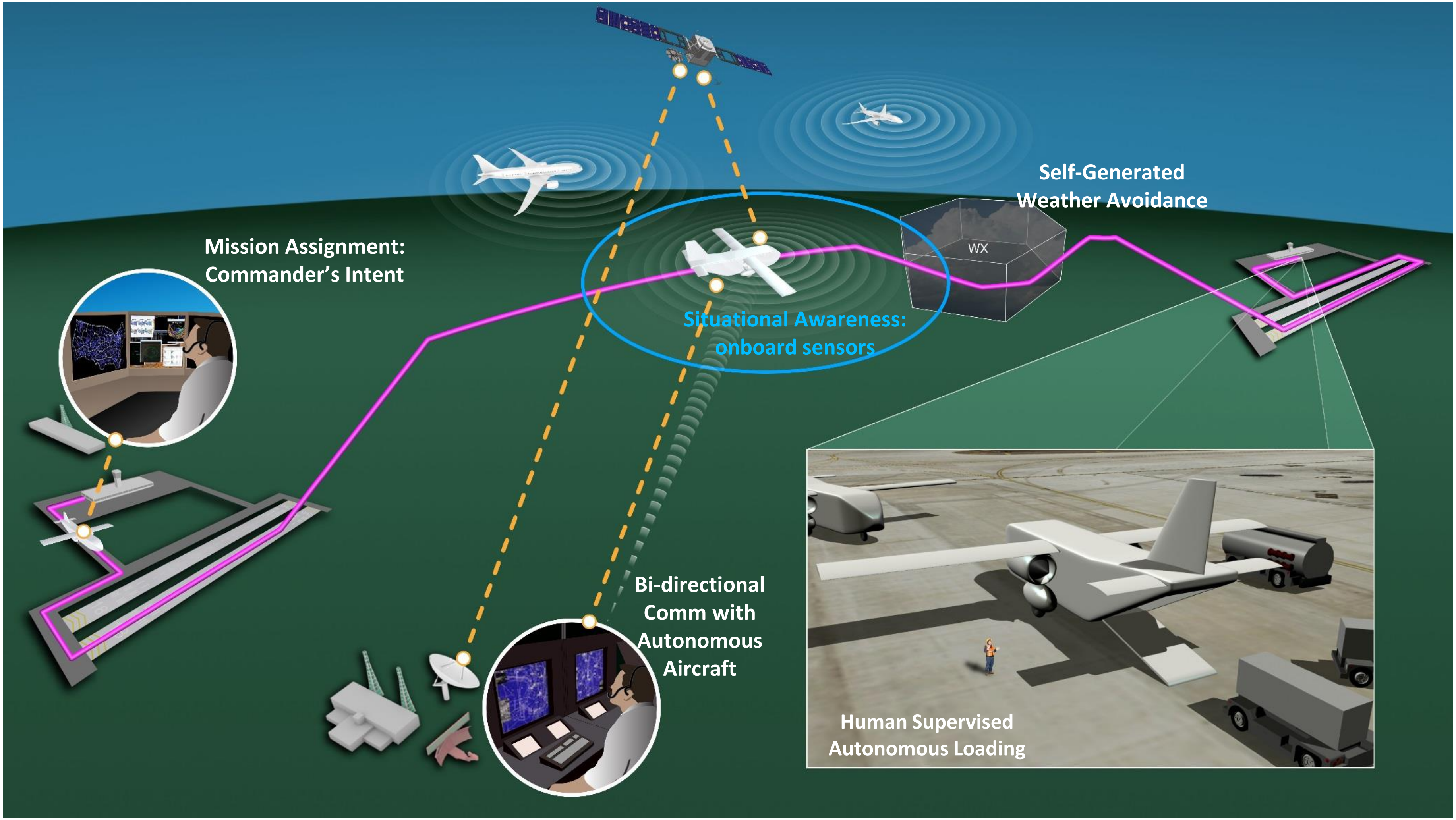
Fully Autonomous Transport Aircraft

Advancement Strategies

Strategy	Description
1a, b	Development of CONOPS and technology requirements, identifying gaps system assurance and certification.
1c	Provides immersion in a paradigm-shifting CONOPS for transport aircraft, leading to establishing a systemic approach to autonomy impact cost/benefit analysis, socialization of new CONOPS and technologies for airframe manufacturers, users and regulators. Slow, systemic buildup of trust in the autonomous aircraft.
1d	Develops system requirements and standards for fully autonomous transport aircraft through spiral development including design and flight test of autonomous aircraft
1e	Identifies technology, tools and methods gaps. Resolves knowledge gaps through design and flight test.
3	Embodies the Revolutionary Autonomy strategy: Clean sheet design-driven; Fully autonomous transport aircraft (no human pilot function) cannot be done without making use of autonomy capabilities; Drives technical advancements and supports technology breakthroughs; Finally, advances autonomy without constraints imposed by legacy systems, legacy infrastructure, regulatory policies and culture.
4	Leverage technology developments for UAS and initial mission/market segment for fully autonomous transport aircraft would use an appropriate size UAS vehicle.
5	Leverages internet-of-things intelligent sensor development, data analytics, SA of the environment
6	Achieves early collaboration on CONOPS, technology development and transfer through mutual-benefit partnerships. Potential co-funding of autonomy technology demonstrator is of mutual benefit. Provides assessment on full impact of autonomy for transport class aircraft.

Fully Autonomous Transport Aircraft

Operational View



13. Mission-Adaptive, Eco-Friendly Autonomous Vertical Lift Vehicles

Goal and Benefits

- **Product:** A small-scale autonomous UAV with reliability and performance enhanced and environmental impacts reduced through use of autonomy-enabled design tools, and operational safety and utility improved through mission-adaptive health state awareness and prediction technologies
- **Autonomy Goal:** Design small-scale Vertical Lift (VL) vehicles as safe, reliable, and eco-friendly through the application of autonomy technologies, and rapidly advance the state of maturity for autonomy technologies that improve vehicle design and vehicle operational safety and efficiency.
- **Benefits**
  - Optimized vehicle performance and efficiency
  - Sustained safety and reliability and reduced environmental impacts by mission adaptive operation.
  - Self-reconfigurable power plants responsive to anomalies/faults enabling safe return to base.

Current-Day Challenges

- Critical VL systems designed to estimated service life in hours - removed from service before reaching these operational hours.
- Manufacturing defects, aircraft environmental and operational conditions can cause system degradation.
- Operational data, propulsion control system and health-state data separately acquired, stored, tracked, trended and monitored.
- Low acceptance of autonomous vehicle in populated areas due to safety and reliability.
- How to assure safety and reliability for autonomous systems is still an open question.
- Technologies for autonomous operation are not ready for wide use.

Concept

- **Integrated design and on-board health state awareness systems**
  - Development of structural and propulsion system design and manufacturing tools and models, used to estimate the system life cycle, integrated with on-board intelligent health-state awareness and regime recognition technologies. The on-board system will learn as the aircraft interacts with its environment, making adjustments, to the reconfigurable power and energy management system, to maintain performance, noise and efficiency based on its mission, operating environment and component status.
- **Autonomous integrated flight/propulsion control system**
  - Development of a new autonomous integrated flight/propulsion control system to maintain optimal power efficiency while adapting to changes in mission from the on-board intelligent health-state awareness and regime recognition technologies. Energy management control strategies will be developed that can take advantage of multiple power sources.
- **Dynamic system models**
  - Development of analysis capabilities and dynamic models to simulate the operating systems, including the modeling of realistic anomalies that can help design and qualify health-state awareness systems, and test their utility in making maintenance decisions demonstrated by validation and verification performance metrics.

Deliverables

- Structural and-propulsion system design tools, dynamic and life models, health-state awareness, regime recognition algorithms and autonomous integrated flight/propulsion control system algorithms for implementation in on-board systems
- Implementation of the technologies into an on-board system
- Demonstration of the on-board system on a UAV

Partner Roles

- NASA develops technologies and initial V&V procedures.
- On-board health monitoring system manufacturers integrates the NASA developed tools with the data acquisitions systems
- UAV designers, manufacturers and operators demonstrate the use and performance of the tools
- FAA involved from the beginning to aid in certification of systems

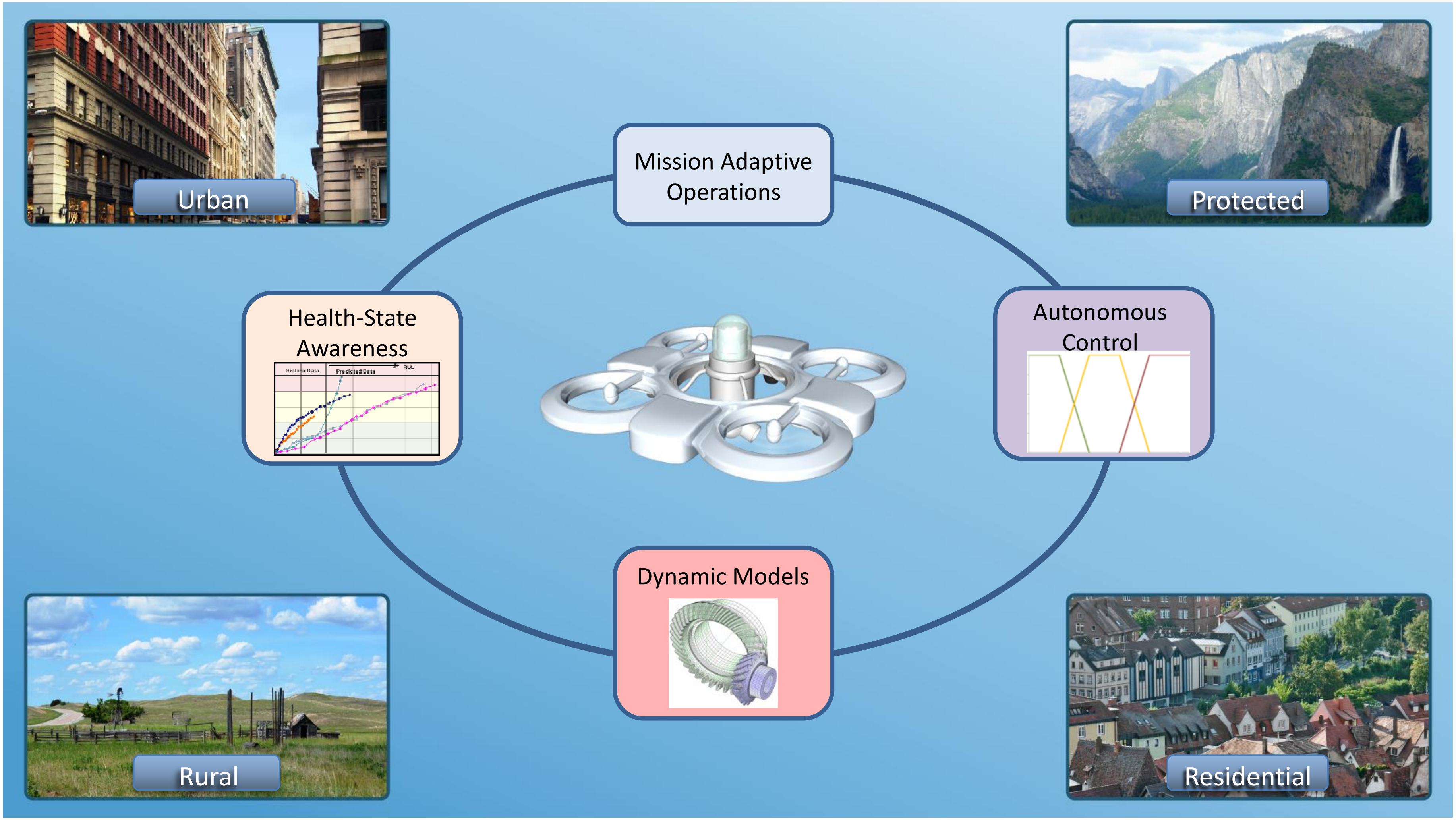
Mission-Adaptive, Eco-Friendly Autonomous Vertical Lift Vehicles

Advancement Strategies

Strategy	Description
1a	Prototype autonomous control and health-state awareness systems.
1b	V & V of autonomous health-state awareness and propulsion control systems.
1d	Qualify health-state awareness systems for maintenance decisions.
1e	Identify and resolve knowledge gaps through lab and field operation.
2a	Validate negative environmental impact (noise, emissions).
2b	Qualify adaptive system response to failure.
3	Demonstrate Mission-adaptive health-state awareness systems.
4	UAV technologies for improved reliability and earth friendly.
5	Utilize automotive and power generation industries modeling and design tools.
6	Leverage community UAS platforms

Mission-Adaptive, Eco-Friendly Autonomous Vertical Lift Vehicles

Operational View



14. Infrastructure for Experimentation, Evaluation, and Testing of Autonomous Systems

Goal and Benefits

- **Product:** Flexible infrastructure for experimentation, evaluation, and testing of autonomous systems and multi-agent collaborations
- **Autonomy Goal:** Enable researchers in academia, industry, and government laboratories to provide consistent benchmarked experimental and evaluation data on autonomous system through well established methods, tools, and infrastructure
- **Benefits**
  - Researchers will have the tools, methods, and infrastructure to develop, integrate, execute, and analyze meaningful experiments on autonomous systems
  - Reusable and reconfigurable tools, methods, and infrastructure will save cost and effort of NASA, academia, and industry researchers
  - Common tools, methods, and infrastructure will provide comparable results across researchers, systems, and designs

Current-Day Challenges

The NRC report identifies "The lack of generally accepted design, implementation, and test practices for adaptive/nondeterministic systems will impede the deployment of some advanced IA vehicles and systems in the NAS" (p 3).

- Infrastructure for Experimentation
  - Current infrastructure does not allow for thorough evaluation of autonomous systems: complex interaction of multiple agents, human-in-the-loop scenarios, complex failure effects analysis
  - Researchers do not have access to comprehensive experimental/evaluation infrastructure for autonomous systems. Experiment/evaluation results are not consistent
  - Data sets from different sources are not comparable due to a lack of consistency in data quality and methods employed
- Autonomous System Requirements
  - Requirements for autonomous systems in aeronautics are not clearly defined, in part, due to a lack of practical experimental results, consistent methods, and tools

Concept

- Experimentation with autonomous systems is necessary in order to understand subtle properties, not-yet-known interactions, emergent behaviors, and other characteristics of autonomous systems
- Researchers from academia, industry, and government laboratories need thorough, versatile, easy-to-use, proven experimental tools, methods, and infrastructure to provide incontrovertible data and results
- Common infrastructure, tools, and methods provide comparable data and results
- Infrastructure includes instrumented test ranges, HMI test laboratories, etc.

Deliverables

- Tools, methods, and infrastructure for experimentation and evaluation of autonomous systems

Partner Roles

- NASA: Develop the tools, methods, and infrastructure; conduct experiments on limited autonomous systems
- Academia: Provide experimental tools and methods; conduct experiments on limited autonomous systems
- Industry (airlines, etc.): Conduct experiments on increasingly complex autonomous systems
- Other government/regulators: Contribute to and benefit from standardized infrastructure and datasets

Infrastructure for Experimentation, Evaluation, and Testing of Autonomous Systems

Advancement Strategies

Strategy	Description
1	Address critical autonomy barrier by developing flexible infrastructure for experimentation, evaluation, and testing of autonomous systems and multi-agent collaborations
2	Experiment and evaluate initial technologies in part to develop tools, methods, and infrastructure to streamline experimentation and evaluation of future technologies
4	Initial focus on the demand for experimentation and evaluation of UAS in relevant environments will enable a rapid development of capabilities.
5	Leverage large investments in non-aviation autonomy technologies by adopting proven tools and methods, incorporating them into an aeronautic evaluation infrastructure.
6	Establish leadership in this area through development of detailed project plans and identification of dedicated workforce and facilities. Identify necessary upgrades to existing laboratories and testing facilities Identify and develop performance benchmarks and metrics for autonomy impacts

15. Initial Certification Standards for Autonomous Systems

Goal and Benefits

- **Product:** Toolset of technologies with potential to enable VV&C of autonomous systems
- **Autonomy Goal:** Breaking through the VV&C barrier through new perspectives, approaches, and methods
- **Benefits**
  - Confidence that Run-Time-Assurance, Continuous Certification, and other approaches to VV&C are viable
  - Autonomy researchers will have a foundation of methods, and metrics necessary for developing autonomous functions which can undergo VV&C
  - Regulators will have the confidence in limited autonomy civil aviation systems to grant certification

Current-Day Challenges

The NRC report identifies "one key, crosscutting challenge" to unleashing the full potential of autonomy in civil aviation: "How can we assure that advanced IA systems – especially those systems that rely on adaptive/nondeterministic software – will enhance rather than diminish the safety and reliability of the NAS?" (pp 32-33)

- VV&C
  - Current VV&C methods are not sufficient for self-governing and complex nondeterministic systems
- Autonomous systems architectures
  - No architectures exist which provide assurance of safety properties of autonomous system
- Cooperation
  - There is not active consortium dedicated to overcoming the VV&C barrier of autonomous systems. An inter-industry cooperate is required in order to ensure interoperability, consistent practices and optimal advancement

Concept

- Current VV&C methods are largely not applicable to autonomous systems
- Without a viable foundation enabling VV&C autonomous systems, little confidence is had that autonomous systems will be able to overcome aviation challenges
- Confidence must be built in the viability of new proposed approaches to VV&C autonomous systems
  - Run Time Assurance
  - Continuous Certification
  - Other approaches
- Initially focusing on well-defined limited-authority autonomous functions enables insight into challenges of VV&C for larger more complex autonomous systems
- An inter-industry consortium will ensure interoperability, standard methods, and robust advancement to overcome the VV&C barrier

Deliverables

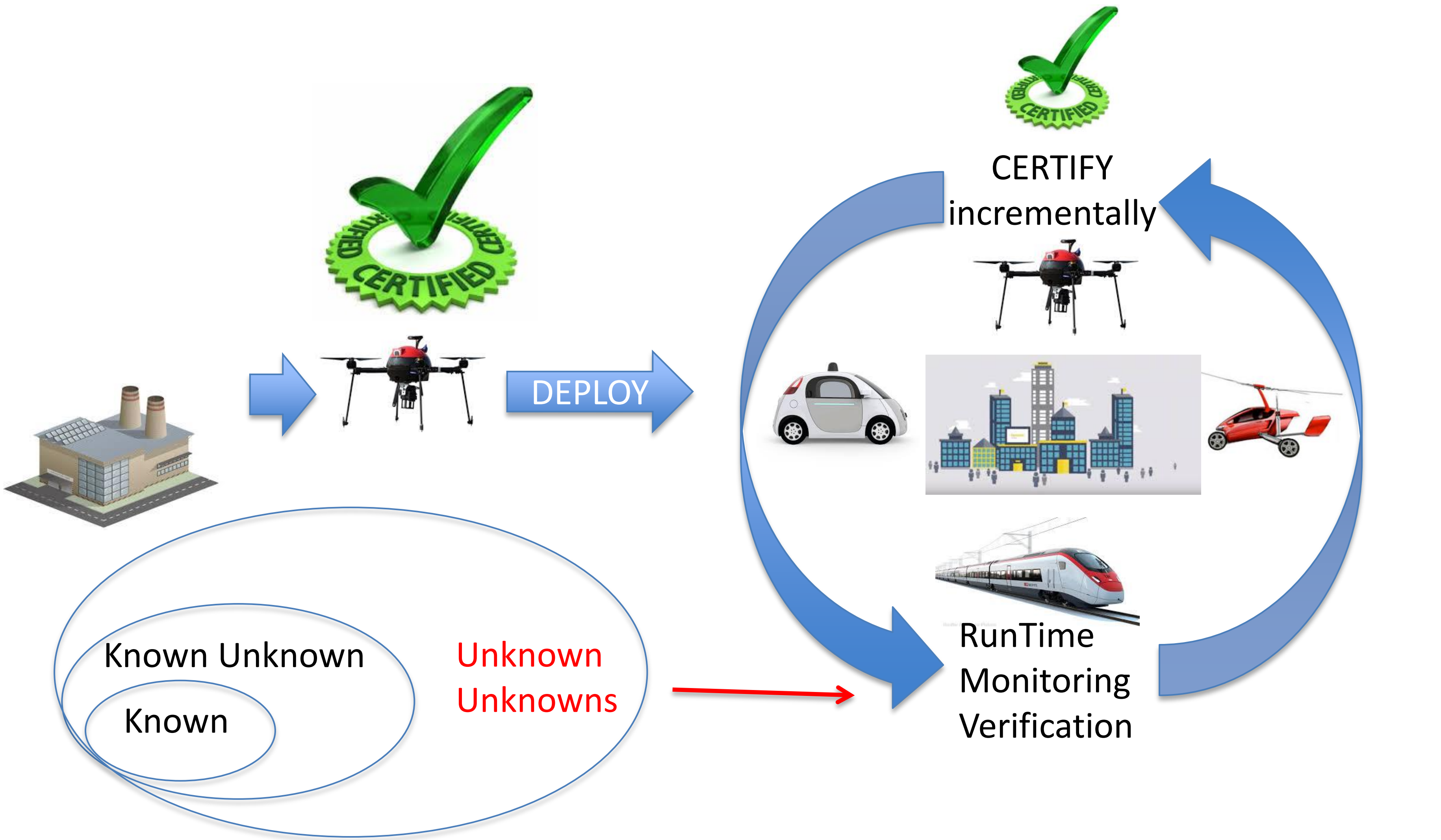
- Toolset of technologies with potential to enable VV&C of autonomous systems including run-time-assurance tools, continuous certification tools , and other tools

Partner Roles

- NASA: Develop and evaluate tools that offer viable VV&C approaches; gather quantitative data on the viability of the approaches; establish an inter-industry consortium to work in partnership to enable VV&C of autonomous systems
- Academia: Develop tools, methods, and metrics
- Industry (airlines, etc.): Application of evaluated approaches to increasingly complex systems

Initial Certification Standards for Autonomous Systems

Operational View



Initial Certification Standards for Autonomous Systems

Advancement Strategies

Strategy	Description
1b	Develop needed tools & methods for assuring and maintaining trustworthiness and certification for complex, nondeterministic systems
1c	Develop methods to evaluate the viability and impacts of autonomous vehicles and operations
1e	Develop metrics, methods and capabilities to assess feasibility, safety, resilience, robustness, trust, performance, and human interactions with autonomous systems
2b	Key enabler to addressing acknowledged aviation safety issues: Identify the system-level and sub-system level metrics for safety and effectiveness impacts of autonomy
4	Initial focus on the demand for experimentation and evaluation of UAS in relevant environments will enable a rapid development of capabilities
5	Will lead an industry-government consortium that will leverage large investments from non-aviation autonomy technologies in V&V methods and autonomous-architecture development.
6	The NASA-led industry-government consortium will 1. Achieve stakeholder consensus on certification standards. 2. Evaluate cost-effectiveness of the proposed enabling V&V toolset

16. Vehicle Structural Health for Maintenance and Safety

Goal and Benefits

- **Product**: Digital Twin for autonomous sustainment/maintenance and real-time structural safety.
- **Autonomy Goal**: Integration of distributed structural sensor network data with model of individual vehicle, decision making on the structural vehicle health and imposition of constraints on performance or mission, and advancement of required autonomous technologies to enable this.
- **Benefits:**
  - Increased flight safety to rarely occurring events by detecting discrete damage and providing feedback to adaptive mission management on what flight constraints would prevent overstressing the structure.
  - Significant cost reductions, increased aircraft availability, and improved fleet management
  - Eliminate costly general periodic checks ("A-Check" through "D-Check")
  - Inspect and repair only when problems have been identified for each vehicle
  - Reduced need for maintenance personnel

Current-Day Challenges

- Design based on conservatively estimated end-of-life structural properties
- Costly development process for large estimated full life cycle structural databases for each vehicle class
- Conservative design philosophy [structural overdesign] - design integrated with an assumed maintenance/inspection schedule for particular aircraft class/model, with maintenance impact on availability based on the schedule rather than actual vehicle state → operational inefficiency and undetected degradation, potential safety hazards
- Excessive barrier to introduction of new technologies:
  - Generation of new databases
  - Unknown risks for structural behavior assessed only during operational inspection
  - Recertification

Concept

- Wide-spread vehicle structures sensor networks to monitor critical internal loads, and structural health/damage characteristics in real-time and during ground checks
- Individual vehicle informatics containing vehicle manufacturing, maintenance, and structural health sensor data (obtained both in real time during flight, and during routine maintenance checks between flights)
- Flight: Real-time, physics-informed models of structural response and structural margins in response to actual and forecast flight maneuvers which allows autonomous adaptive mission management software to maximize vehicle performance while maintaining safety
- Ground: high-fidelity, physics-based models to ascertain structural degradation and repair requirements during ground maintenance
- Techniques for Data Fusion from sources mentioned above for both real-time and off-line structural health diagnosis and prognosis

Deliverables

- Prototype Digital Twin System with the ability to demonstrate:
  - Structural deformation/strain sensor integration and measurement networking into an on-board data acquisition system
  - Sensor/model data fusion to identify discrete source or fatigue damage and estimate reduction in residual strength/structural margins
- Experimental validation of measurement accuracy and residual strength/structural margin predictions described above
- Initial integration of Digital Twin System margin data into flight control system limits
- Prototype initially demonstrated on ground test article, with identification of and planning for an appropriate flight experiment.

Partner Roles

- NASA, Airframe industry, DoD: Ground and flight demonstration

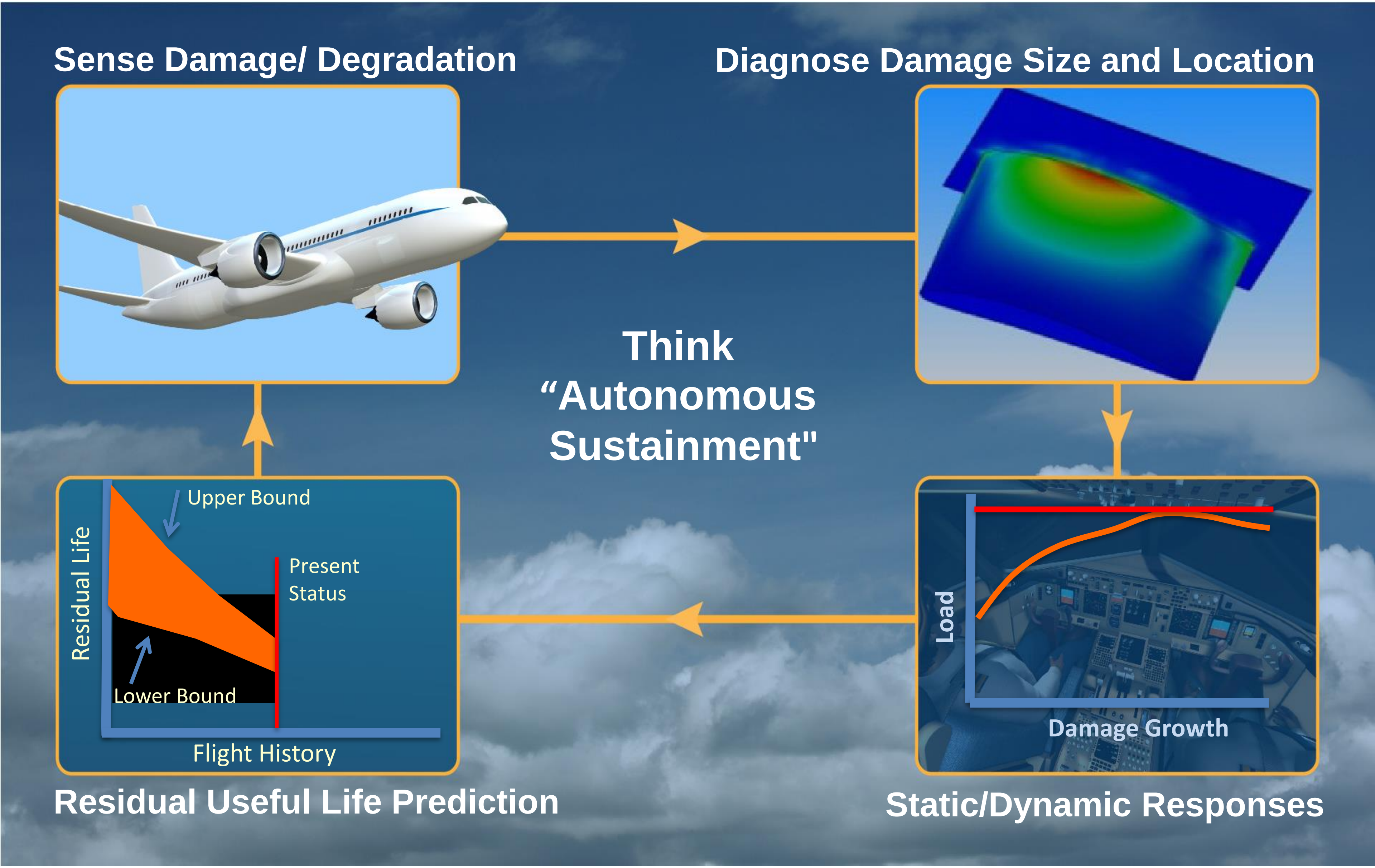
Vehicle Structural Health for Maintenance and Safety

Advancement Strategies

Strategy	Description
1a, b	Developing and assessing methods for design, manufacturing and life-cycle sustainment system for vehicle structural health management system and techniques for its certification
1c	Provides immersion in a paradigm-shifting design, manufacturing and maintenance for aircraft, leading to establishing a systemic approach to autonomous end-to-end individual vehicle structural health management system (Digital Twin), socialization of new approach and technologies for airframe manufacturers, users and regulators. Slow, systemic buildup of trust in the highly autonomous aircraft systems.
1d	Develops system requirements and standards for autonomous individual vehicle structural health management system (Digital Twin), through spiral development including design and flight testing of appropriate experiments
1e	Identifies technology, tools and methods gaps. Resolves knowledge gaps through design and flight test.
3	Embodies the Revolutionary Autonomy strategy: Digital Twin cannot be done without making use of autonomy capabilities; Drives technical advancements and supports technology breakthroughs; Finally, advances autonomy without constraints imposed by legacy systems, legacy infrastructure, regulatory policies and culture.
5	Leverages internet-of-things intelligent sensor development, data analytics, advances in materials and manufacturing
6	Achieves early collaboration on design, manufacturing and maintenance CONOPS, technology development and transfer through mutual-benefit partnerships. Potential co-funding of autonomy technology demonstrator is of mutual benefit.

Vehicle Structural Health for Maintenance and Safety

Operational View



17. Autonomy-Enabled Concepts for Achieving the ATM+3 Vision

Goal and Benefits

- **Product**: Stakeholder vetted autonomy-enabled integrated air/ground concept alternatives that will enable millions of manned and unmanned platforms operating in the US airspace in a safe and efficient manner
  - Develop integrated air/ground autonomy-capable concept alternatives and enabling autonomy technologies
  - Develop models, conduct initial benefits and feasibilities assessments
- **Autonomy Goal**: Advance autonomy technologies to enable future National Airspace System densities, diversities, efficiencies while maintaining higher affordability and competitiveness
- **Benefits**
  - Enable future densities, operator flexibilities while maintaining system efficiencies, safety and affordability for all stakeholders

Current-Day Challenges

- While maintaining priorities of safe, expeditious and efficient flows; operator efficiency suffers which results in delays or excessive fuel burn
- Current roles and responsibilities put the Air Navigation Service Provider (ANSP) in the middle of constraint management and tactical trajectory changes; these human-centric operations limit the scalability
- These problems will only become worse as new entrants, and their volume, in airspace will continue to grow – traditional aircraft, personal aircraft vehicles, unmanned aircraft vehicles, commercial space launches, supersonic/hypersonic vehicles, internet balloons, wind turbines, etc.
- An entire new paradigm is needed where higher densities and diverse users can be accommodated without human workload bottlenecks

Concept

- *Reverse the paradigm of control* – shift responsibilities towards operators and third party service providers for planning under constraints
  - Allow operator flexibility and autonomy by providing information about constraints and other operations instead of creating plans that are checked for demand/capacity imbalance after the fact
- Flexibility where possible and structure where necessary, integration where possible and segregation where necessary
- Leverage common application protocol interface, internet based systems, cloud-based architecture, machine learning, and connected systems to enable operator autonomy
  - ANSP's role is to provide constraints and manage by exception

Deliverables

- Integrated suite of air/platform and ground justifiable autonomy-capable concepts and technologies that are offer strong scalability and affordability benefits as well as early feasibility – with clear roles and responsibilities for users, operations centers, platforms, and service providers
- Demonstration of concepts and technologies in simulation – integrated airline operations, air platform, and service provider capabilities
- Stakeholder vetted justifiable autonomy-capable concept alternatives and human-autonomy teaming alternatives

Partner Roles

- NASA and Private Sector: concepts, architectures, technologies, platforms/vehicles, simulation environment, models
- Airlines: Data and subject matter expertise
- Platforms: Range of small to large vehicle models
- Service Providers: Technology adoption and refinement in collaboration with NASA , subject matter expertise