(A Sample of the)
U.S. Academic Community's Views on Research Contributions to NextGen

Presented by:

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Background

- Formed at the suggestion of Dr. Helen Gill (NSF)
- Group of aviation researchers under the leadership of Prof. Eric Feron
- Purpose:
  - Identify key challenges related to the Next Generation Air Transportation System (NextGen) and its successors
  - Provide a logical path from the (safety-critical) problems faced by NextGen to a list of fundamental research topics

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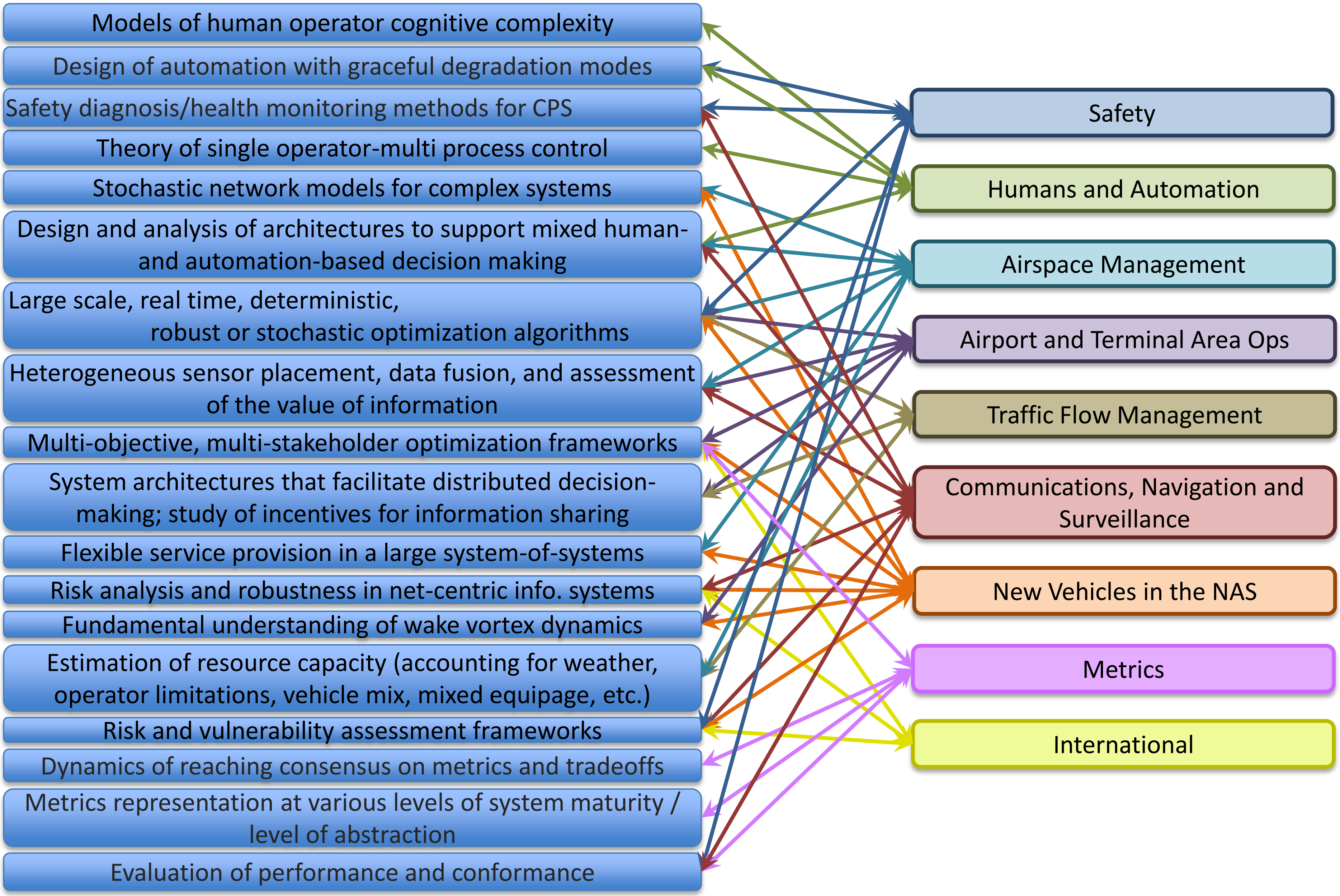
Process

- Initial coordination telecon to brainstorm and identify NextGen “topics”
- Breakout groups formed for each topic in order to identify key challenges and basic research problems associated with the topics
- This presentation is distilled from the output of these preliminary brainstorming sessions

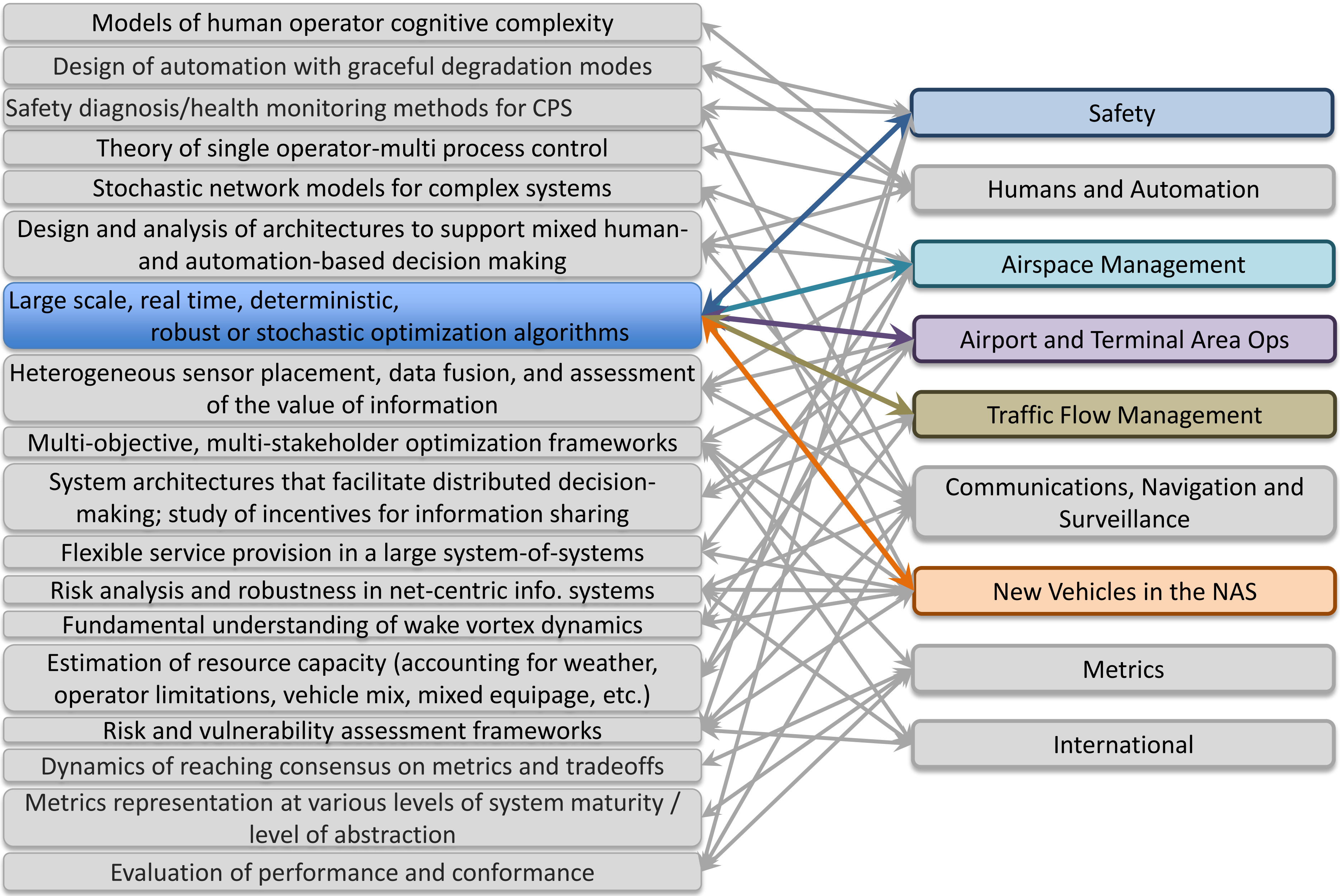
Nine NextGen Topics Identified

1. Safety
2. Humans and Automation
3. Airspace Management
4. Airport and Terminal Area Ops
5. Traffic Flow Management
6. Communications, Navigation and Surveillance Systems
7. New Vehicles in the NAS
8. Metrics
9. International Operations

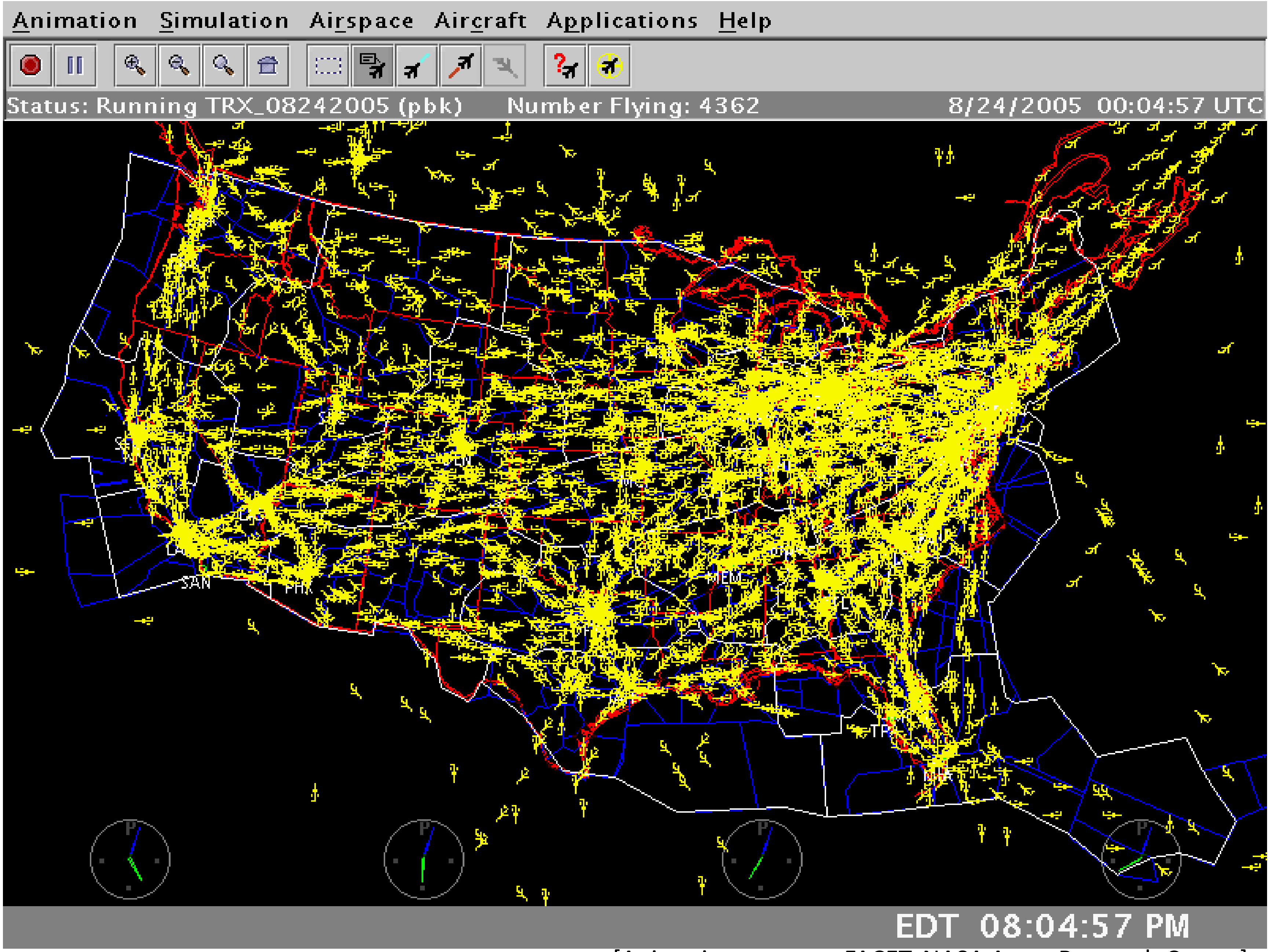
A Mapping of Basic Research Problems to Topics



Basic Research Problem Example

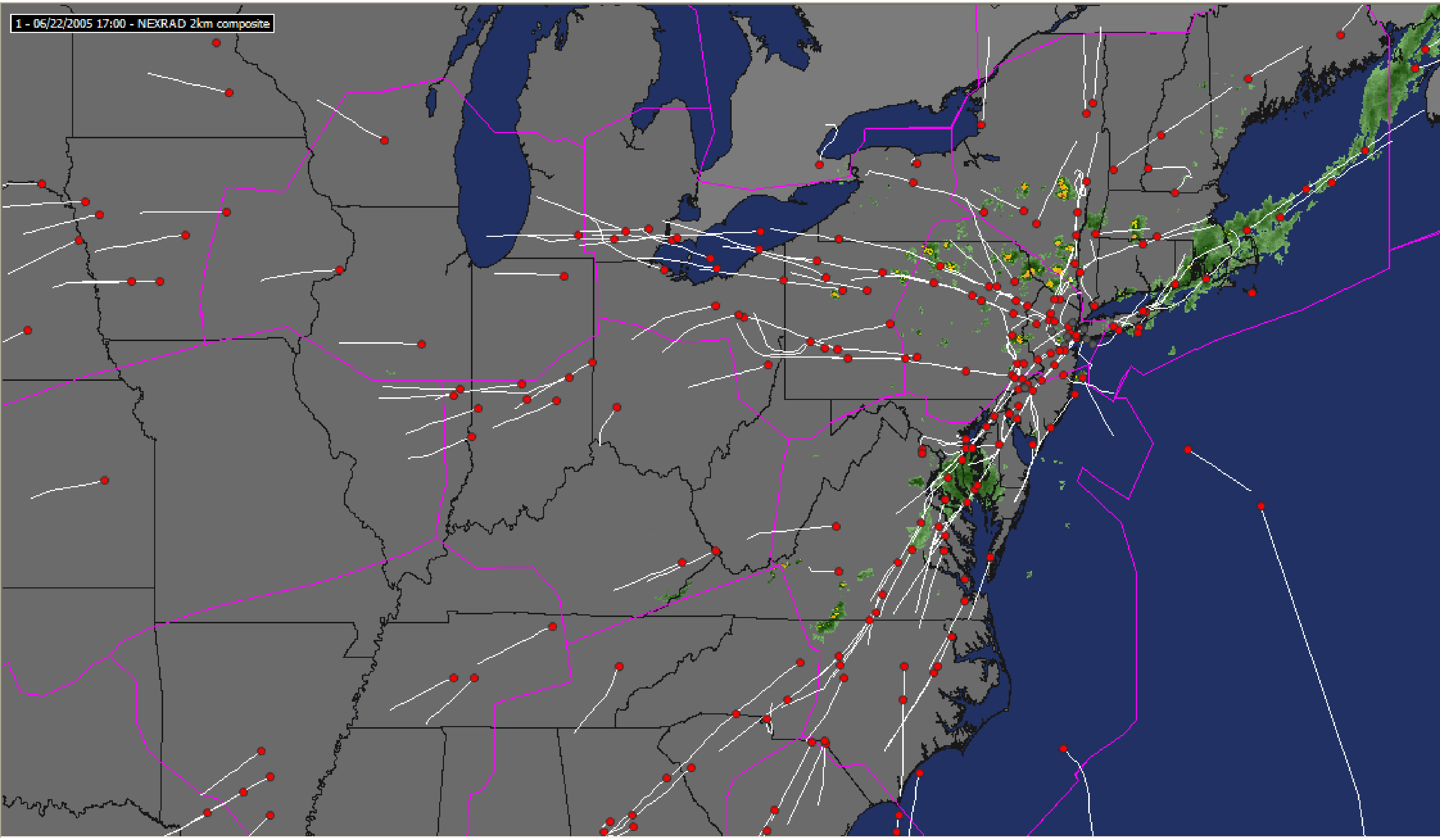


Need for Large Scale Optimization



[Animation courtesy FACET, NASA Ames Research Center]

Need for Robust/Stochastic Optimization

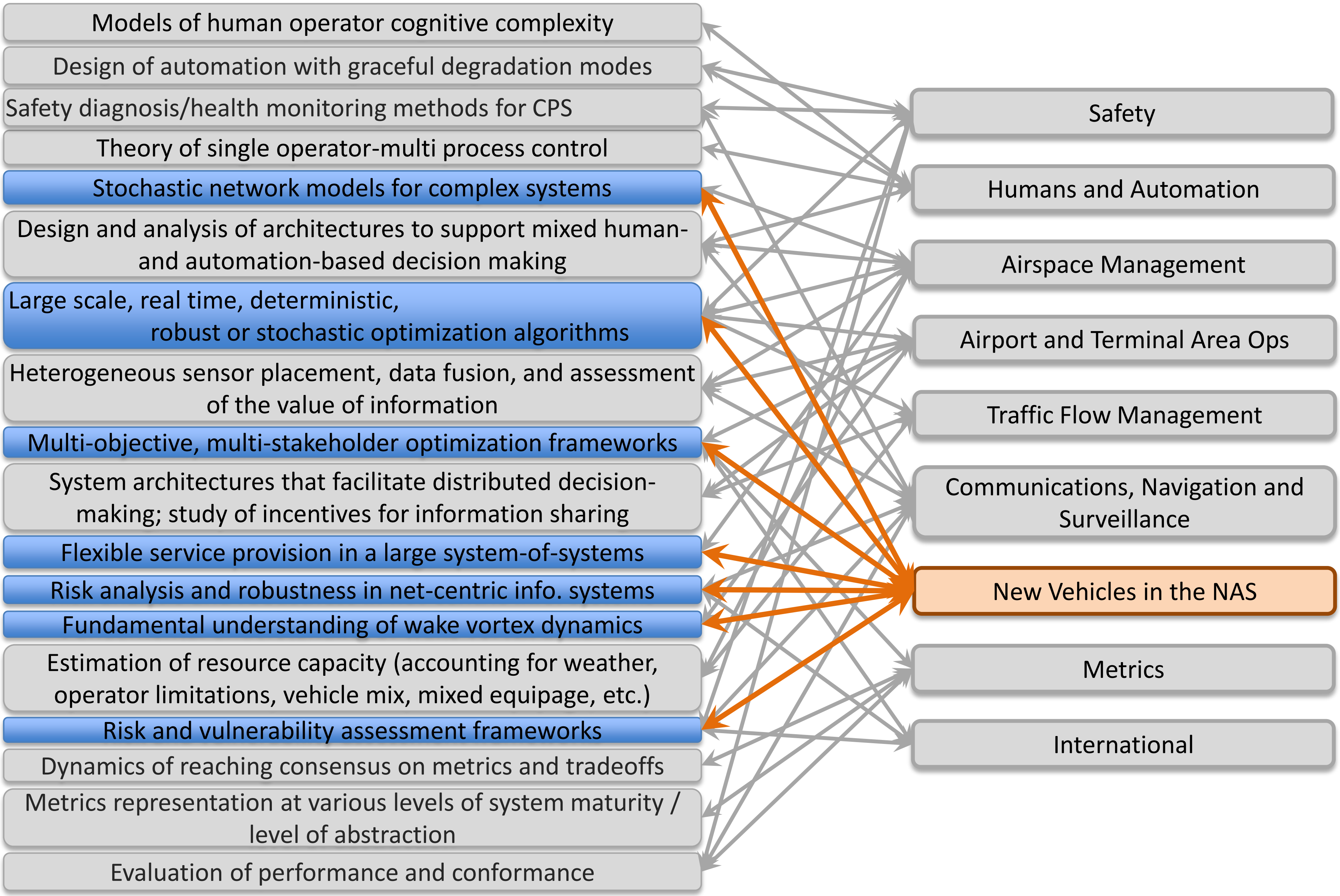


[Animation courtesy MIT Lincoln Laboratory]

Large Scale, Real Time, Deterministic, Robust or Stochastic Optimization Algorithms

- **Safety:** *Conflict resolution subject to scheduling, weather and TFM constraints*
- **Airspace management:** *Computationally efficient optimization methods for large-scale, complex systems with uncertainties*
- **New vehicles:** *Large scale optimization with unique, diverse partitioned spaces*
- **Airport and terminal areas:** *Large-scale, real-time, stochastic optimization algorithms for resource allocation*
- **Traffic Flow Management:** *Computationally efficient, large-scale combinatorial optimization problems*

Example of Topic-focused View

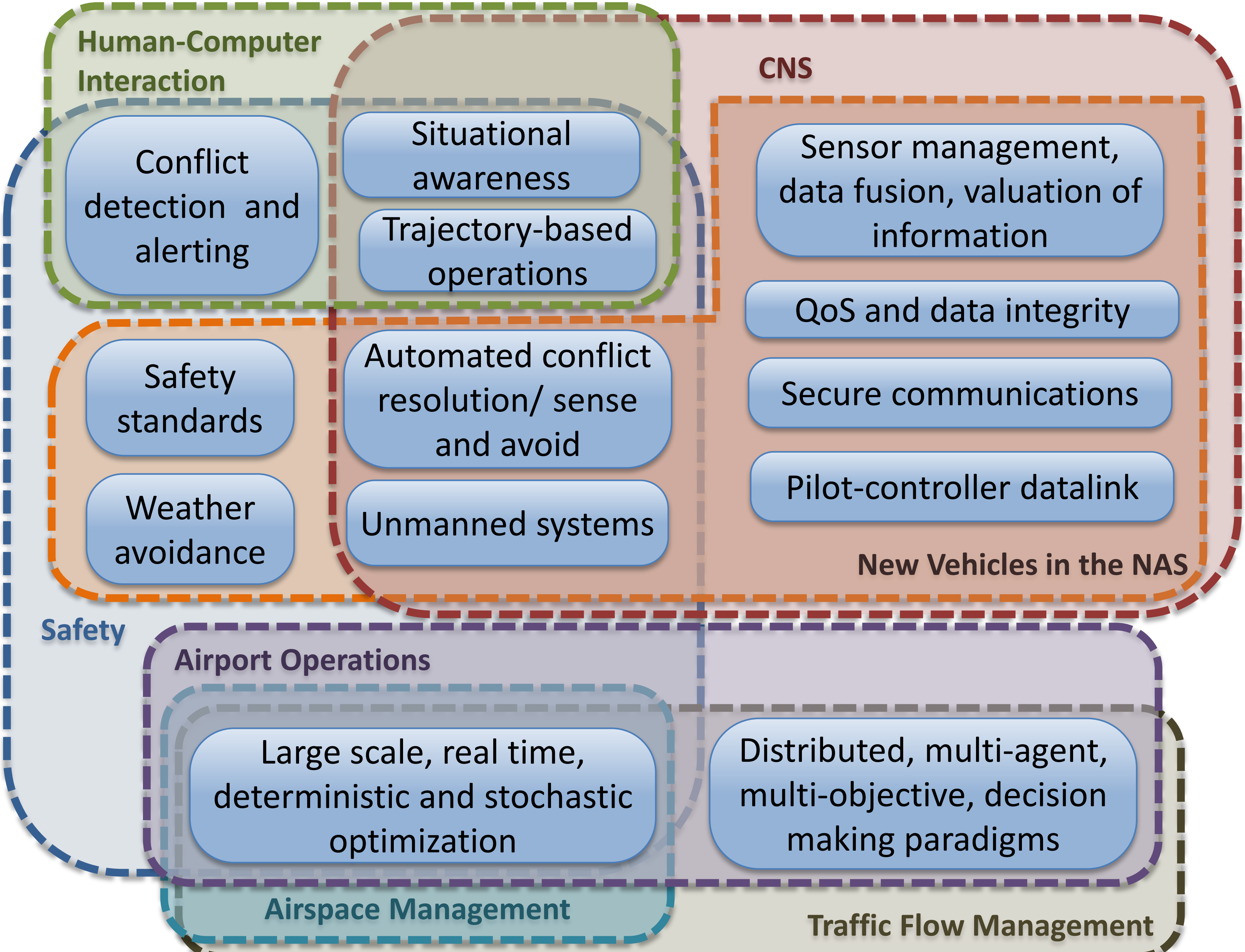


Topic: New Vehicles in the NAS

New Vehicles in the NAS: Basic Research Problems

- Fundamental research needed into flexible service provision in a large system-of-systems
- Sense and avoid capability in autonomous systems
- Large scale optimization with unique, diverse partitioned spaces
- Link analysis and robustness in net-centric information systems
- Multi agent operations when agents have very different characteristics and performances
- Fundamental understanding of wake vortex dynamics, device manipulation, and inclusion in FAA regulations

Many cross-cutting themes



Summary

- NextGen and its associated topics present several fundamental research problems
  - Individual “NextGen topics” require solutions to several basic research problems
  - Many recurring themes among basic research problems
  - Different NextGen challenges and the associated basic research problems are closely related
- Basic research problems are well-aligned with the NSF Cyber-Physical Systems program
- Next steps:
  - Potential reference document with details of discussions on NextGen research challenges

Appendix:
Summary of Subtopic Discussions

NITRD “Safety” focus group

Need for Safety?

- Civil air transport is the safest dynamical system, thus the system at the forefront of safety methods eventually applicable to all cyberphysical systems
- Grand challenge: Develop processes and methods of assuring safety, reliability and availability properties in the complex safety-critical, real-time infrastructure known as NextGen

Different levels of attention to safety

- **Monitor** for safety and **Design** for safety

- **Vehicle** issues and **system** issues
- Traceability through life cycle
- Data-mining challenges

- Many aspects of complex systems safety will follow from NextGen specific **emergent** phenomena

- A naturally very rich field of application of CPS

Interface flow management / Safety:

- Conflict resolution subject to scheduling/TFM constraints
- Trajectory optimization
- Weather/ using aircraft as weather probes / data assimilation
- Conformance monitoring
- Development of dynamic macro-models for network control purposes

- *Basic research issue 1:* combinatorial constraints handling
- *Basic research issue 2*: Online data assimilation schemes
- *Basic research issue 3:* Converting large amount of data into efficient decision support tools
- *Basic research issue 4:* Evaluation of performance and conformance when baseline should be estimated or inferred
- *Basic research issue 5*: Dynamic macro-model for network control

Verification &Validation and Certification (1)

- NextGen evolution and system integration: compositional approaches in software and system design/verification. Need to be able to integrate/replace subsystems and technologies without having to recertify the whole system
- Integration of highly automated systems – analysis of their modes of failure and interaction with humans

- *Basic research issue 1*: Analyses of large CPS systems,
- *Basic research issue 2*: Design of automation with degradation modes that can be handled by humans

Certification, Verification &Validation (2)

- Certification of embedded and real time software at the algorithmic level
- Cost and development time reduction of certified software
- Develop methods for safety diagnosis and prognosis (eg. Qantas engine explosion)

- *Basic research issue 1:* Model-based software validation
- *Basic research issue 2:* Certified-by-design software
- *Basic research issue 3:* Develop safety diagnosis/health monitoring methods for dynamical systems

Data exchange / safety

- Safety and security of data links (e.g. ADS-B and GPS):
- Robustness to cyber attacks
- Passenger network versus safety critical onboard systems

- *Basic research issue 1:* Integrity monitoring of advanced communication systems – Impact of failure on airspace safety
- *Basic research issue 2*: Development of embedded logic which is robust to cyber attacks
- *Basic research issue 3*: Firewall protection between heterogeneous networks

Complex systems analysis

- System wide analysis
- Highly automated system to document, develop and certify the interaction of complex systems
- Development of techniques to enable the design and development of scalable, mixed equipage, quality critical systems

- *Basic research issue 1*: Scalable, property-preserving compositional reasoning for highly interconnected systems
- *Basic research issue 2:* Mathematical modeling /abstractions of subsystems
- *Basic research issue 3:* Components health monitoring
- *Basic research issue 4*: Making formal proofs on complex systems accessible to humans
- *Basic research issue 5*: Designing fault protection envelopes for CPS

NITRD “Humans & Automation” focus group

Challenges in Humans and Automation

- Decision Support
  - Effective use of the new information streams in NextGen?
  - Appropriate abstractions and interfaces?
- Human Factors
  - Human capabilities and liabilities?
  - Robust and effective work constructs?
- Mixed Human-Automation Design
  - Systematic processes?
  - Evaluation of design methodologies?

Recommended Basic Research

- Need quantitative models for the conditions under which human operators may inject errors into the decision process and when they instead reduce the operational complexity
- A systematic theory is missing for how to enable single operators to interact with and control multiple automatic processes
- Should understand the function and interaction of different modules of human movement control and cognitive tasks, as required by NextGen systems
- Characterization of effective design flows that explicitly supports human and automation-based decision making

Topic: Decision Support

- How make effective use of the new information streams that will be made available, e.g., through the ADS-B in order to effectively integrate human and automatic decision makers?
- What are appropriate abstractions and interfaces that allow human operators to participate in air traffic management alongside automatic processes in an intuitive yet effective manner?

Topic: Human Factors

- In some situations, humans are potential causes for errors, while in others, they are highly effective at overcoming complexities. How should these diverging human capabilities and characteristics be harnesses within the NextGen framework?
- In aviation, the breakdown is typically not in human performance or automation per se, or their interface, but rather in work constructs that are too complex, or too brittle, to provide efficient, repeatable, robust operations. How can this challenge be overcome?

Topic: Mixed Human-Automation Design

– What are the systematic processes through which human performance can be incorporated into the design of NextGen in an integrated fashion?
– How can integrated human-automation design paradigms be evaluated and tested?

NITRD “Airspace Management” focus group

Challenges in Airspace Management

- Modeling and analysis of airspace structures/operations to accommodate uncertainties in air traffic, weather, human factors, etc
- Designing efficient, provable and robust ways of analyzing a set of 4D trajectories
- Dynamic airspace reconfiguration to cope with ever changing traffic
- Workload metric and workload transition
- Automated safe separation assurance
- Modeling and prediction of weather
- Decision supporting tools for airspace management

Recommended Fundamental Research

- Robust and stochastic networked system modeling which can account for the complex nature of the networked system and various uncertainties in it
- Research on human factors
- Computationally efficient optimization methods for large-scale, complex systems with uncertainties
- High-confidence systems and software

Topic: 4D Trajectory Planning

- NextGen (and SESAR) introduces a new basic object in ATM : the 4D trajectory planning.

- Basic research needs
  - It is thus of primary importance to design efficient, provable and robust ways of analyzing a set of 4D trajectories.
  - Associated complexity and robustness have to be also managed.
  - 4D trajectories planning has its roots in geometry and topology and some obstructions to reach a conflict-free situation are a consequence of the state-space structure.
  - Complexity of traffic, interpreted as an intrinsic severity/robustness measure, is related to dynamical systems theory, approximation and interpolation algorithms and geometry.

Topic: Dynamic Airspace Configuration

- Airspace for NextGen needs to be flexible, dynamic and adaptable based on traffic demand, equipage, and weather.
  - Reconfiguring airspace
  - Adaptable airspace
  - Generic airspace

- Basic research needs
  - Research on human factors, especially workload.
  - Efficient and provable optimization methods for large-scale, nonlinear complex systems with uncertainties
    - Simple, efficient, robust and safe.
  - Related to trajectory optimization, separation assurance, super density and metroplex operations airspace topics.

Topic: Conflict Detection and Resolution

- NextGen: use Datalink com to share information
- Basic research needs
  - Robustness to uncertainties and errors.
  - Efficient and provable optimization methods.
  - Need to deal with incomplete information.
  - HMI issues: how do you show conflicts to controllers and pilots?

Topic: Decision Support Tools for Airspace Management

- High-confidence systems and software for NextGen airspace management
- Basic research needs
  - Systems must be robust and degrade gracefully.
  - Applied distributed systems theory.
  - New techniques for demonstrating safety and reliability in analyzing conflict detection simulation.
    - New decision procedures, proof techniques, etc.
    - Abstracting away almost anything in the analysis (floating point arithmetic, turn dynamics, etc.) seems to affect the analysis to the point of leaving corner cases open. How do we get sufficient coverage?
  - HMI issues
    - Well-defined interfaces among different modes/components.

Airport and Terminal Airspace Operations in NextGen

Airport Operations

- Airports are the critical nodes of the air traffic network.
- Airport capacity drives system capacity.
- Important to consider interactions between airport and airspace operations.
- Key research issues include
  - Efficient utilization of existing and new infrastructure.
  - Enhancing safety of surface operations.
  - Minimizing environmental impact (noise, air quality).
  - Improving coordination and distributed decision-making (especially in congested, multi-airport terminal-areas).

Efficient utilization of airport resources

- Improved scheduling of ground resources (e.g., runways) to maximize airport throughput.
  - Wake vortex studies for determining separation standards for new aircraft types.
  - Algorithms for runway configuration scheduling, including in multi-airport contexts, using weather and demand forecasts.
  - Integration of surface surveillance data into real-time resource scheduling and decision-making.
- *Basic research question:* Large-scale, real-time, stochastic optimization algorithms for resource allocation.

Enhancing safety and situational awareness

- Airport surface is shared by aircraft, ground support equipment, ground crews, etc.
- Minimizing runway incursion incidents and improving situational awareness on the surface.
- Using surface surveillance (sensor) data to
  - Improve predictability of airport processes.
  - Assess value of information for surface sensor data.
  - Integration of various data sources (radar, ADS-B, ASDE-X, weather from ground and onboard sensors).
- *Basic research question:* Heterogeneous sensor placement, data fusion, and assessment of the value of information.

Mitigating environmental impacts

- Airport and terminal-area operations have significant impact on low-altitude noise and emissions, and therefore air quality.
- Important to balance environmental objectives with those of maintaining safety and throughput.
- Multiple stakeholders with competing objectives (airport operators, airlines, ATC, neighboring communities).
- *Basic research question:* Algorithms for multi-objective, multi-stakeholder optimization under uncertainty.

Distributed Decision-Making

- Many congested airports in the network results in decision-making at different parts of the system
  - Efficiency requires coordination between multiple decision-makers, while maintaining distributed decision-making
  - Enables efficient, flexible and responsive airport operations in a dynamic environment
  - Information-sharing enabled by CNS technologies such as ADS-B and datalink
- *Basic research question:* System architectures that facilitate distributed decision-making, and study of incentives for information sharing.

Traffic Flow Management

Basic observations

- Traffic Flow management is about expediting air traffic through macroscopic operations involving dozens or hundreds of aircraft at once.
- Include activities such as opening/closing sector due to weather.
- Ground delay programs to match arrival demand to available airport capacity
- Central Flow Management Units in US and in Europe

Airspace Capacity

- Airspace Capacity is one of critical elements of TFM.
- Airspace operation dominated by human actors and current capacity figures rely on human experience
- Airspace capacity depends on airspace geometry, traffic characteristics, and human/automatic operator
- Flow rates in and out of airspace may temporarily greatly exceed acceptable rates over the long term
- Capacity significantly affected by weather

- *Basic Research Issue 1:* Define and compute the capacity of a 3-D volume under various communication and control protocols.

Analytics of TFM

- Aircraft flow management huge optimization problem.
- Simplest instance is multi-commodity network flow problem with capacity constraints at nodes, including sinks.
- True problem involves several decision makers involved in a real-time traffic optimization process
- Hedging strategies at core of well-designed traffic flow management (Traffic Services Provider) and aircraft routing (Airlines)

- *Basic Research Issue 2: Develop computationally efficient, large-scale combinatorial optimization problems*

- *Basic Research Issue 3: Develop a unified approach to include real-time considerations in large-scale, combinatorial optimization problems, including stochastic programming*

- *Basic Research Issue 4: Introduce robustness and flexibility concepts in real-time, large-scale combinatorial optimization problems*

Communication, Navigation and Surveillance

Challenges in CNS

- NextGen depends on improved communication, navigation, and surveillance (CNS)
  - Trajectory-Based Operations
  - Improved and common situational awareness
- Future air transportation system is an embedded system with components connected via wired and wireless communication
- Data communication replaces controller/pilot voice communication
- Migrating from point-to-point to service oriented architecture
- Automatic Dependent Surveillance Broadcast (ADS-B) and GPS replaces RADAR in both air and ground traffic management

Surveillance

- Improved surveillance to maximize state information
- What is the impact on human factors in changing communication patterns
- Pilots will no longer have access to the traditional party-line voice communication
- How will changes in communication patterns, sensor failures, and blind spots in sensor networks affect state information and control
- What are the consequences of replacing RADAR coverage with ADS-B
- Basic Research: How information impacts the manner humans make decisions, managing uncertainty in systems theory, assessing the quantitative impact of information sources

Interacting Components

- Many components
  - Surface management, tailored arrivals, ...
  - Interfaces need to be well specified
- How to architect a system that evolves over the decades as technology and requirements changes
- Need architectural patterns that incorporate fault detection techniques
- Basic Research: Specifying and verifying flows of authority among human and automated components in complex systems, designing systems for evolution, logical and statistical fault detection

Data & Communication

- What quality of service (QoS) guarantees are needed to ensure safety?
  - Spatial and temporal accuracy of surveillance data
  - Data drop rates
  - Availability
- How to we analyze and track information flow
  - Ensure separation of flight critical information from passenger information
- Improve management of many data streams
- Basic Research: Data fusion, filtering, and smoothing, data provenance, simulation and analysis techniques for safety-critical networks, information flow theory applied to safety polices

Security in NextGen

- ADS-B and GPS have no cryptographic protections and not likely in foreseeable future
  - ADS-B spoofing has been demonstrated
- Need new surveillance techniques that validate the integrity of CNS data
- How to best secure and and voice communication
  - How can we scale a cryptographic infrastructure to enable authenticated/secure communication in such an open system?
- Need new techniques for aircraft conformance monitoring
- Basic Research: Scalable cryptographic infrastructures, detecting and mitigating attacks against sensor networks

Manageable and Reliable

- Advances in network configuration management technology and techniques needed
  - Current FAA network has ~17K network devices, but must grow
  - In Nov 2009 configuration errors brought current FAA network down and air traffic to crawl
  - New methods to update, verify, and validate configurations on the fly
- Need architectures that are robust, reconfigurable, reliable, and gracefully degrade
  - Reacts and compensates for outages
  - Redundancy and design diversity
  - Account for humans in loop
- Basic Research: Develop a discipline of complex system configuration, verification of system architectures, robust and fault-tolerant systems design

New Systems in NAS

Context

- In addition to increases in throughput, safety, etc, NextGen must accommodate new vehicle types that the industry may bring into existence
- NASA funded two large research projects in 2007-2009 to identify any research issues associated with integrating new vehicles into a (NextGen-enabled) future NAS
- Wide range of vehicles covered
  - UAS (of different classes)
  - Supersonic
  - ESTOL
  - Super Heavy (A-380 size)
- Some findings pointed toward technology issues, but some (many) were also procedural
  - And the issues/needs varied widely across vehicle classes

Probing the link between new systems and NextGen (1)

- New vehicles need to have optimized “business-case” trajectories in order to be economically/operationally viable
  - NextGen’s services must be flexible and scalable
- Needs of Super Heavies
  - Precision surface movement monitoring to support Super Heavy Transports
  - Separation and wake vortex
    - More super heavies cause higher separations, lower capacity
- Across all vehicles, need better predictive safety analysis at conceptual stages
- For UAVs, sense and avoid capability in autonomous systems for integrated airspace
- Segregated airspace mixed with 4D Trajectory management
- UAV integration with NextGen concept of Net-enabled ops
  - Managing efficiency and cyber-security in information network

Probing the link between new systems and NextGen (2)

- Mixed equipage issues
  - new systems are likely to be equipped with new technologies enabling them for more complex operations; older systems won’t
- Integration of fuel/noise optimal operations for the new types of aircraft
  - The new types of aircraft have different performances (VTOL, VLJ with very high climb rates). To obtain the maximum benefits from the new aircraft types, the new conops should be able to accommodate everyone.

Extending to basic research needs

- Fundamental research needed into flexible service provision in a large system-of-systems.
- Sense and avoid capability in autonomous systems
- Large scale optimization with unique, diverse partitioned spaces.
- Link analysis and robustness in net-centric information systems
- Multi agent operations when agents have very different characteristics and performances
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NextGen Metrics

Air Transportation Metrics

1) Access,
2) Equity
3) Cost effectiveness,
4) Efficiency,
5) Flexibility
6) Predictability
7) Environment
8) Capacity
9) Safety
10) Security
11) National Defense
11) Global interoperability
12) Human factors (workload,
    situational awareness, etc.).

FAA proposed performance metrics (Source GAO)

JPDO's proposed performance metrics

Our group

From GAO (July 2010)

Metrics Have Yet to Be Developed to Measure the Performance of NextGen Improvements in Relation to Specific NextGen Goals, but Some Performance Metrics Are Available for Specific Programs

Finding appropriate metrics

- “Devil is in the details”, from concepts to math
- Metrics negotiated among stakeholders
- Current metrics are incomplete: eg related to the “physical” part of NextGen, but usually not to the “cyber” part. Example: Capacity offers obvious physical interpretation, what is the cyber component?

- *Basic research 1:* The dynamics of reaching consensus on metrics and trade-offs when several actors are present.
- *Basic Research 2:* Observability into the cyber- and physical-contents of the system generated by each metric.

Use and Usability of Metrics

- Metrics become part of optimization system and part of measurement system
- Metrics accuracy and importance may evolve from system design to operations to upgrades

- *Basic Research 3:* Metrics representation at various levels of system maturity / level of abstraction
- *Basic Research 4:* Ability for Metrics to be captured in efficient optimization / monitoring schemes

International Issues

Basic observations

- Air transportation inherently international
- The same aircraft need to fly, communicate and navigate over wide variety of countries
- New threat environments (terrorism)

Identity management

- Tagging of people/cargo/items
  - –Secure supply chain across borders
  - –“Fast pass” across skies.
  - –People carry Passport with them
  - –What’s electronic tagging?
  - –Machine Readable Document (MRD)
  - –In some situations: Maintain anonymity (eg Air Force One on visit abroad)

Basic research issue 1: Secure and convenient electronic tagging of people and goods, when documents & goods are not necessarily collocated.

NextGen vs Rest Of World

- NextGen must interface with the rest of the world
  - Different CNS infrastructure (including none)
  - Different procedures
  - Issues at the boundary

- *Basic research issue 2: Multi-agent dynamic system under heterogeneous control laws.*

Secure Data-Link Communications

- Today, anyone can jam/spoof ADS-B communications with equipment worth $500 from Radio Shack

- What if ghost aircraft are suddenly plotted on the controller's screens in dense areas ?

- Data-Link Communications need to be secure before voice communications are replaced – voice communication contains useful “fingerprint” information

- This is an Important Cryptography issue

Basic research issue 3: Build appropriate, secure communication systems throughout air transportation system. Peer-to-peer security.

How can Data-Link communication replace voice communication ?

- How can Data-Link communication replace voice communication ?
- Voice Communication informs pilots on:
  - Surrounding traffic
  - The controllers workload
- Controllers also get information on pilots stress and level of emergency (cf Avianca Flight 52 accident)

- Can Data-Link replace Voice Com ?

- How can Data-Link Com keep the same level of information as Voice Com ?

- *Basic research issue 4:* System observability with humans-in-the-loop under various communication media, and different languages.

What data for what trajectory prediction?

- Every country share the same aircraft and will share the same downloaded data.
- Nextgen is about taking the best benefit of the available data by using Data-Link
- What Data should be sent to the ground to meet ground trajectory prediction requirements ?
- How can we build efficient ground trajectory prediction with missing data (ex: aircraft weight, pilot intent) ?
- *Basic Research issue 5:* trajectory prediction with missing data.