A Safety-Driven Framework for Developing System Architectures

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The Evolution of Complex Systems

More Components,
More Connections,
More Software

Increasing Emphasis on Desired Properties

Safety

Cybersecurity

Sustainability

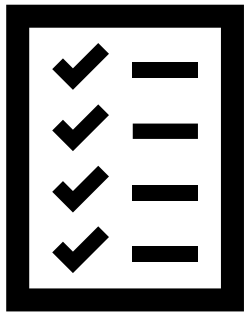
Need to design desired properties into the system architecture

[1] Image from: https://www.wired.com/2016/12/googles-latest-self-driving-car-minivan/
[2] Image from: https://www.aurora.aero/urban-air-mobility/
[3] Image from: https://www.nats.aero/news/london-city-is-first-major-airport-controlled-by-remote-digital-tower
[4] Image from: https://www.theguardian.com/technology/2023/aug/01/uber-self-driving-arizona-deadly-crash
[5] Image from: https://onboard.thalesgroup.com/connected-cybersecure-aircraft-tackle-challenge/
[6] Image from: https://www.cnn.com/2024/02/21/climate/space-debris-solution-climate-scn/index.html

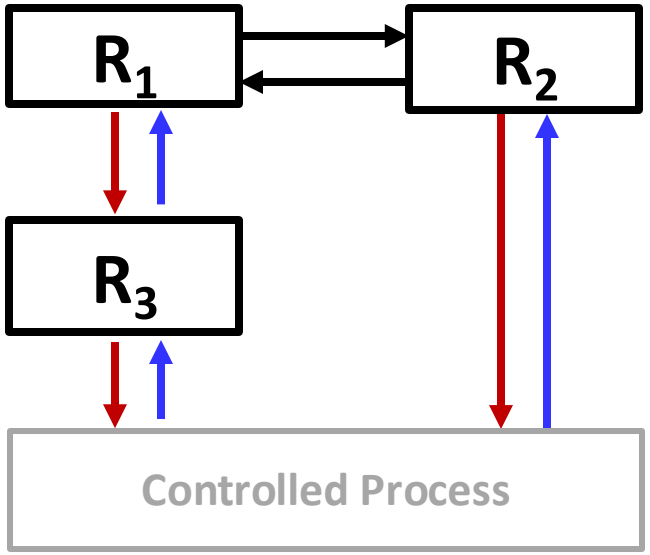
Types of Design Decisions in Architecture Development

System Architecture: Description of system entities and relationships between them

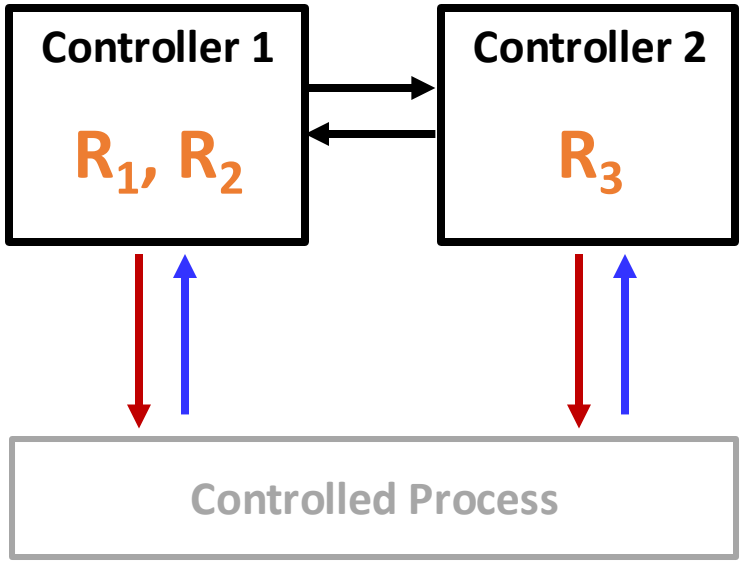
1 **Identify System Requirements**



2 **Define Responsibilities (Functions) & Relationships**



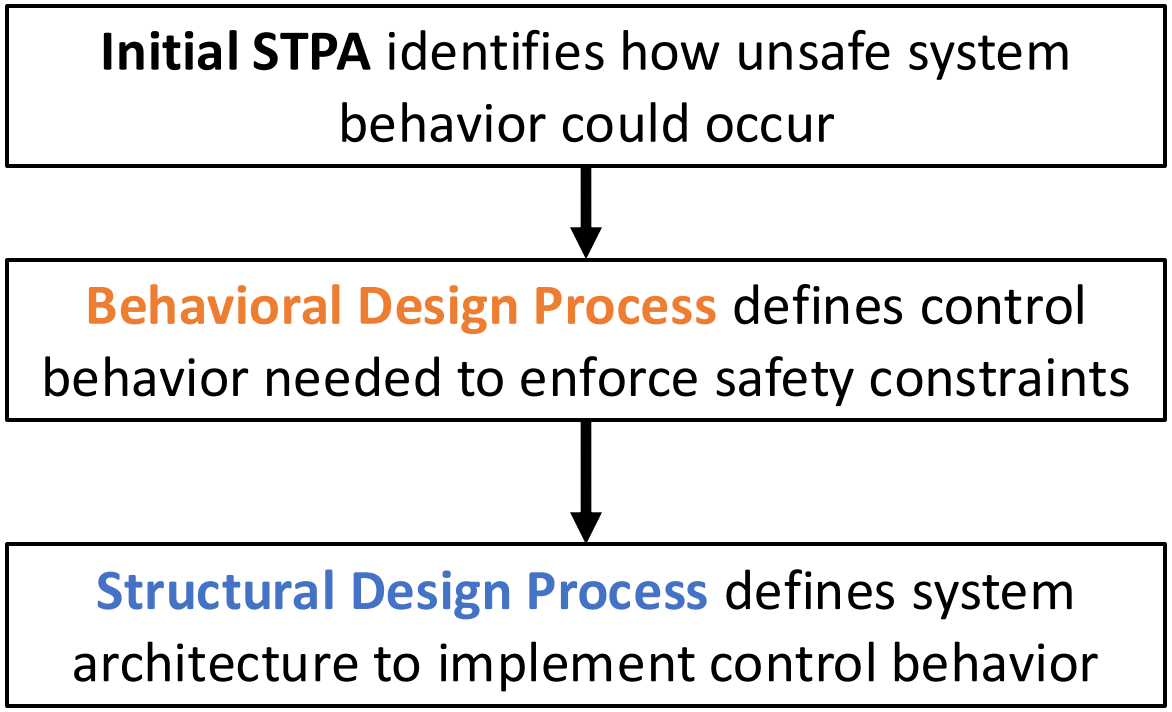
3 **Allocate Responsibilities to System Elements**



Research Objective: Develop a framework for considering safety upfront when making these design decisions

Overview of Framework

Approach: STPA drives design decisions



Key Output: Conceptual Architecture
Functional control structure of desired control behavior

Key Output: Benefits & Tradeoffs
Used to inform decisions about the preferred system architecture

Result: Safety designed into the system architecture from the beginning

Case Study: Urban Air Mobility

- **Urban Air Mobility (UAM)**: On-demand cargo or passenger flights within a metropolitan area
- Today's air traffic management system not designed to handle UAM air traffic characteristics


[7]

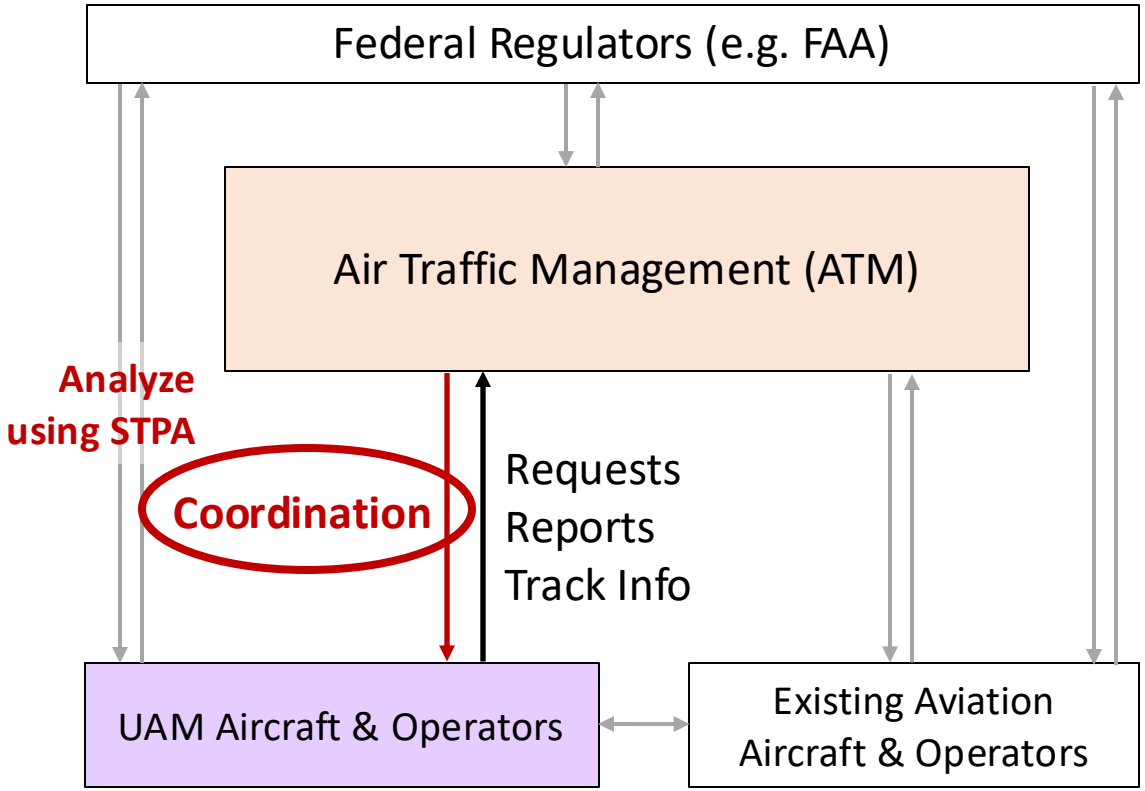
Case Study Goal:

Develop an alternative air traffic management architecture to safely manage UAM air traffic (prevent collisions)


[8]

[7] Image from: *NASA, Urban Air Mobility OpsCon: Passenger-Carrying Operations, May 2020*
[8] Image from: UAM Vision Concept of Operations (ConOps) UAM Maturity Level (UML) 4, Version 1.0, NASA (2020)

Part 1: Early-Stage STPA Analysis of ATM System



Start: Abstract ATM control structure

Unsafe Control Action: Air Traffic Management (ATM) does not **Coordinate Aircraft Movements** when a collision between two aircraft is imminent

Causal Scenario: ATM receives feedback about a conflict (potential collision) but is preoccupied addressing other conflicts and does not address this one

Part 2: Deriving Desired Control Behavior From STPA Scenarios

Input: STPA Scenarios

1. **Derive System Requirements:** Safety constraints to mitigate or prevent unsafe behavior

2. **Define Control Elements & Relationships:** Responsibilities, control actions and feedback needed to meet system requirements

Output: Conceptual Architecture

Functional control structure representing desired control behavior

Example: Deriving Collision Avoidance Requirements

Causal Scenario (from STPA): ATM receives feedback about a conflict (potential collision) but is preoccupied addressing other conflicts and does not address this one

Req-1: ATM system must coordinate the movement of aircraft to resolve any identified conflicts

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System Requirements

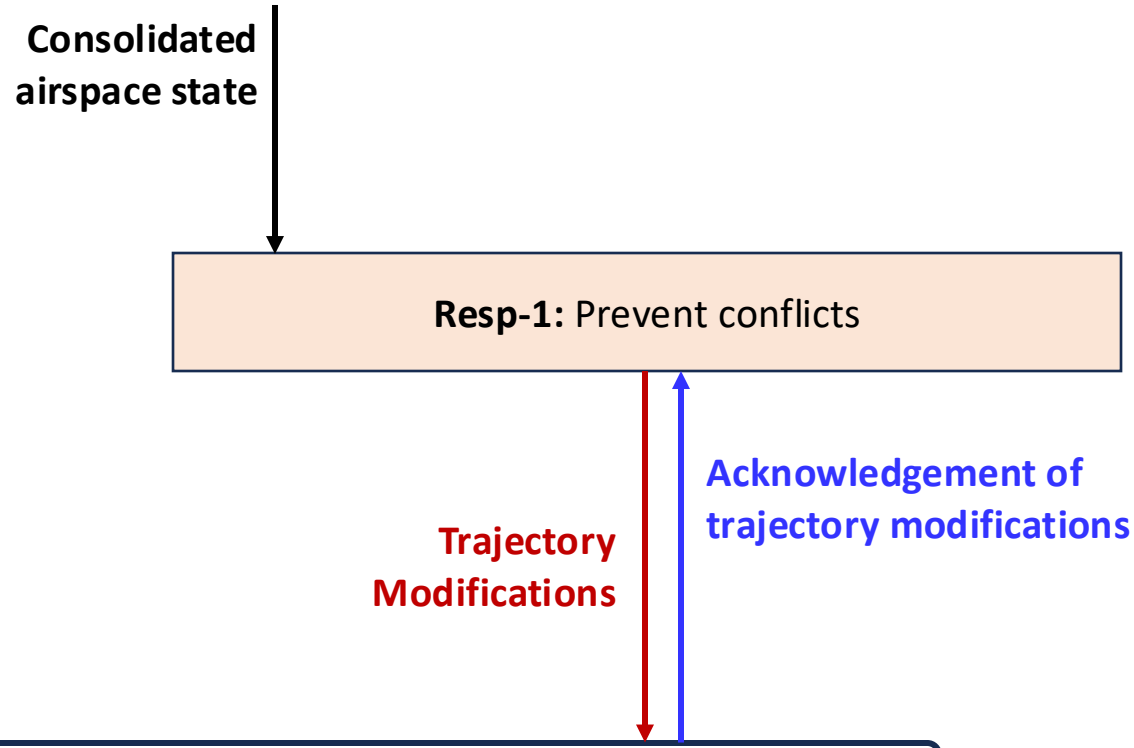
Req-1: ATM system must coordinate the movement of aircraft to resolve any identified conflicts

Req-3: ATM system must only allow as many aircraft to access the airspace as it is capable of managing

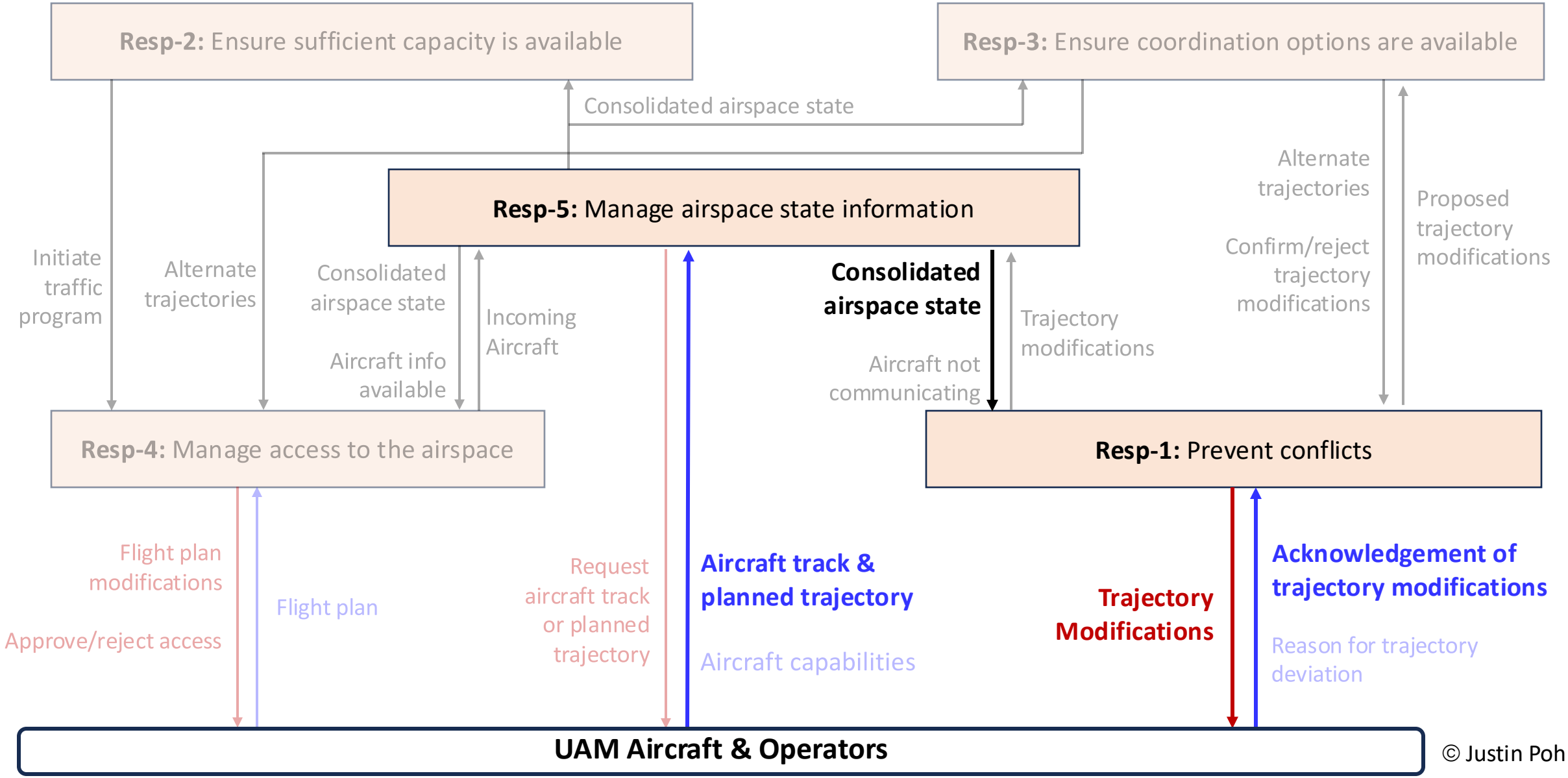
⋮

Deriving Control Elements From Requirements

Req-1: ATM system must coordinate the movement of aircraft to resolve any identified conflicts



Creating the Conceptual Architecture for Collision Avoidance



Part 3: Creating and Comparing Architecture Options

Input: Conceptual Architecture

1. **Create Architecture Options:** Ways to assign responsibilities to system controllers
2. **Analyze & Compare Options:** Comparing STPA scenarios identified for each option highlights qualitative differences in control behavior

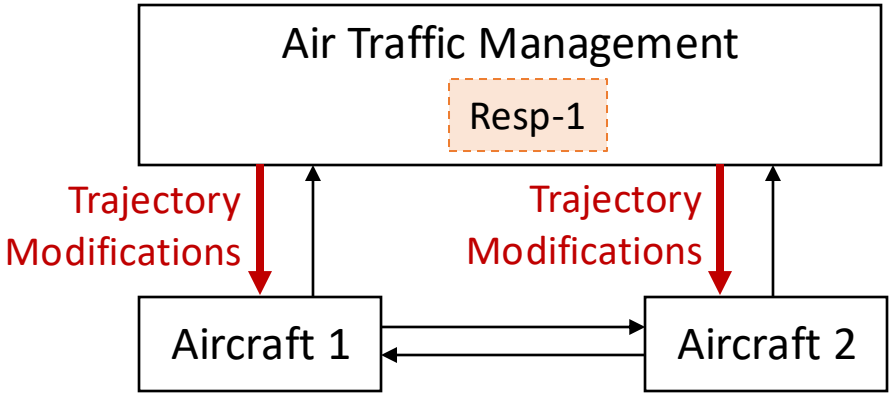
Output: Control-Related Benefits and Tradeoffs

Used to select responsibility assignments that best achieve emergent properties

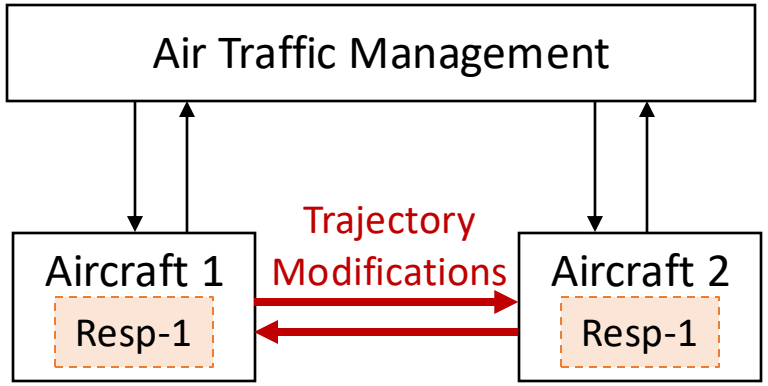
Creating Potential Collision Avoidance Architecture Options

Case Study Scope:
Focus on assignment of Resp-1 to develop a collision avoidance architecture for UAM

	A1: Centralized Collision Avoidance	**A2:** Decentralized Collision Avoidance
Resp-1: Prevent conflicts	**ATM**	**Aircraft**
Resp-2: Ensure sufficient capacity	ATM	ATM
Resp-3: Generate alternate trajectories	ATM	ATM
Resp-4: Manage access to the airspace	ATM	ATM
Resp-5: Maintain consolidated airspace state	ATM	ATM



A1: Centralized Collision Avoidance



A2: Decentralized Collision Avoidance

Analyzing and Comparing Architecture Options

1

STPA Analysis of Architecture Options

Architecture Option	Identified Scenarios
A_1	SC-1, SC-4
A_2	SC-2, SC-3, SC-4

Consolidate to create master set

Evaluation Criteria: Qualitative description of differences in control behavior

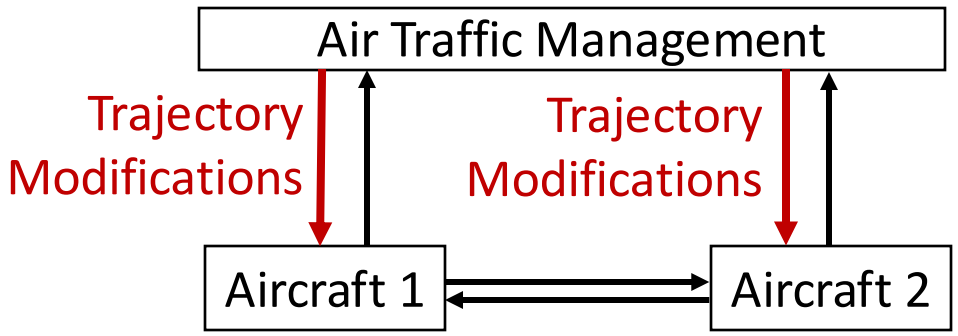
2

Create Architecture Comparison Table

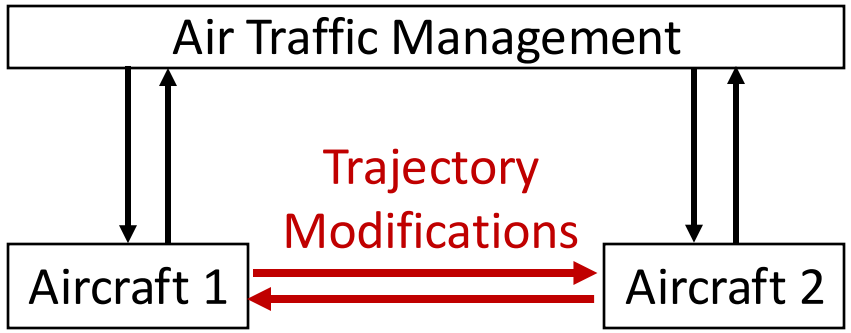
Identified Scenarios	Scenario Occurs?		Evaluation Criteria
	A_1	A_2	
SC-1	YES	NO	EC-1
SC-2	NO	YES	EC-2
SC-3	NO	YES	EC-3
SC-4	YES	YES	N/A

Comparing Centralized v.s. Decentralized ATM Architectures

Centralized Architecture



Decentralized Architecture



Evaluation Criteria	**Centralized Architecture**	**Decentralized Architecture**
Responsiveness of decisions in densely populated airspace	⊕	⊖
Ability to make appropriate decisions when multiple conflicts occur	⊕	⊖
Vulnerability of trajectory modifications when communications errors occur	⊖	⊕

⊕ Benefit ⊖ Tradeoff

Full details published in [Poh, Leveson, Neogi '24]

Evaluating Identified Evaluation Criteria

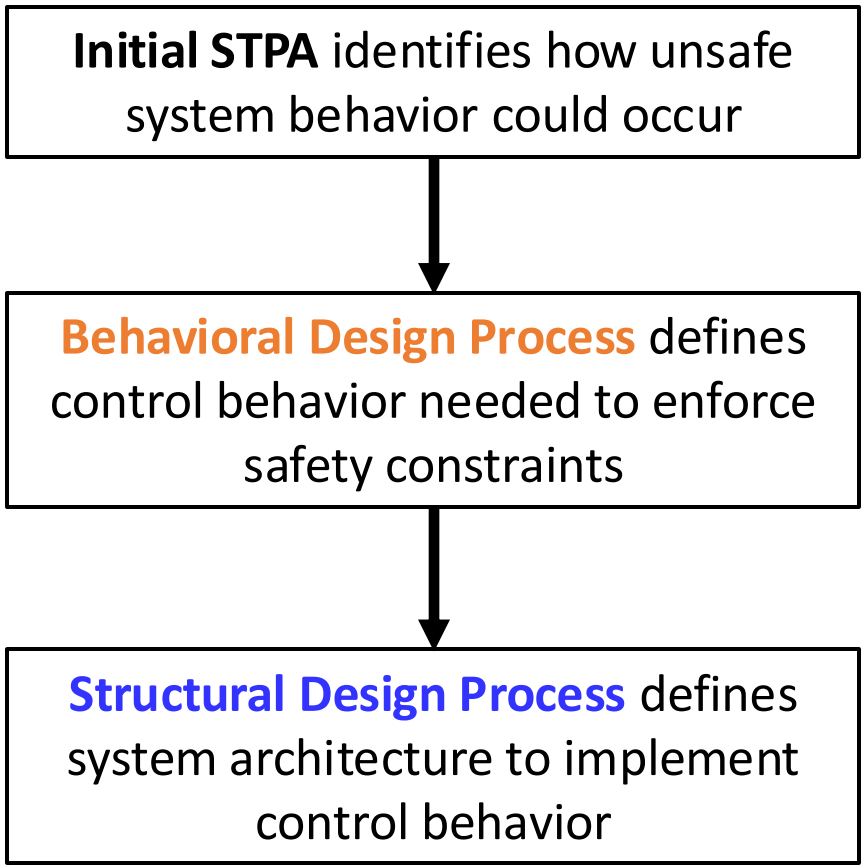
Compare benefits and tradeoffs found using this framework with those found in existing literature
[Xue '20], [Mondoloni et al '03]

Benefits/tradeoffs found using this framework: **19**
Benefits/tradeoffs found in existing literature: **9**

Control Aspect	Found In Existing Literature	Found Using This Framework
Decision Making	5	8
Process Models	1	3
Feedback and External Inputs	0	5
Control Path	3	3

- **More benefits and tradeoffs that cover more aspects of control**
- **STPA-based comparison is more focused on control-related differences and why they occur**

Summary



Research Objective: Develop a framework for developing system architectures that considers safety upfront

- Framework provides structured processes to enable **more informed early design decisions** driven by safety considerations
- STPA-based comparison of architecture options **focuses on control-related benefits and tradeoffs**

Questions?

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