

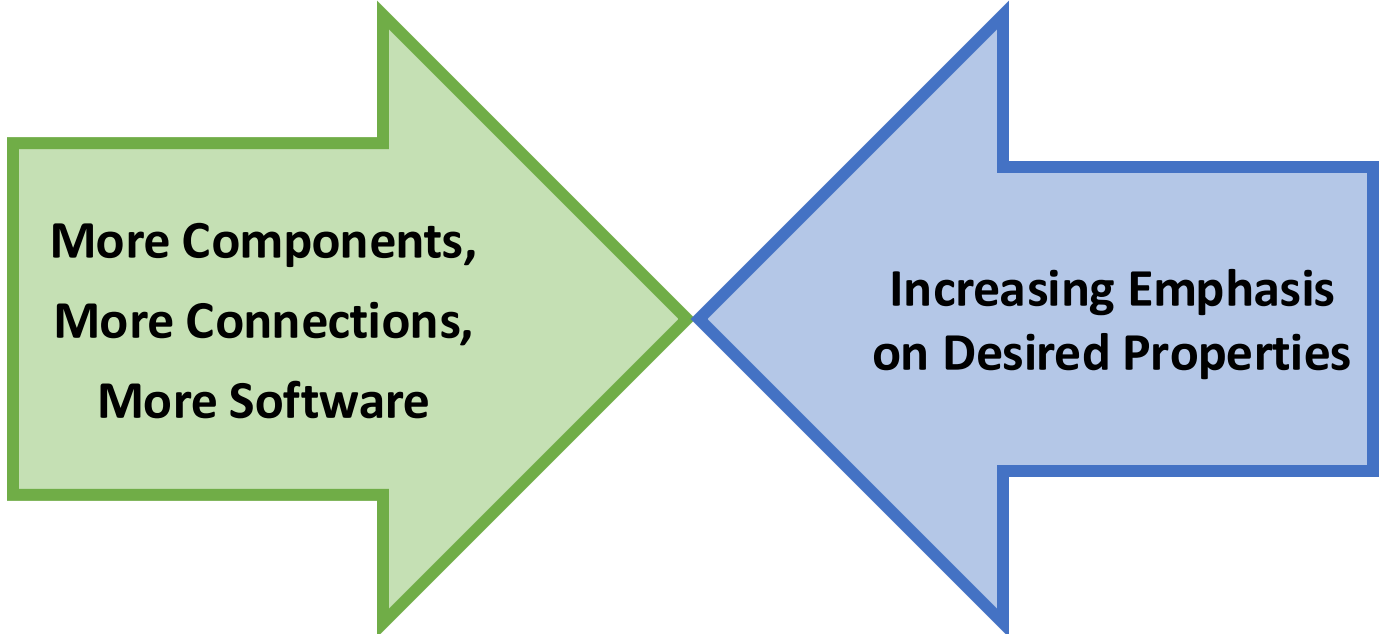
A Safety-Driven Framework for Developing System Architectures

2025 MIT STAMP Workshop

Justin Poh
25 March 2025



The Evolution of Complex Systems



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>

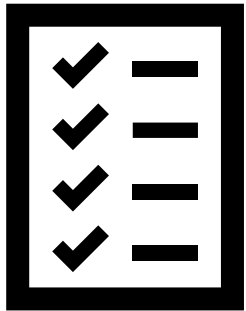
[5] Image from: <https://onboard.thalesgroup.com/connected-cybersecure-aircraft-tackle-challenge/>

[6] Image from: <https://www.cnn.com/2024/02/21/climate/space-debris-solution-climate-scni/index.html>

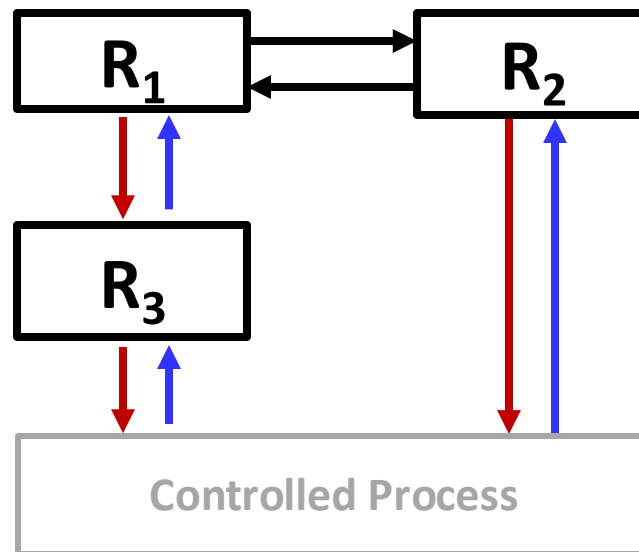
Types of Design Decisions in Architecture Development

System Architecture: Description of system entities and relationships between them

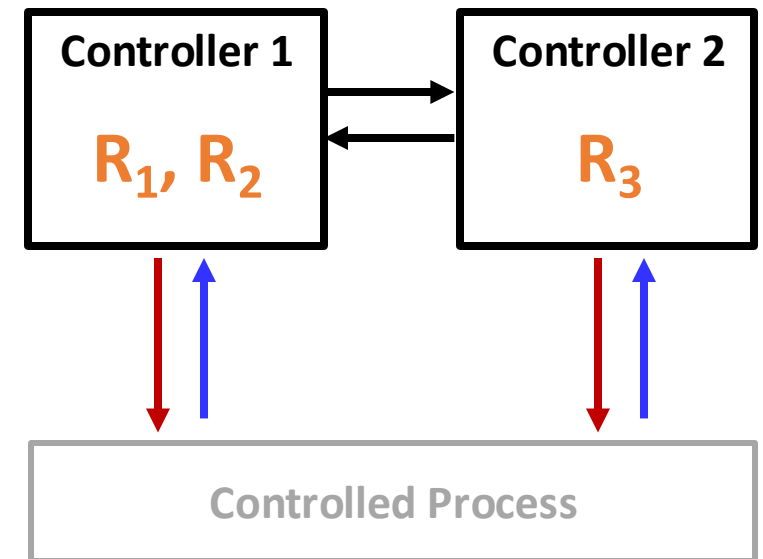
1 Identify System Requirements



2 Define Responsibilities (Functions) & Relationships



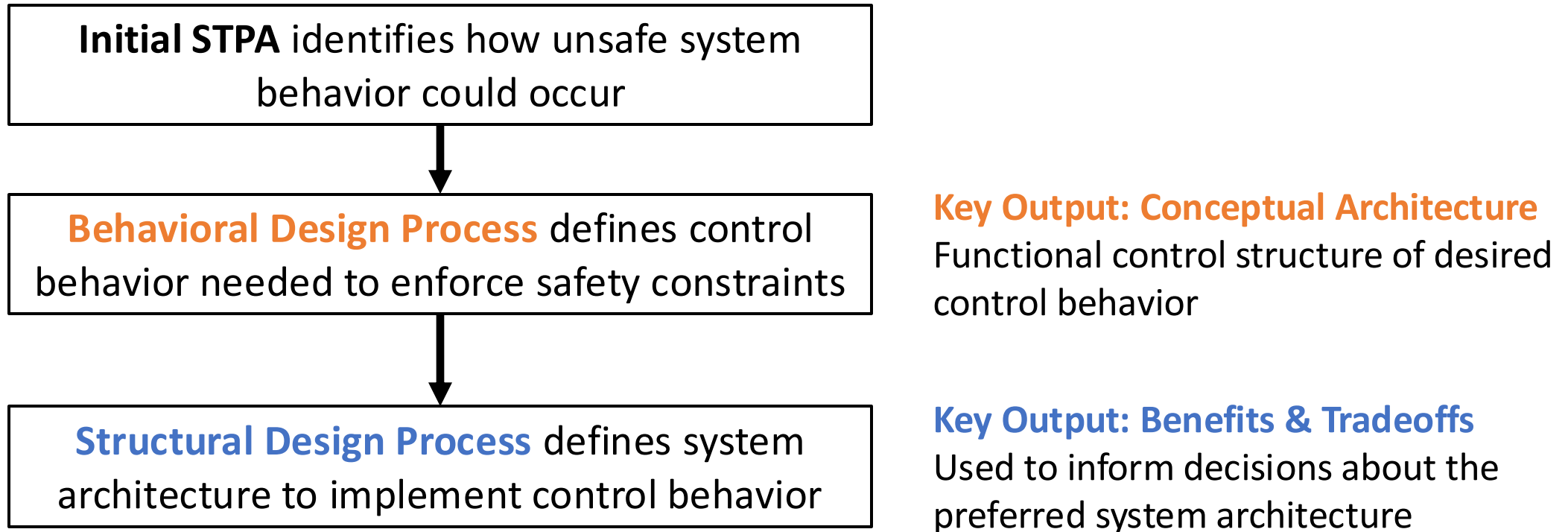
3 Allocate Responsibilities to System Elements



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

Overview of Framework

Approach: STPA drives design decisions



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

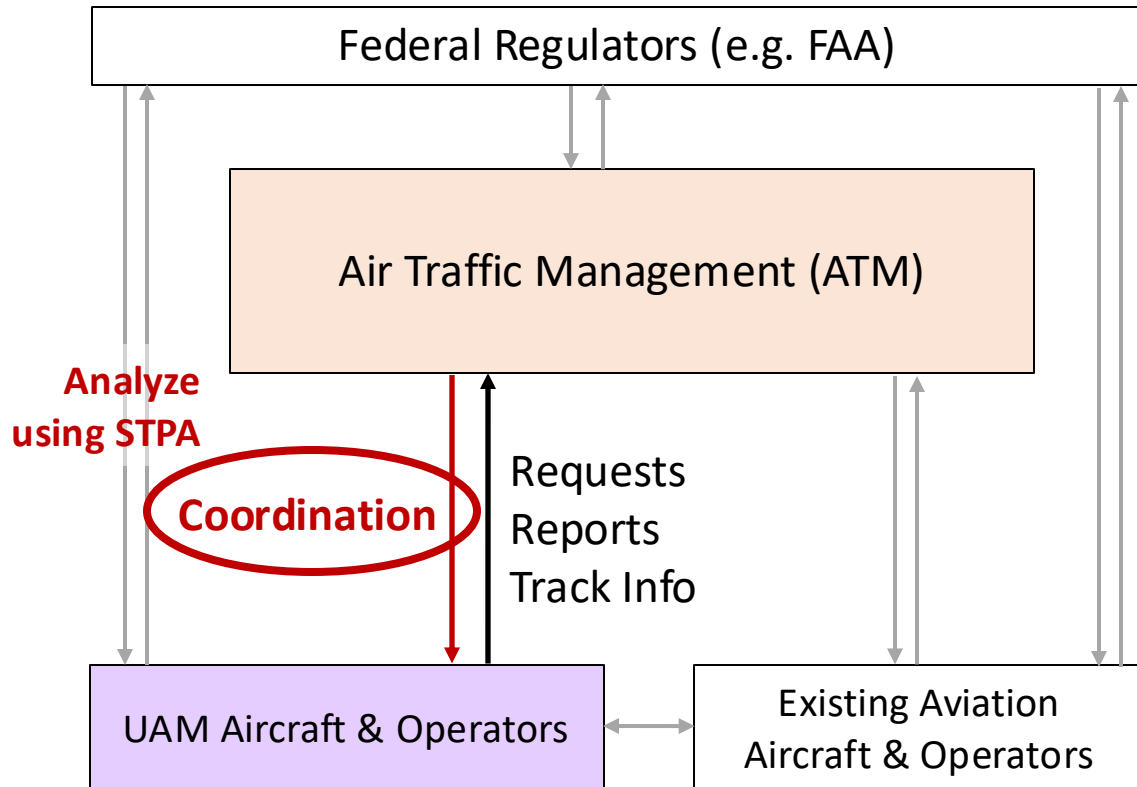
Case Study Goal:

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

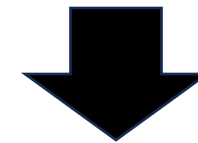


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Part 1: Early-Stage STPA Analysis of ATM System



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

Start: Abstract ATM control structure



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

System Requirements

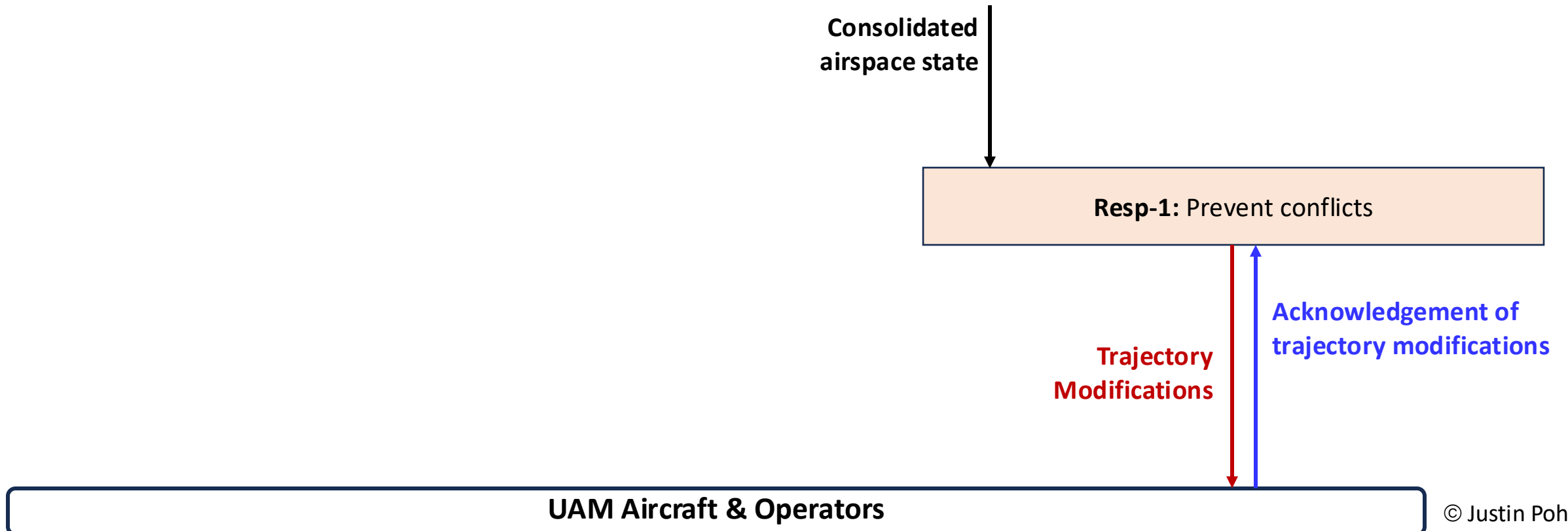
Req-1: ATM system must coordinate the movement of aircraft to resolve any identified conflicts

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

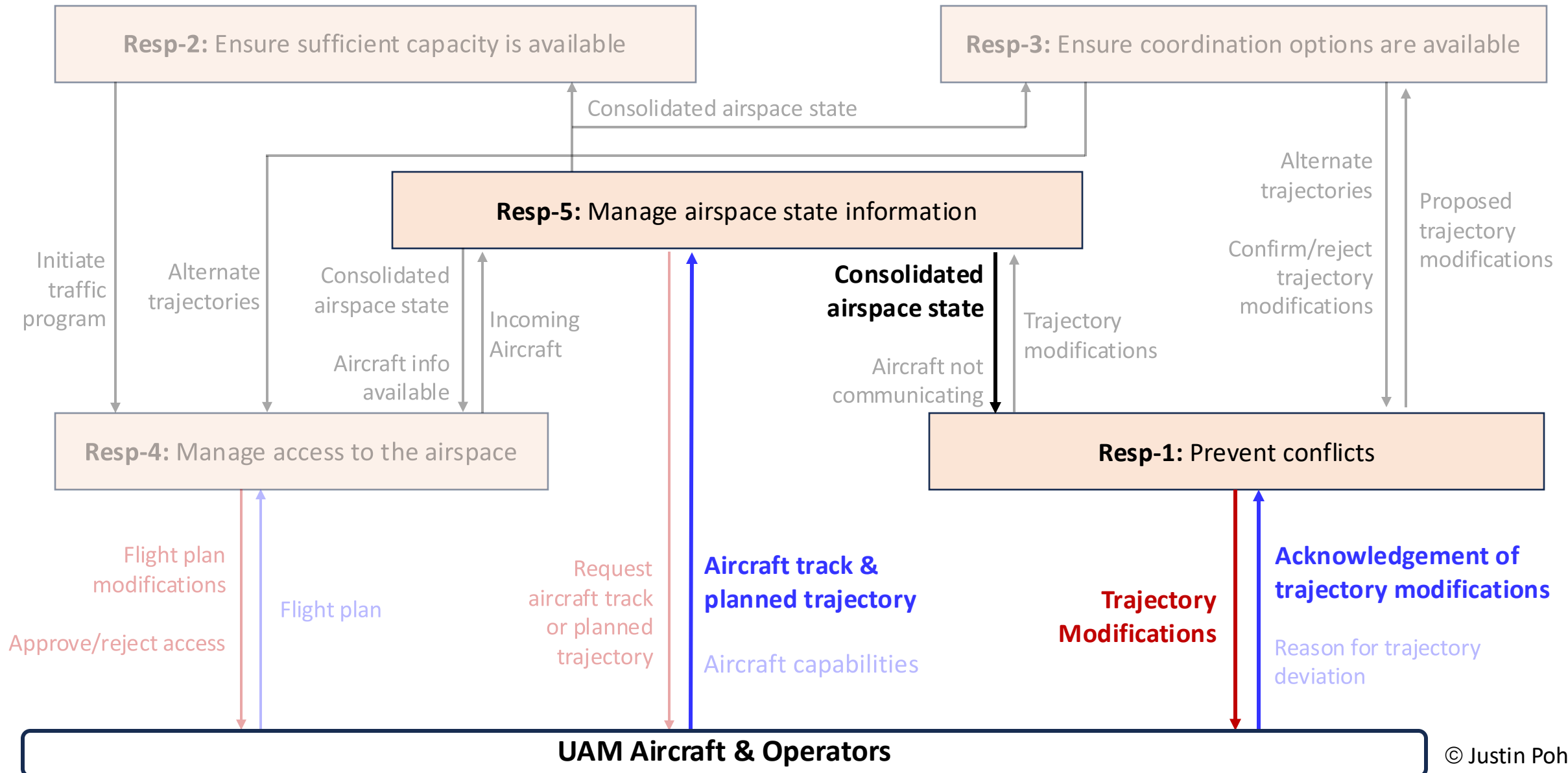
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Deriving Control Elements From Requirements

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

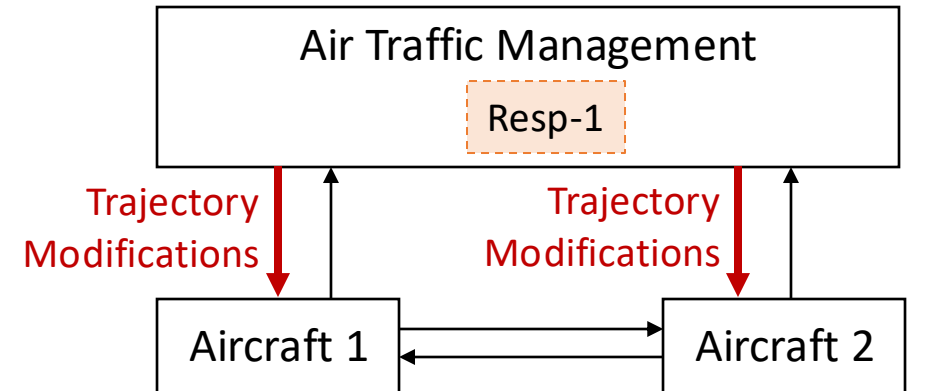


Creating Potential Collision Avoidance Architecture Options

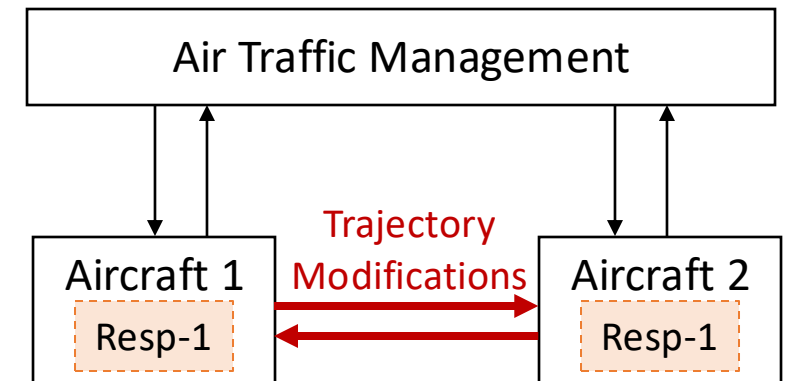
Case Study Scope:

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

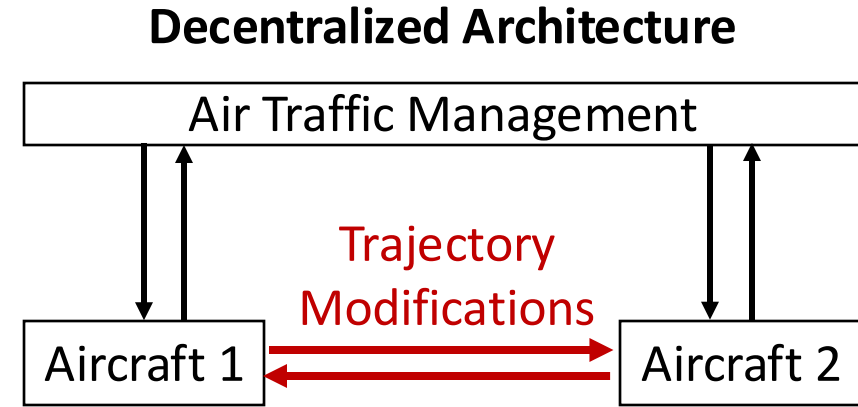
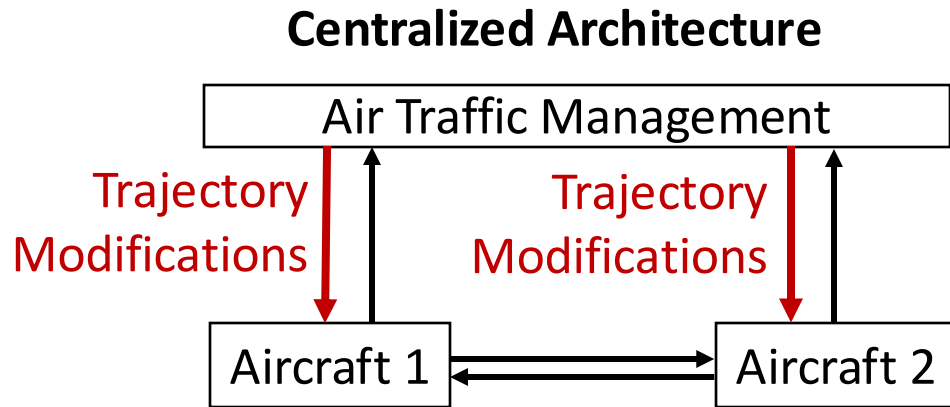
Evaluation Criteria:
Qualitative description of differences in control behavior

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



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

Evaluating Identified Evaluation Criteria

Compare benefits and tradeoffs found using this framework with those found in existing literature

[Xue '20], [Mondoloni et al '03]

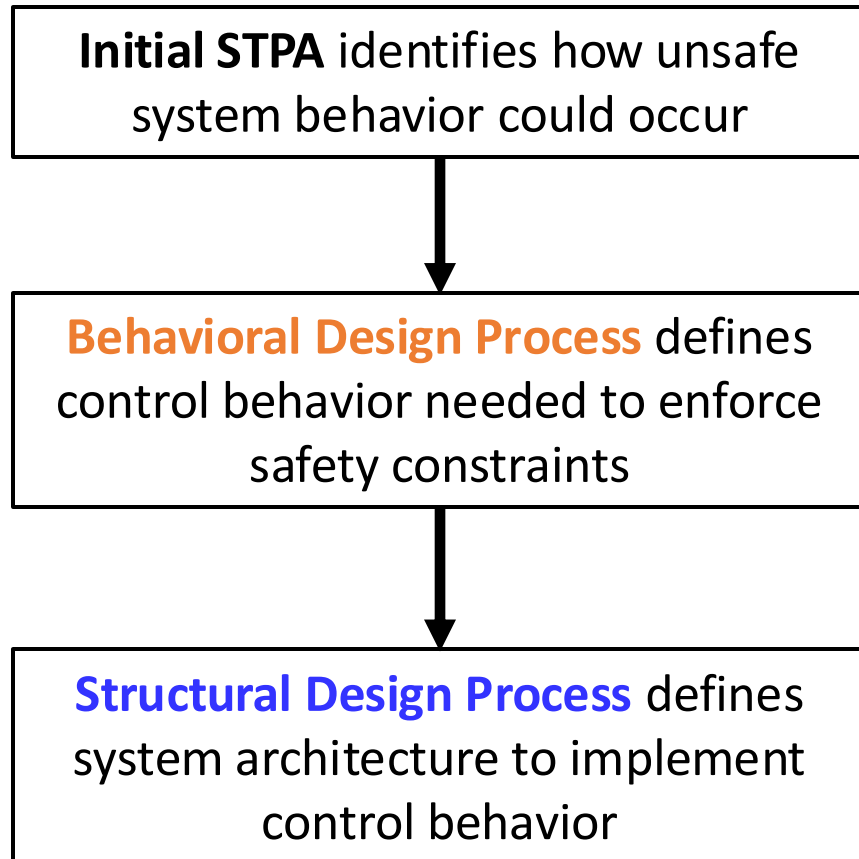
Benefits/tradeoffs found using this framework: **19**

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?

justin@justinpoh.com

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