Autonomous Aerial Cargo Operations At Scale

Kick-Off Meeting

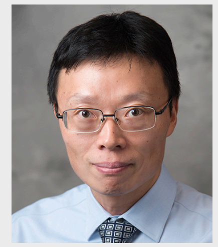
October, 2021

Introductions and overview

Team Introduction

PURDUE UNIVERSITY


Karen Marais


Dengfeng Sun

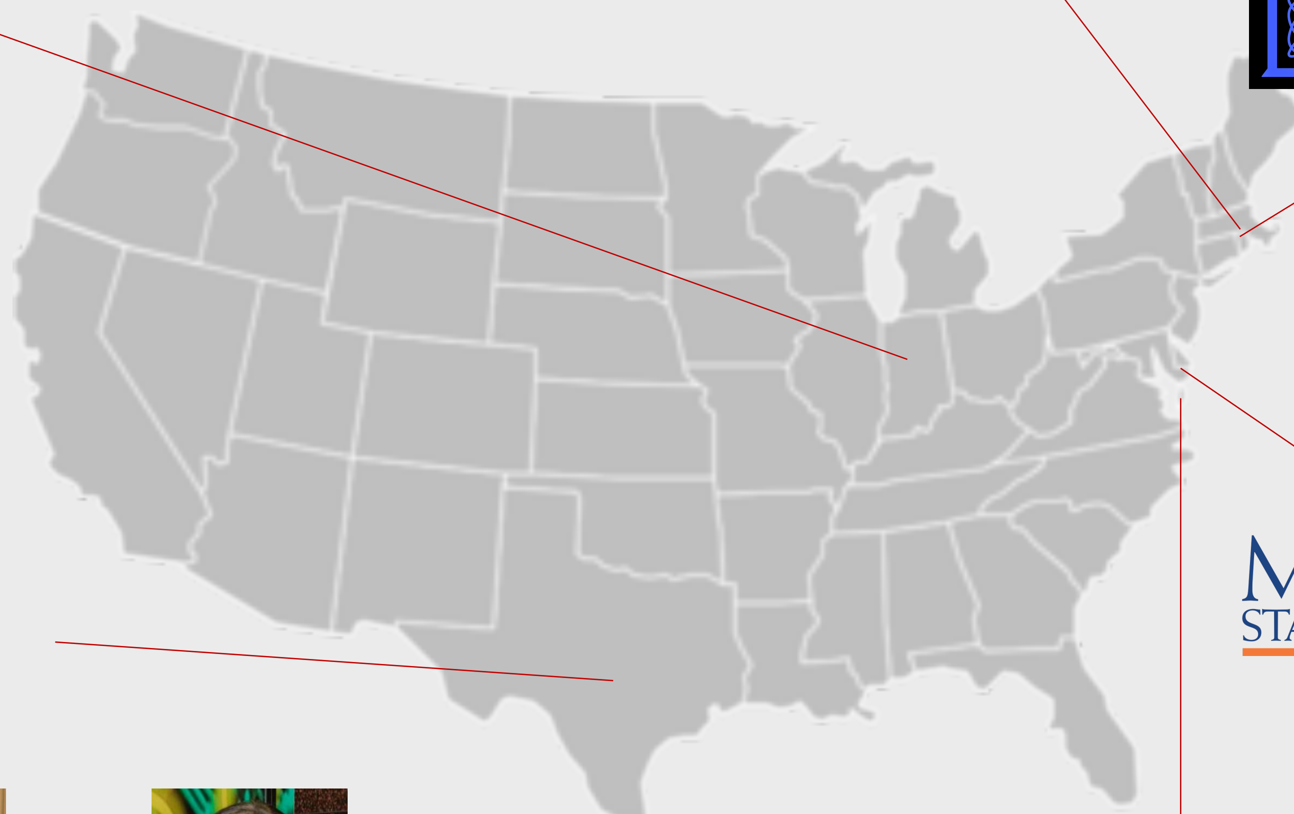
Massachusetts Institute of Technology

Hamsa Balakrishnan


MIT Lincoln Laboratory


Matthew Edwards


Allison Chang



TEXAS
The University of Texas at Austin

MORGAN STATE UNIVERSITY

Willie Rockward



John-Paul Clarke


Ufuk Topcu


Karen Willcox

CAVAN SOLUTIONS


Mel Davis

Objective

Establish a foundation…

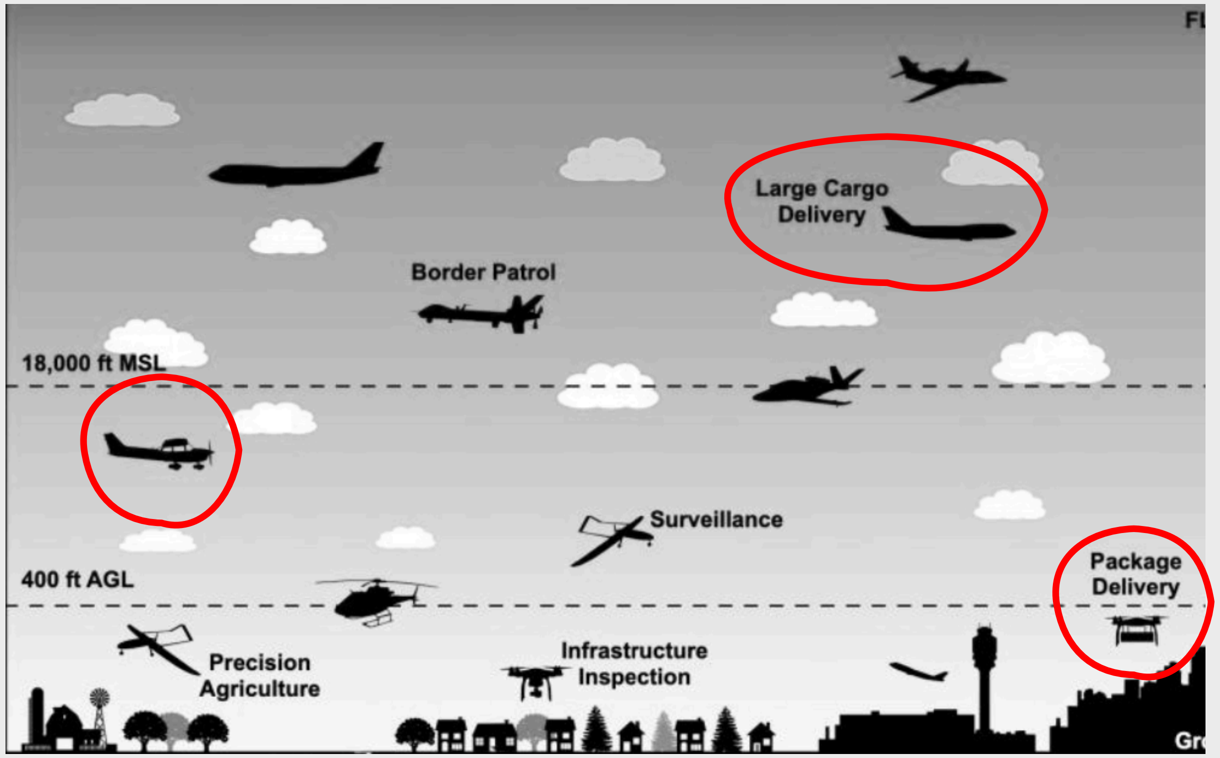
- theory and algorithms for design, verification and operation
- concepts of operation and demonstrations

… that will support the development, deployment and adoption of advanced air mobility systems…

- including vehicles, traffic, and fleets

… for autonomous cargo operations at scale

- all classes of airspace (and the transition between them)
- all vehicle types



Figures from NASA.

Overview

Compliant with regulations?

Verifiably safe?

How can we scalably verify system-level safety and identify appropriate requirements?

Avoid putting the public at risk due to weakness of regulation or hinder growth due to overly strict regulations.

Adopted by the public?

How can we constrain the design and operation to account for noise footprint, communication, risk and privacy?

Help align the investments with the public's sensitivities.

Economically justified?

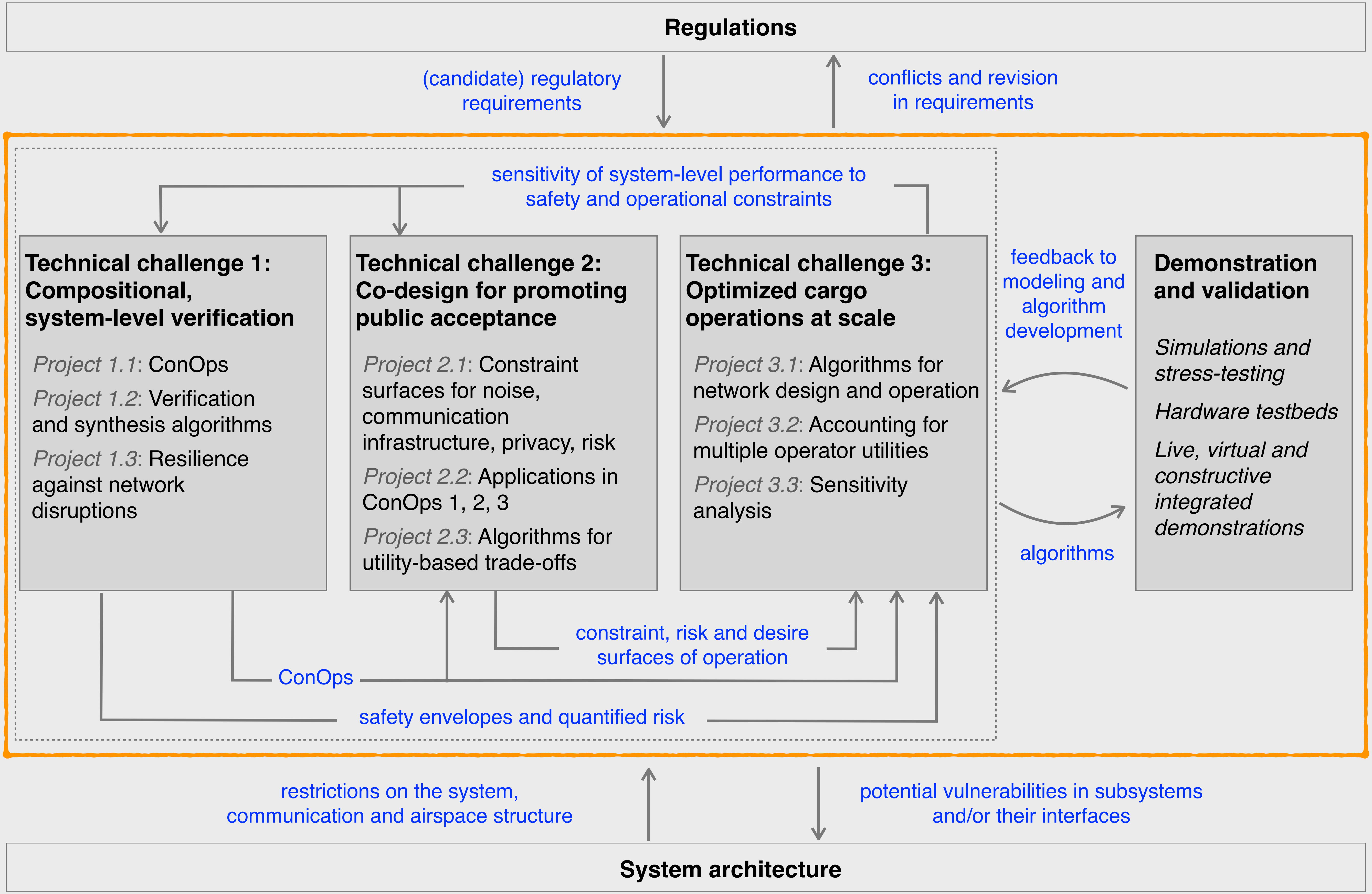
How can we optimize the operation of air mobility systems at all relevant scales?

Inform whether the necessary investments can add sufficient economic value and create new business models.

Compatible with the infrastructure?

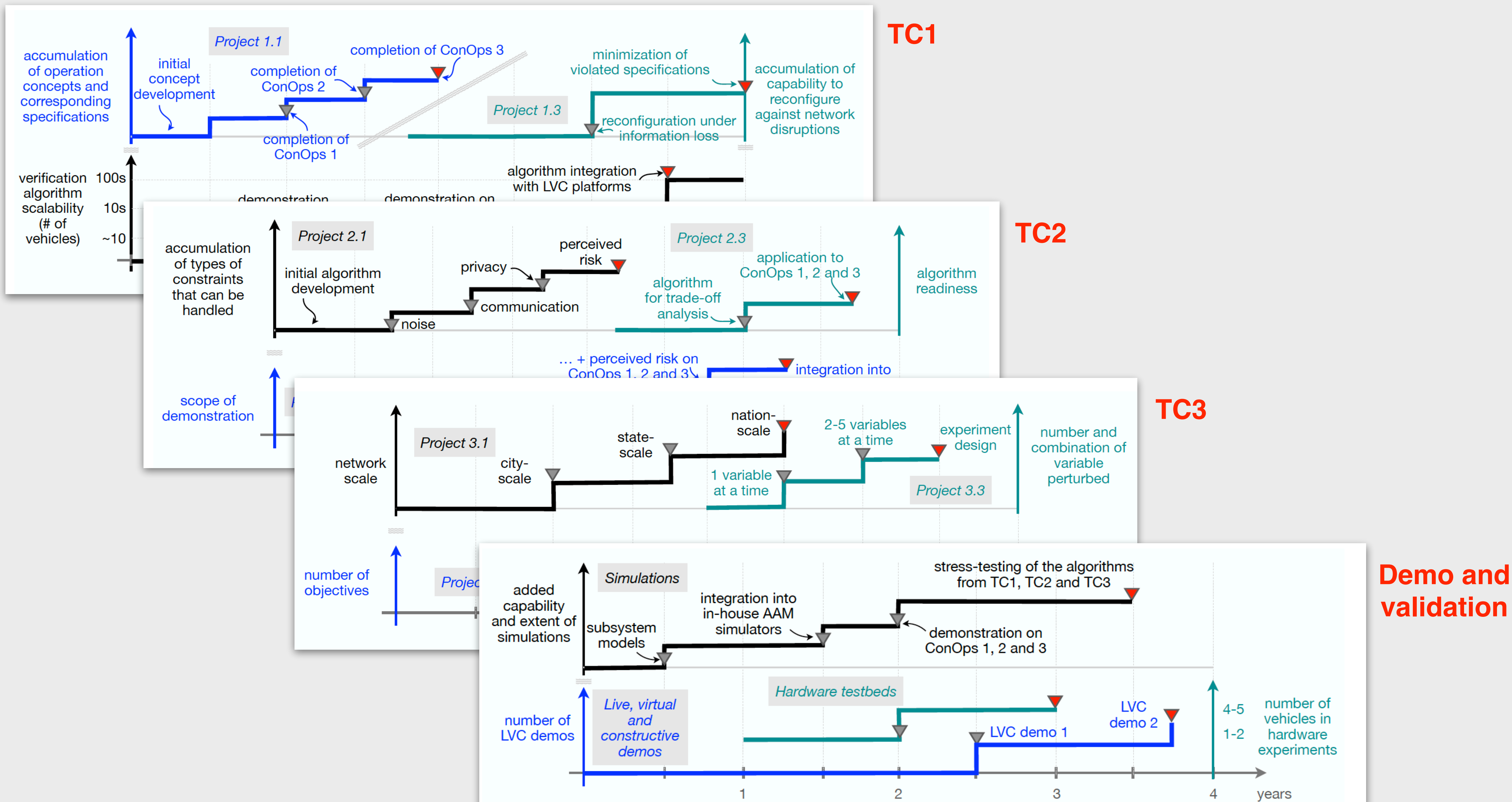
Education and outreach to expand and diversify the workforce

Research Plan

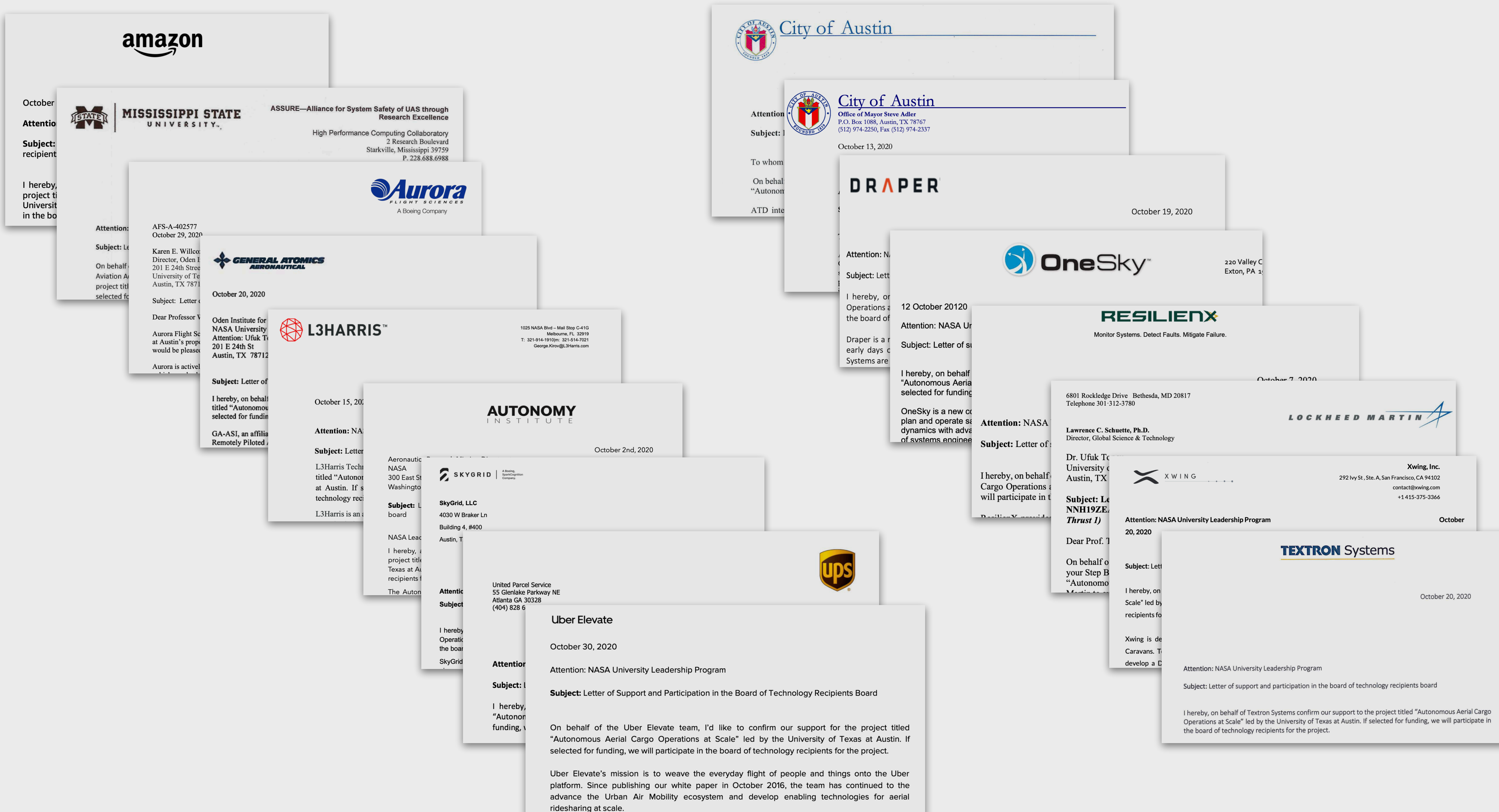


Timelines and Representative Metrics

Year 1	Year 2	Year 3	Year 4
Formulation and initial algorithm development	Algorithm maturation	Interrogation and initial integration	System-level integration



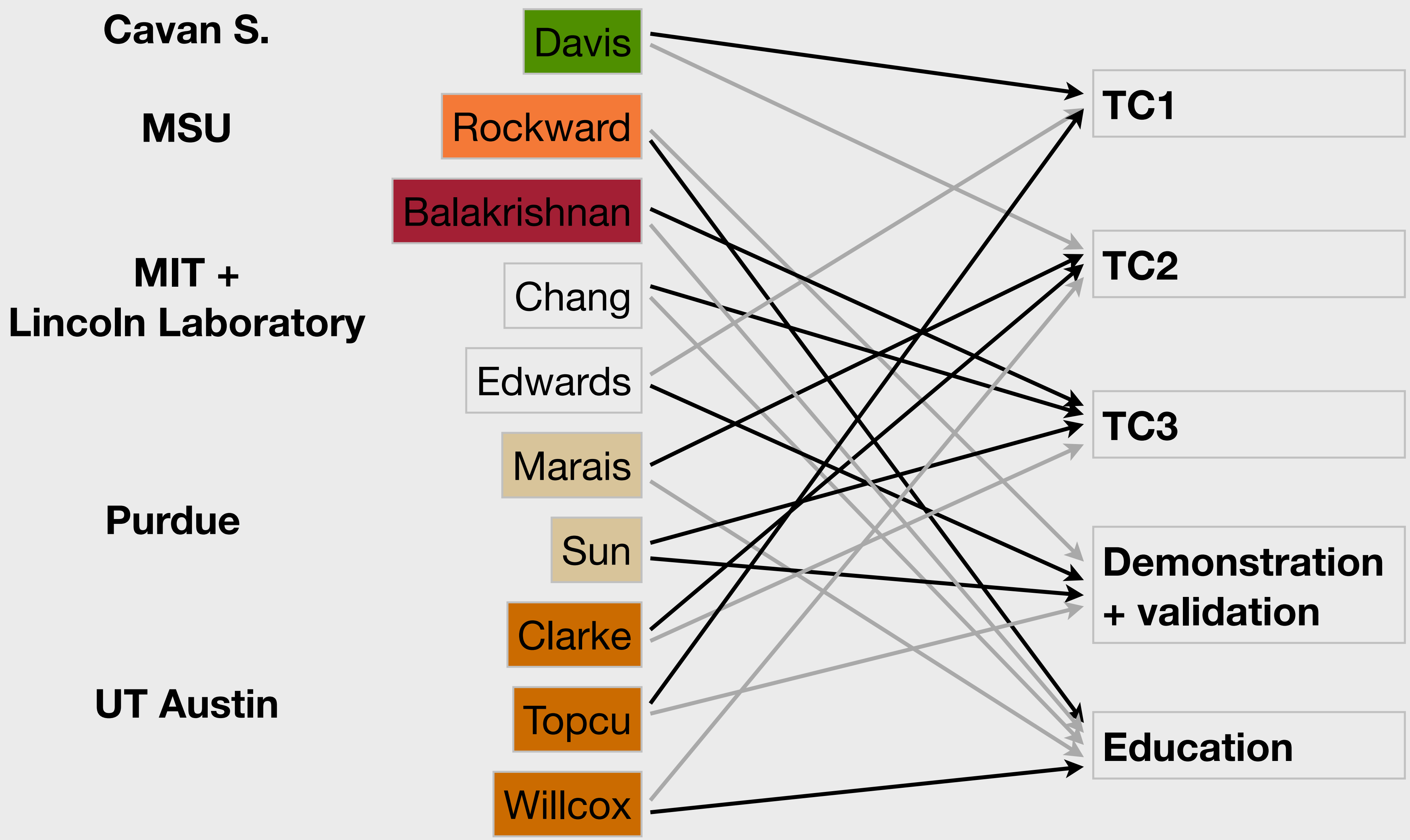
Technology Recipients



More recently: Honeywell, Sandia National Labs, Dash Shipping

Who does (or leads) what?

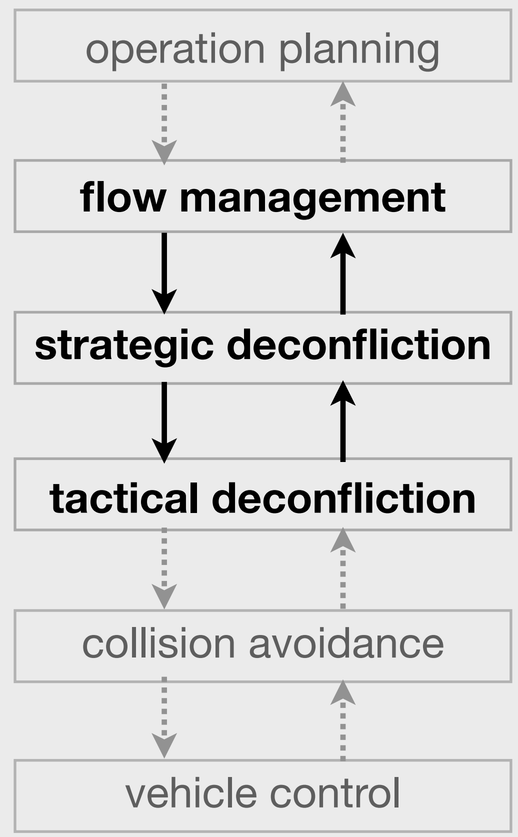
(And, the flow for the rest.)

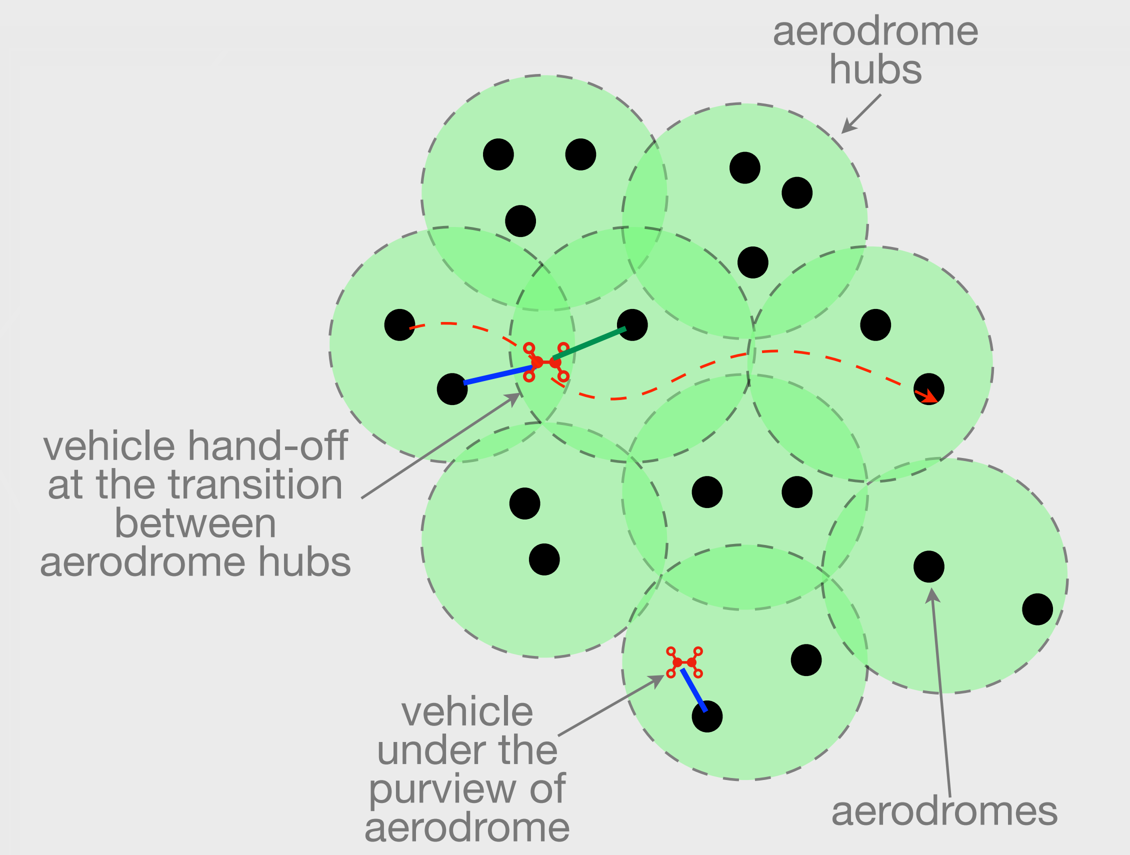


Technical challenge 1

TC1: Compositional, system-level verification

- Verifiability either by post-design analysis or by synthesis
- Layer-wise as well as when integrated
- Merge design-time and run-time approaches





- Exploit and impose architectural constraints
- Algorithms will not rely on specific architectural choices. On the contrary, they will inform the exploration of the architectural choices.
  - How the overall system operation should be partitioned,…
  - which operator or service provider (or central authority) should be responsible for which functionality, and…
  - how they should coordinate.

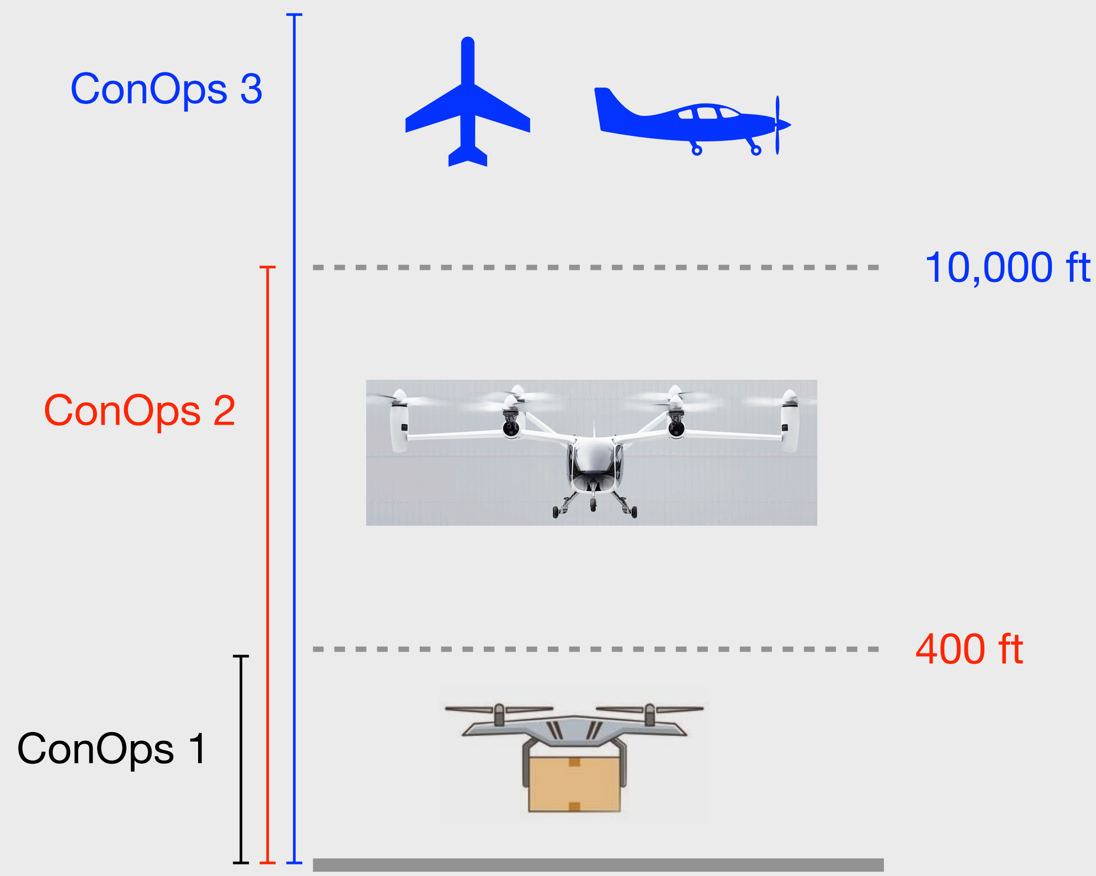
ConOps development

- Concretize the scope for TC1, TC2, and TC3.
- Outline the salient characteristic of the…
  - environment and the infrastructure
  - objectives of operation
  - actors involved, their interactions
  - applicable rules

- Beyond 10,000 ft (likely below FL 180)
- Large vehicles, e.g., payload larger than 5,000 lb
- Significant interaction with manned aviation
- Help investigate complements for hub-and-spoke models

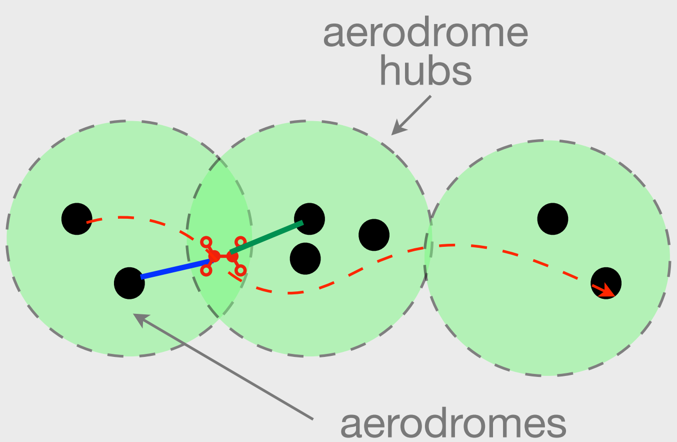
- Beyond the UTM range up to 10,000 ft
- Mid-size vehicles, e.g., payload of 500-1,500 lb
- Focus on a conventionally under-utilized yet vast airspace
- Transitions across different airspace types and with manned (and general) aviation

- In the UTM range
- Small-size vehicles, e.g., payload below 55 lb
- Extend the UTM ConOps to include autonomous vehicles and services



A strategy synthesis problem

A sample problem focusing on **dynamic airspace management** and its interactions with pre-flight authorization



controllers for aerodrome hubs 1,…,k

$$\left(\mathcal{D}_1 \circ (S_1^1 \circ \dots S_1^m)\right) \circ \dots \left(\mathcal{D}_k \circ (S_k^1 \circ \dots S_k^m)\right) \models \bigwedge_{i=1\dots k} \varphi_i$$

controllers for aerodrome 1,…,m in aerodrome hub 1

specifications composed as one for each aerodrome hub i

Specify behavior in temporal logic

$$\vdots$$

$\Box$(fewer than N vehicles in aerodrome hub k)

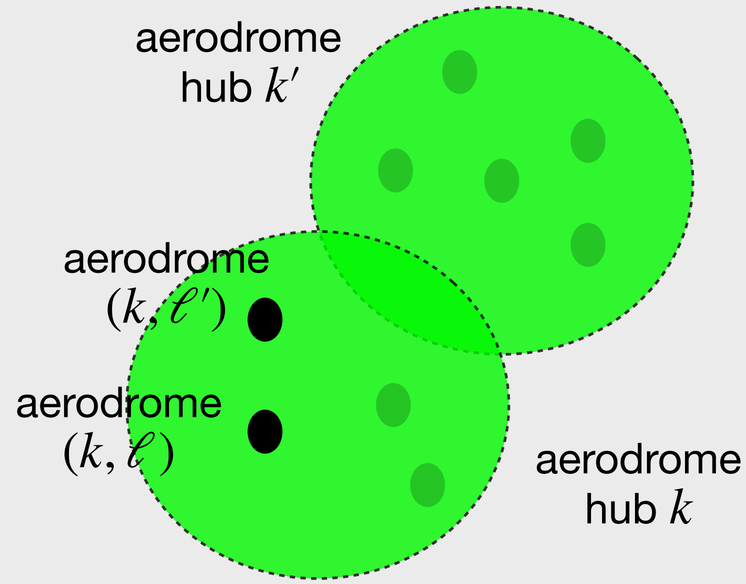
$\wedge\ \Box\Diamond$(request of vehicle j in aerodrome hub k is granted)

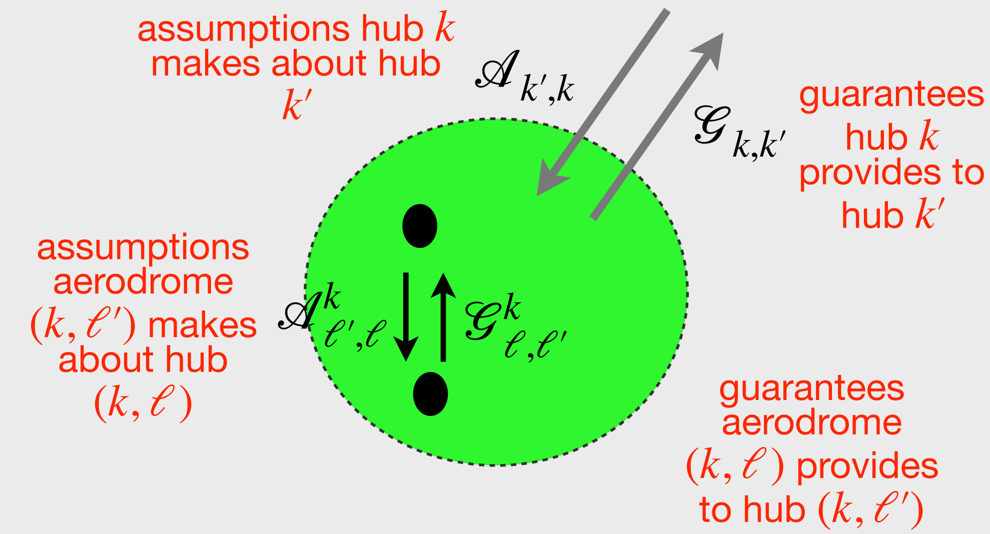
$\wedge\ \Box$(delay for vehicle j $\leq T$)

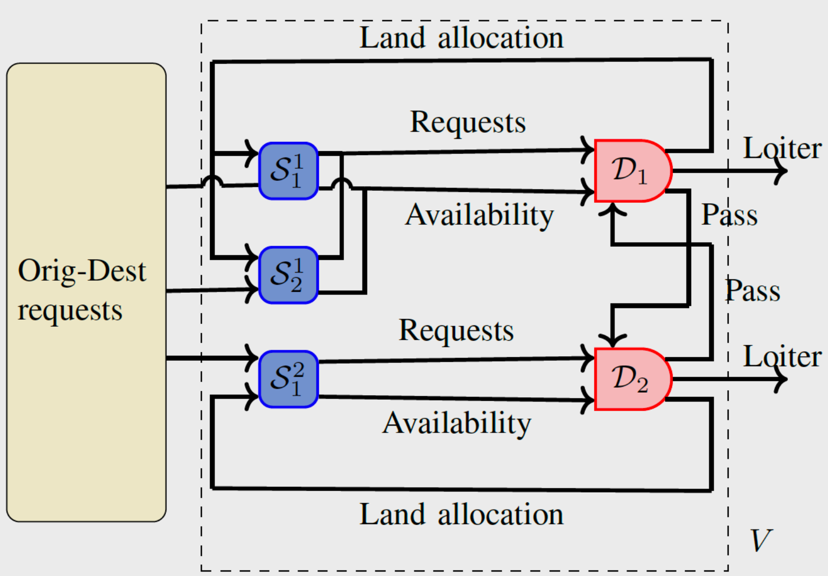
$$\vdots$$

Distributed strategy synthesis

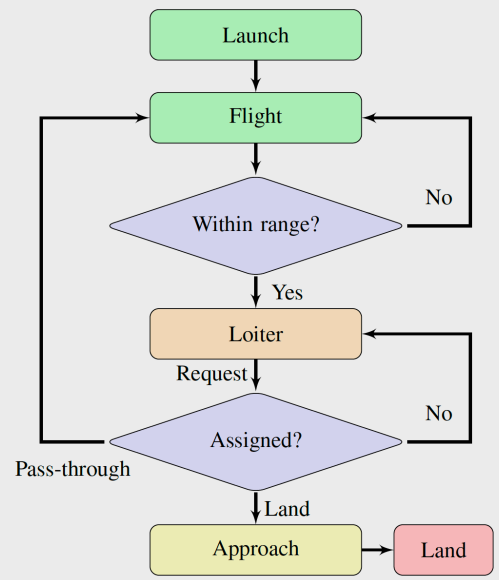
Contract-based reasoning for synthesis







system-level implementation



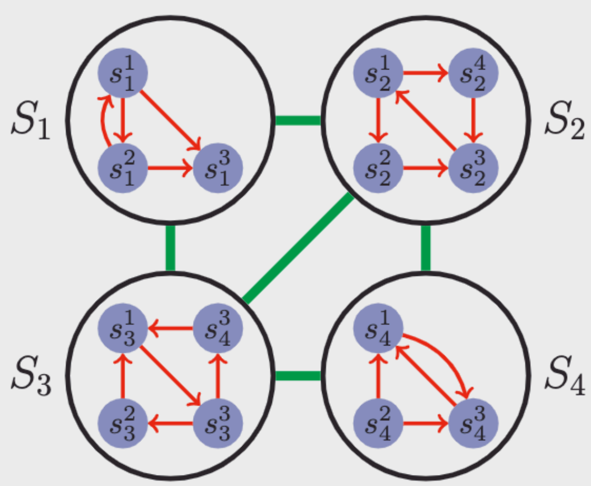
vehicle-level implementation

sample simulation

Additional thoughts from the proposal

Automated refinement of contracts and feedback generation

Probabilistic synthesis and effect of information limitations

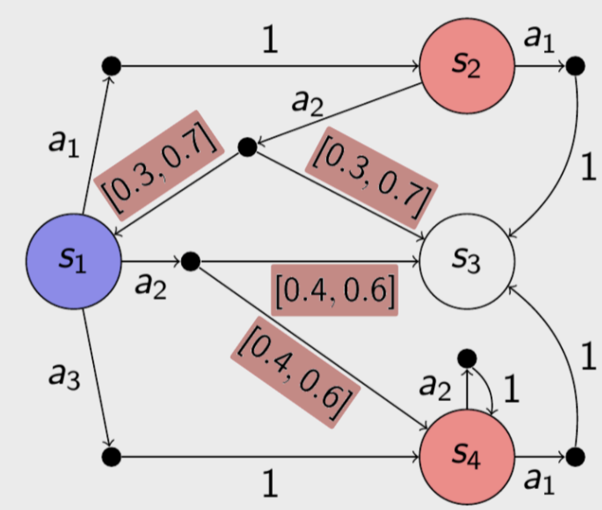


$$\exists^2 \bigcirc_{y \leq 1} (x \geq 1)$$

there are at least two neighboring nodes…

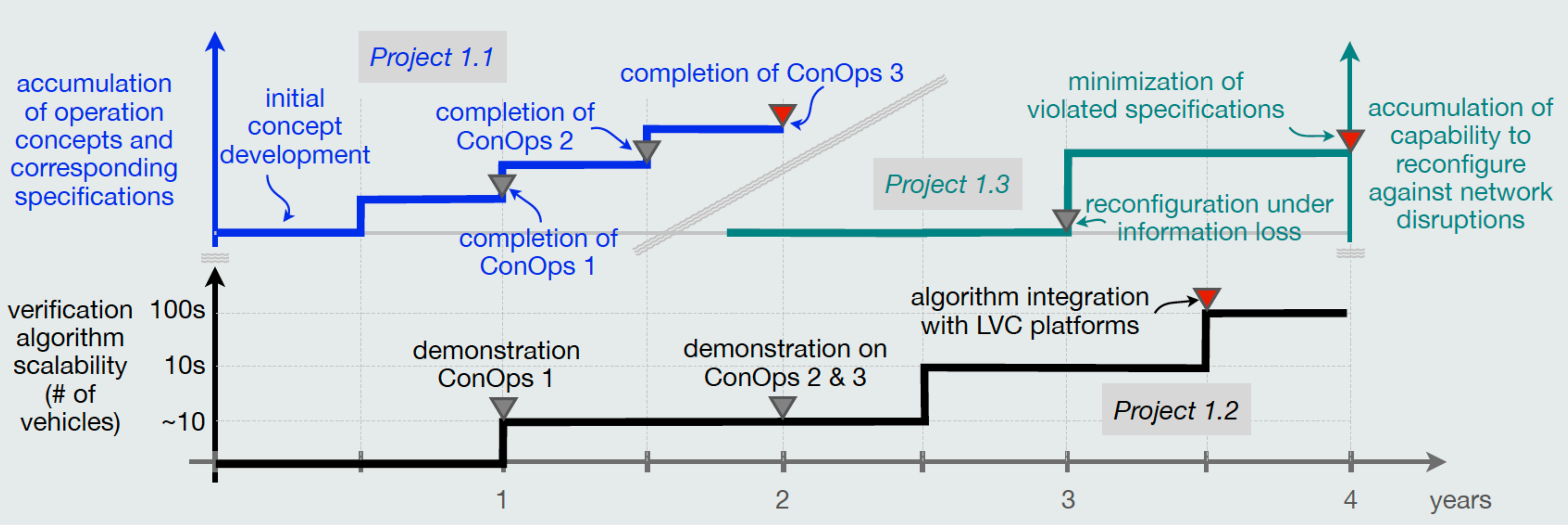
…with an edge label of at most 1…

…where the node labels are at least 1



Minimum-violation synthesis

Tentative timeline



Technical challenge 2

Converting societal constraints into “virtual” terrain...

Societal constraints on aerial cargo operations define “no-fly” zones…

regions where operations are not possible (e.g., restricted airspace) or not desired (e.g., due to noise and privacy concerns)

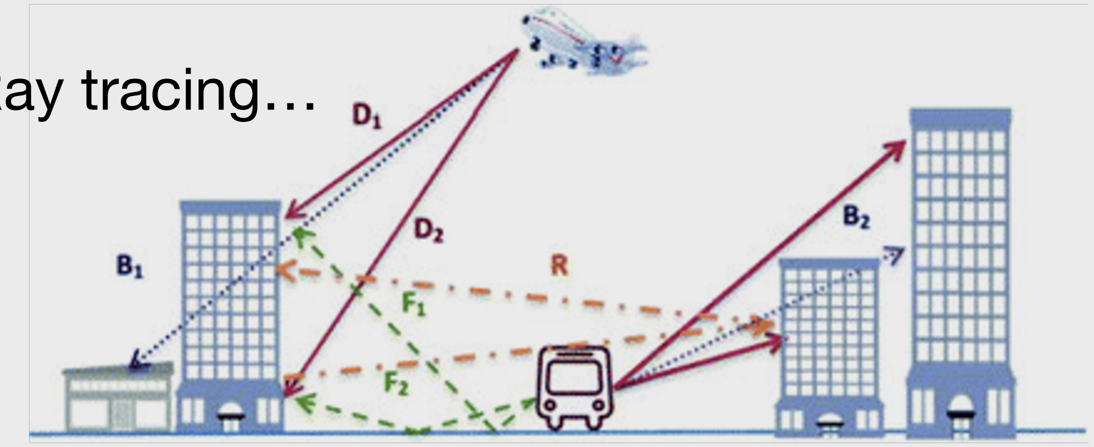
… while performance constraints define “must-fly” zones.

regions where operations can be performed (e.g., where the requisite communication and surveillance are available)

… that can all be described using three-dimensional surfaces where aircraft cannot either enter or leave.

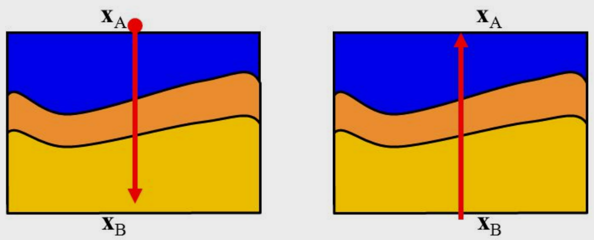
these surfaces could be time dependent if one of more of the constraints vary with time

Ray tracing…



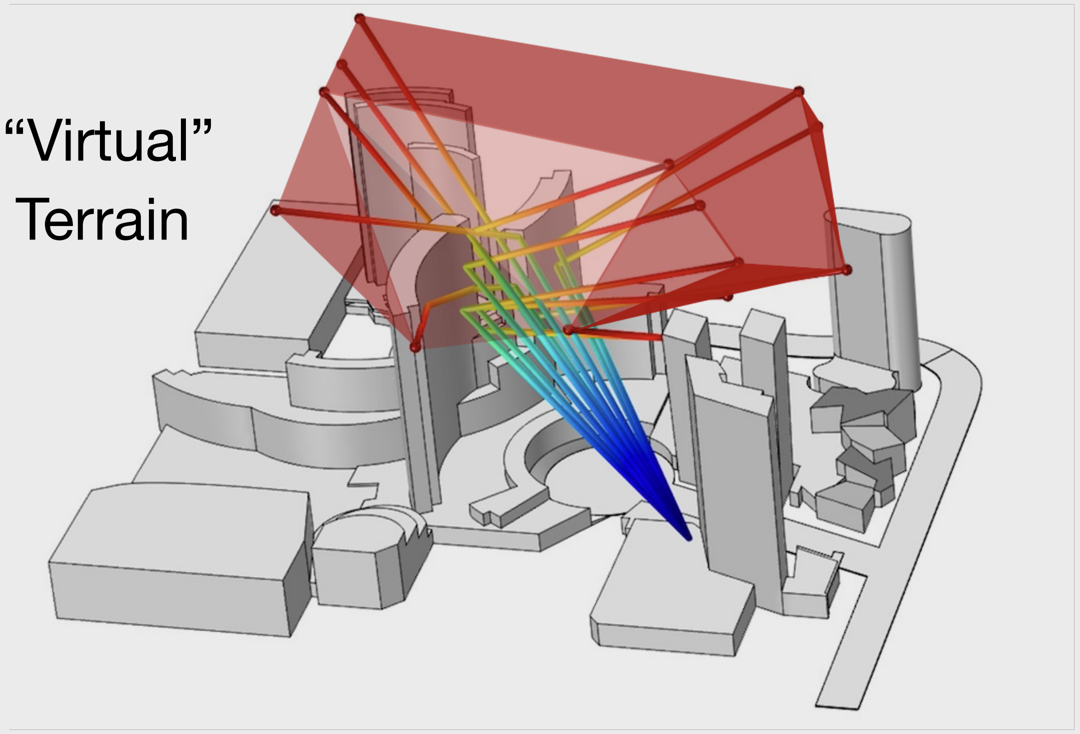
Acoustic rays (in vertical direction) from road traffic and aircraft
SOURCE: Lu L., Becker T., Löwner MO. (2017) 3D Complete Traffic Noise Analysis Based on CityGML. In: Abdul-Rahman A. (eds) Advances in 3D Geoinformation. Lecture Notes in Geoinformation and Cartography. Springer, Cham. https://doi.org/10.1007/978-3-319-25691-7_15

\+ Reciprocity…



$$P_A(\mathbf{x}_B, \omega) = P_B(\mathbf{x}_A, \omega)$$

= “Virtual” Terrain



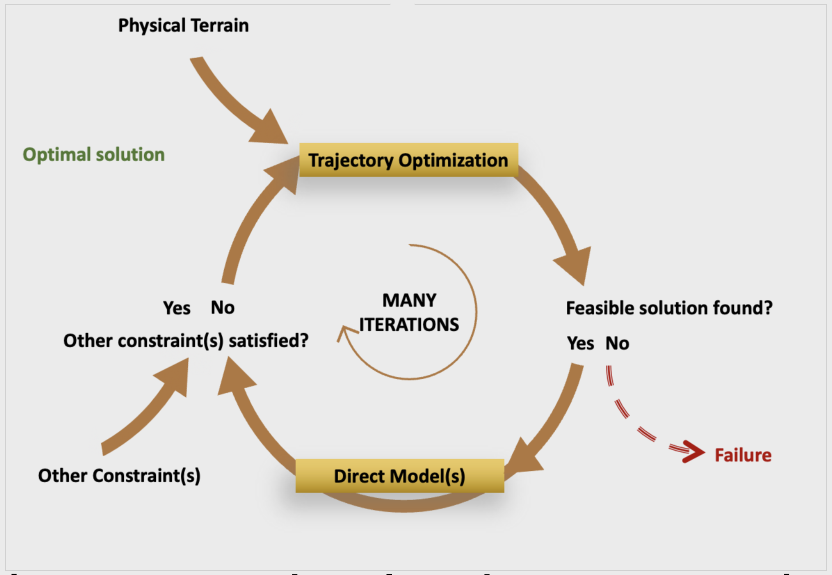
..enables simultaneous and efficient consideration of physical, performance, and societal constraints...

Rather than optimize the trajectory considering physical constraints…

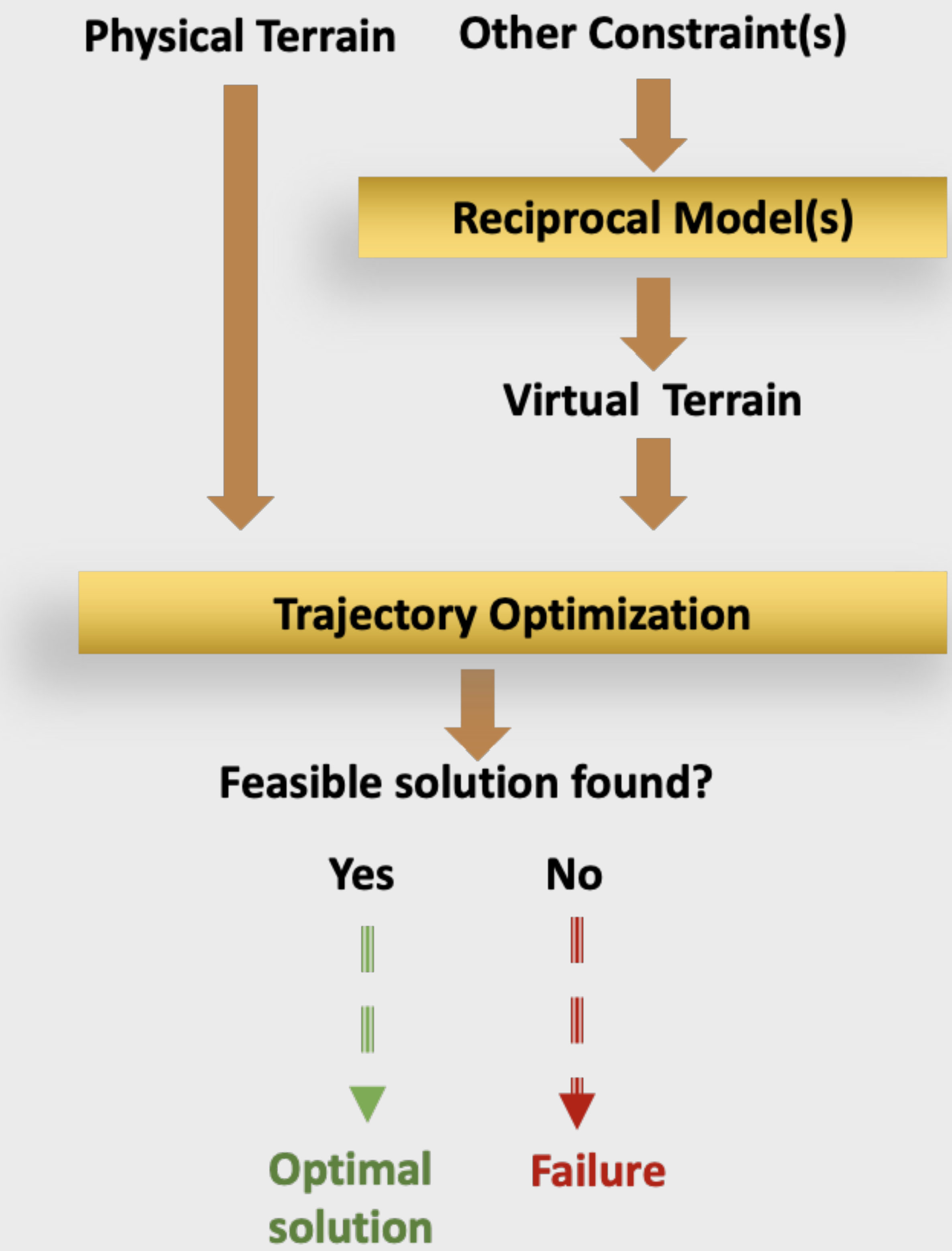
e.g.. path planning to avoid physical obstacles such as hills and buildings

… and then estimating the performance and societal consequences, and using those estimates to “adjust” the trajectory …

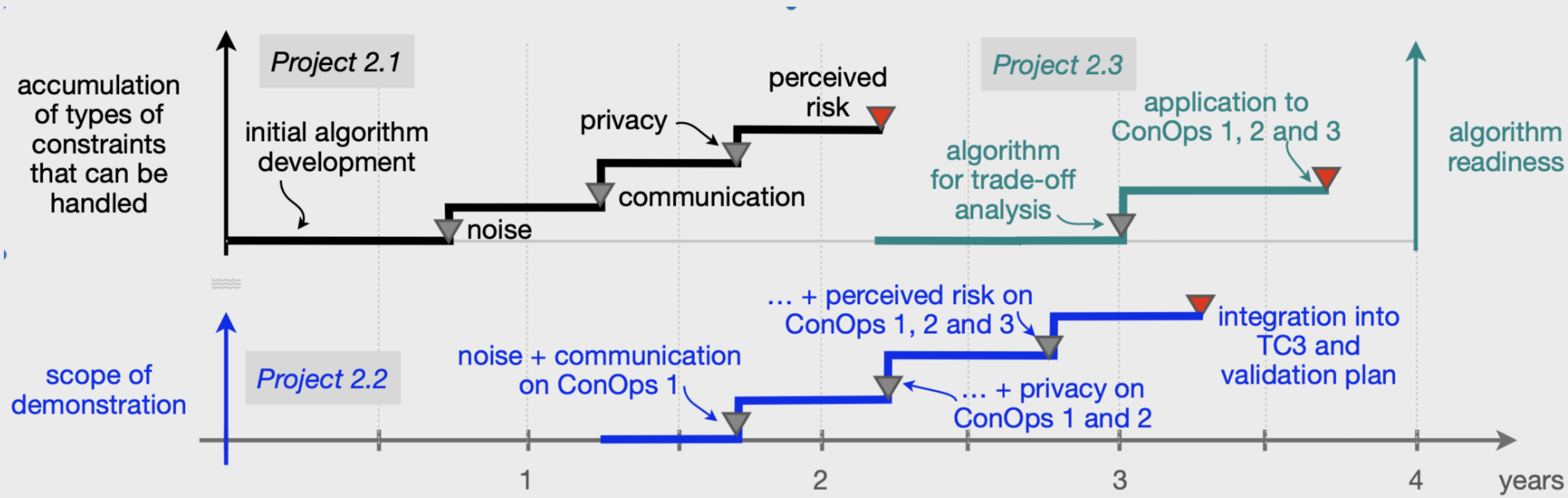
i.e., a computationally expensive and oftentimes ad hoc process



… the true optimal trajectory can be derived using existing path planning algorithms.



..over our 4 year timeline.



Technical challenge 3

TC3: Optimized Cargo Operations at Scale

1. Scalable algorithms for network design and optimization of air cargo operations

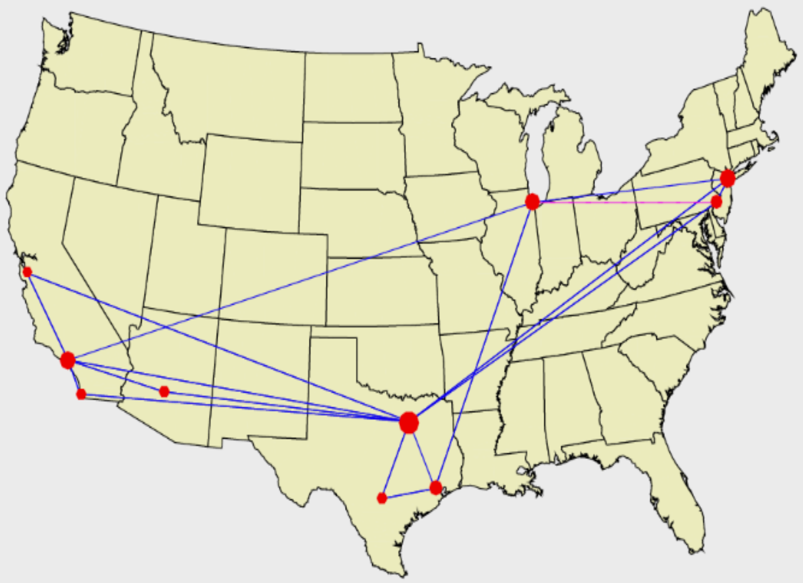
2. Eliciting and accommodating multiple operator utility functions

3. Sensitivity analysis

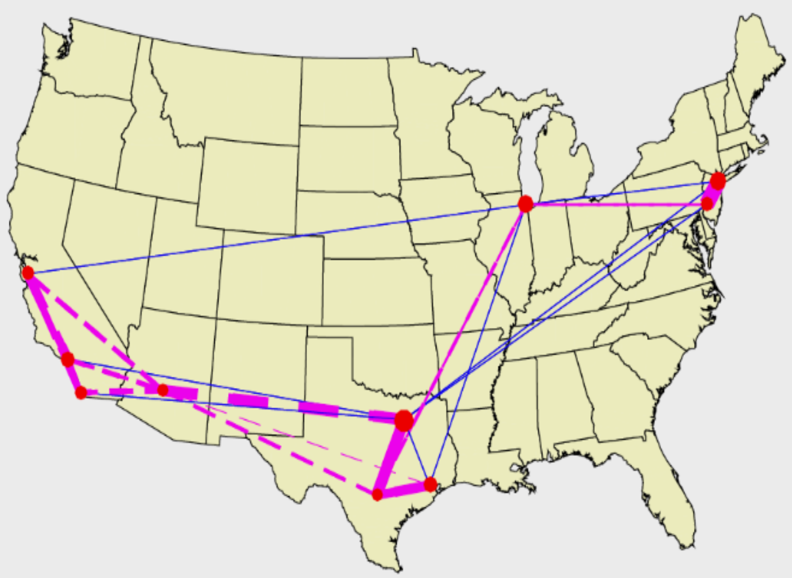
3.1 Algorithms for Network Design and Operation

- Develop optimization algorithms for network design (incl. vertiport location), vehicle assignment, routing, and scheduling, accounting for outcomes of TC1 and TC2

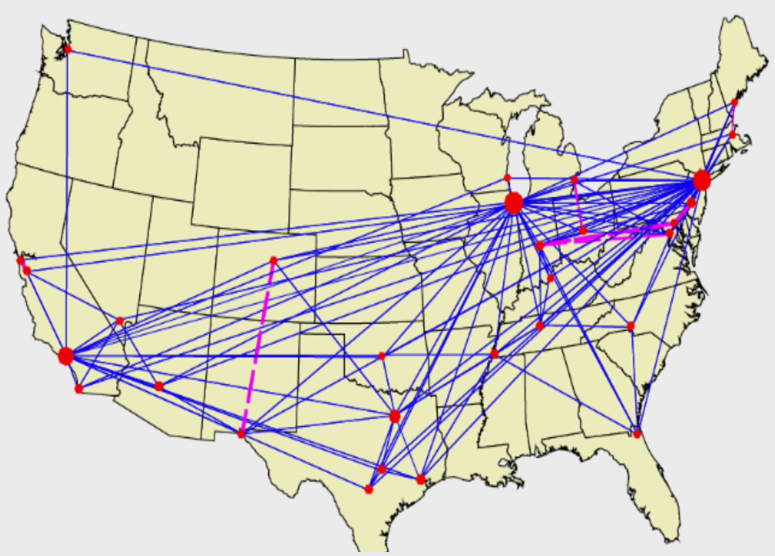
- Tackle challenges posed by multiple spatial and temporal scales (long-haul freight to last-mile delivery), scalability to large numbers of aircraft, heterogeneity of vehicle types, and the need for network resilience



10 cities; 2 a/c types; baseline costs



10 cities; 2 a/c types; smaller a/c (magenta) 75% less expensive than in baseline



30 cities; 2 a/c types; baseline costs

3.2 Accounting for Multiple Operator Utilities

- Elicit utility functions from operators
- Characterize tradeoffs between efficiency, fairness, resilience, and other objective functions, given differing operator preferences and utility functions
    - Large-scale, multiobjective optimization algorithms
- Study network design in the presence of competition

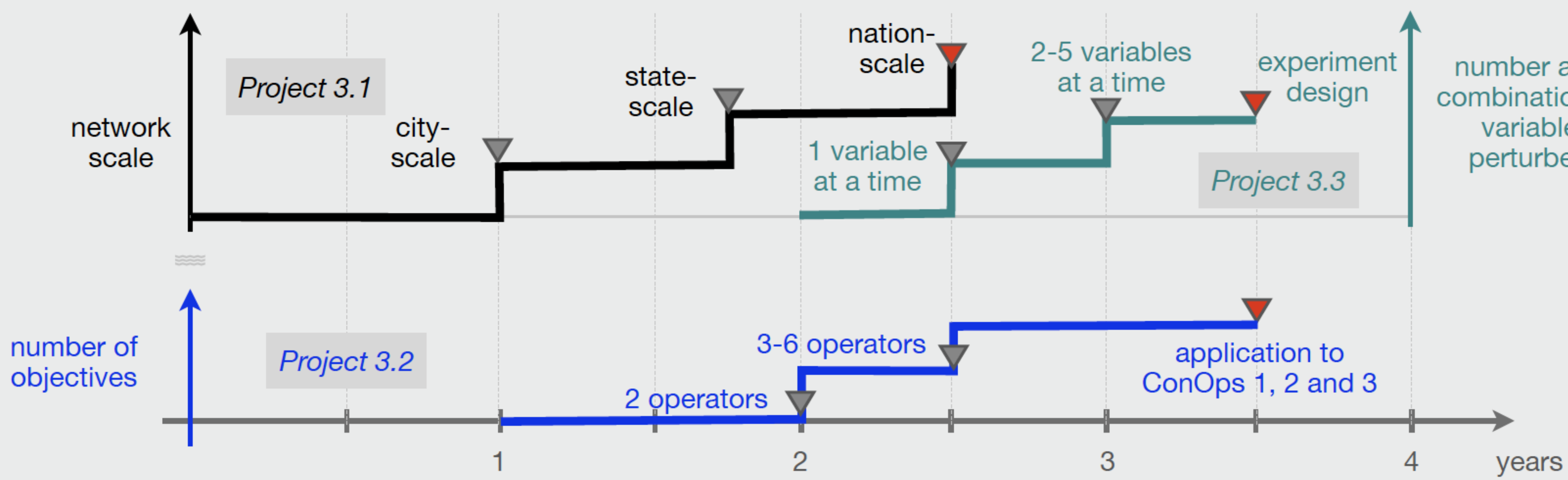
3.3 Sensitivity Analysis

- Optimization formulations in 3.1 and 3.2 will incorporate potentially competing constraints due to safety (from TC1) and noise, privacy and risk (from TC2)

- Conduct a systematic sensitivity analysis to identify which constraints have the highest impact on system-level performance

- Identify critical bottlenecks in the system and characterize underlying causes

Planned Timeline for TC3



- Algorithms developed in TC3 will be validated through integrated network operation simulations at multiple scales (coming up next)

Demo and validation

Demonstration and Validation Plan

"Scalable growth" and the ability to demonstrate and validate are at odds at times.

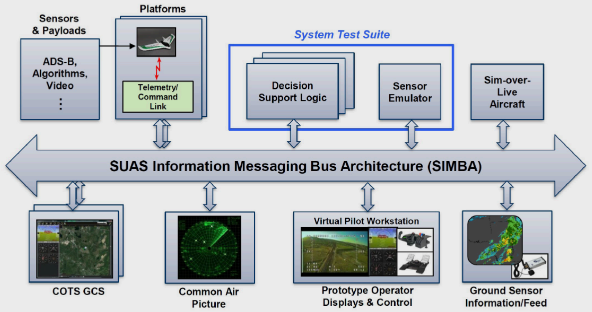
hardware testbeds

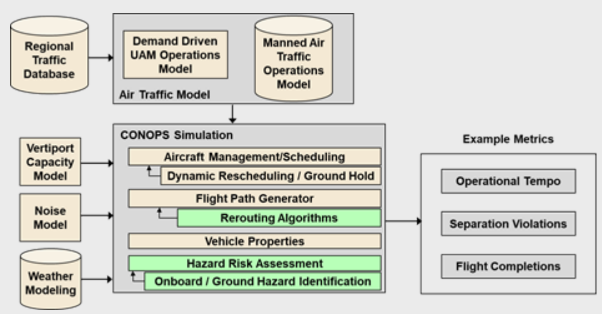
subsystem-level sensitivities

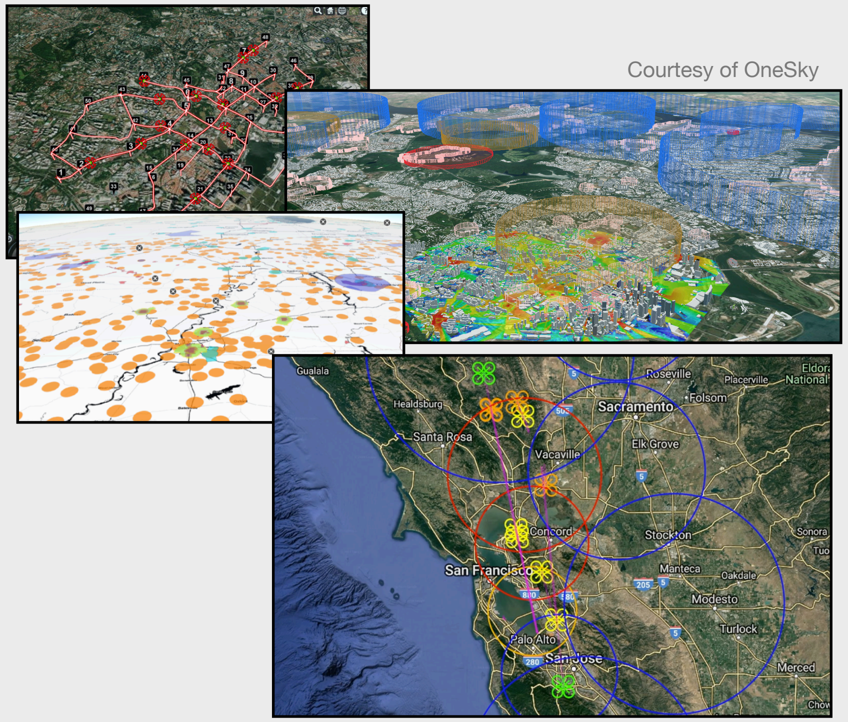
real(elastic) data

high-fidelity simulations

scalability and stress-testing







Courtesy of OneSky

Live, Virtual and Constructive

integrated demonstrations with 2-5 real vehicles and 10-100 simulated vehicles

Courtesy of NASA Langley

MIT LL AAM Assessment Framework

AAM Objectives

Separation Standard Impact on Network Efficiency

Weather Impacts

Corridor Capacity Estimation

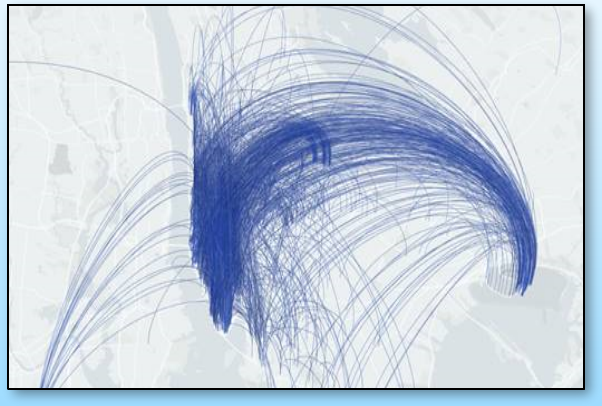
Effectiveness of ATM automation

Corridor Design for Robust Operations

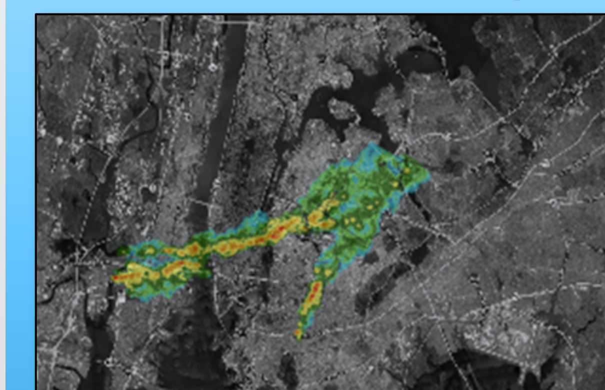
Veritport Location and Capacity Requirements

Contingency Impact

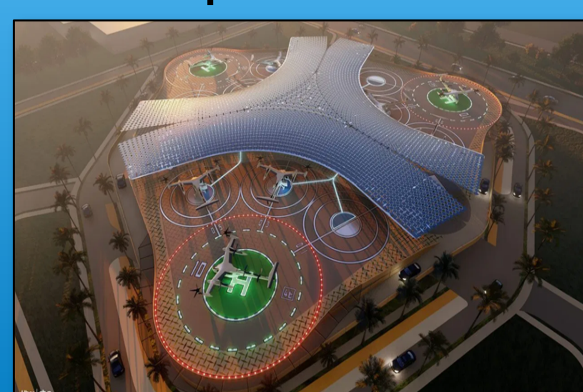
Demand Modeling



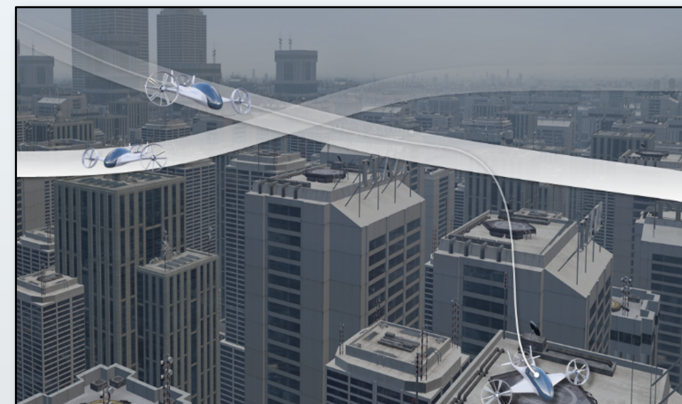
Urban Micro-weather Impacts



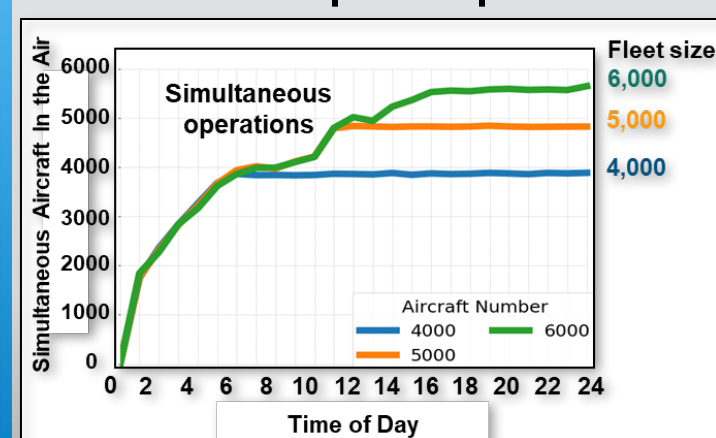
Vertiport Networks



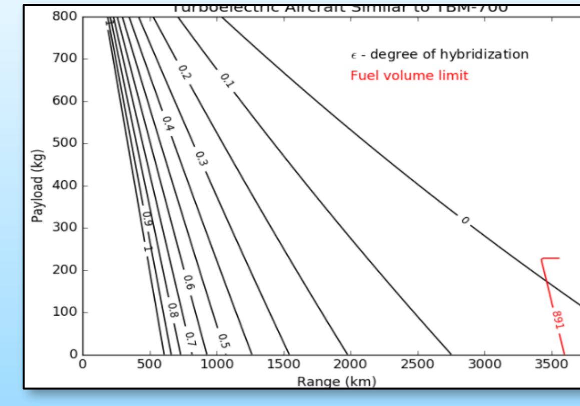
UAM Traffic Management Simulation



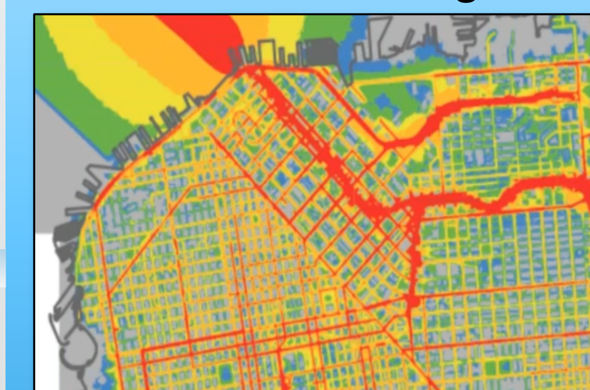
Example Output



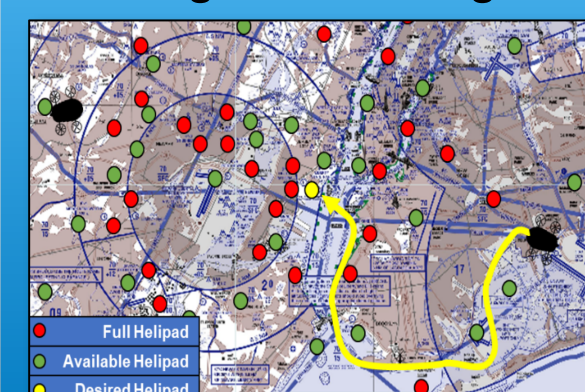
Aircraft Dynamic Limits



Noise Modeling



Flight Scheduling



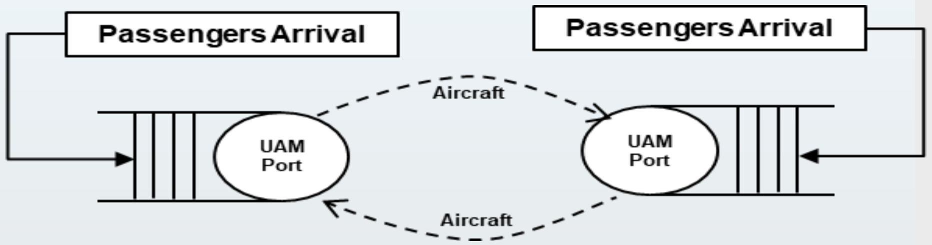
Lincoln AAM testbed provides flexibility and scope to conduct wide range of fast-time architectural studies

MIT LL AAM Modeling and Simulation Framework

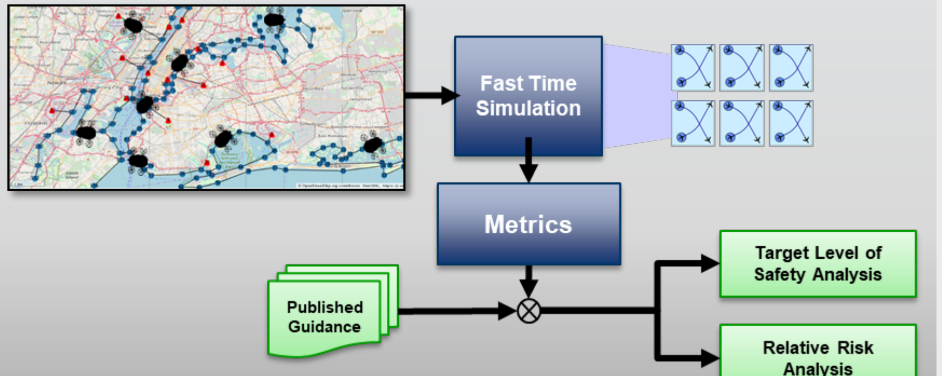
Inputs → **Modeling and Simulation** → **Example Supported Outputs**

- **Origin-Destination demand model**
- **Vertiport characteristics**
- **UAM route network rules and design**
- **Vehicle fleet characteristic**
- **Vehicle scheduling scheme**
- **Weather scenarios**

Event-Driven Model



Discrete-Time Model



Infrastructure:
- Network and vertiport design tradeoffs
- Contingency planning analysis

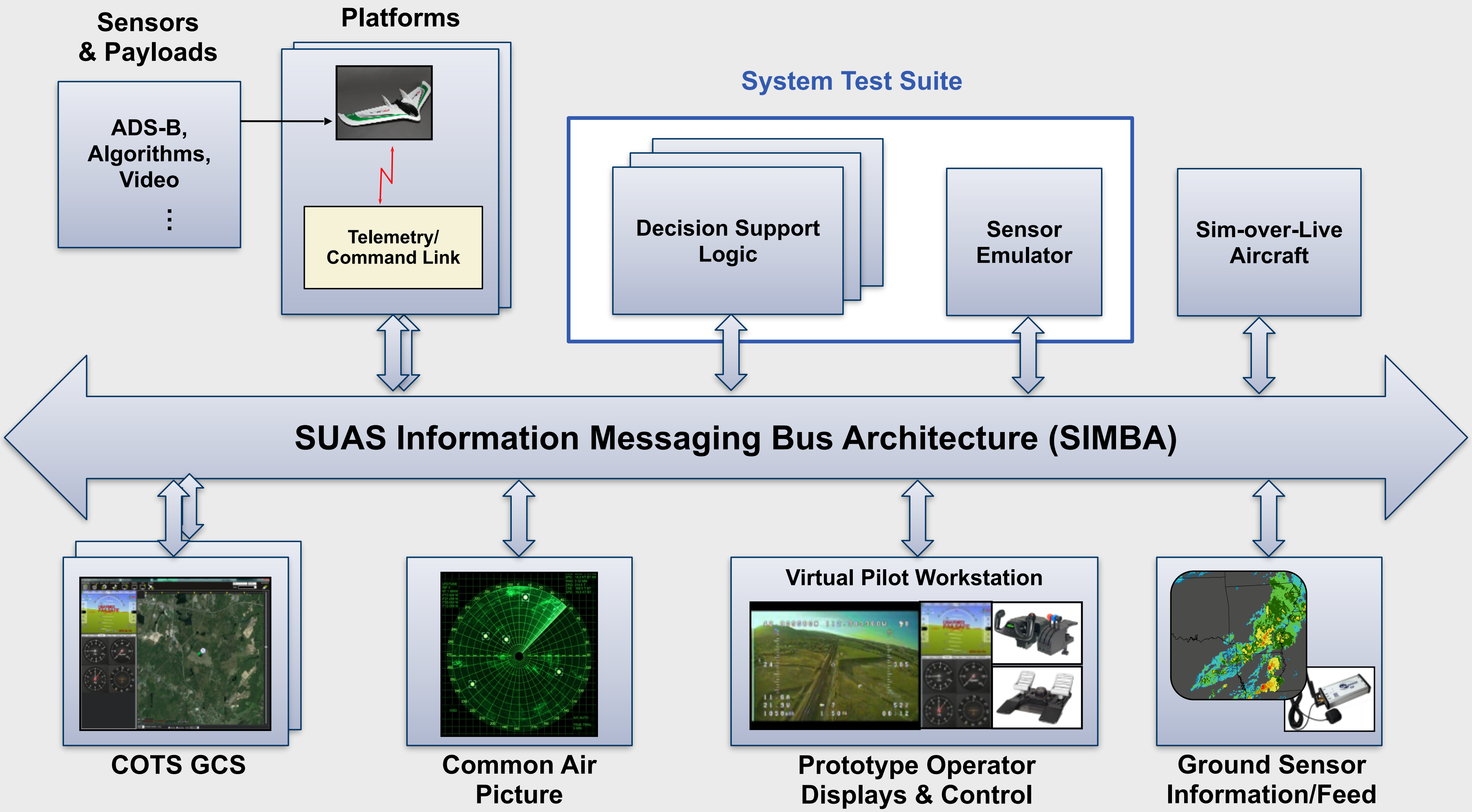
Operations:
- Fleet size, routing strategies, rebalancing tradeoffs, passenger adoption rate

Traffic density:
- Detect and Avoid, separation standards, surveillance requirements

Weather:
- Data requirements, operational restrictions, sensor standards

Societal:
- Noise analysis, energy distribution requirements

MIT LL sUAS Testbed Architecture



- Ability to explore distributed and centralized control
- Architecture permits rapid integration of new sensors and systems on low-cost platforms
- System under test implemented on platform or on ground
- Supports live, simulation, and sim-over-live environment

sUAS testbed will be leveraged as initial flight test platform as stepping stone to NASA capabilities

Purdue UAS Research and Test Facility

Benefit: The airport district is full of aerospace infrastructure

- A UAS (Unmanned Aerial System) runway is planned
- Aviation tech collaboration, UAS program students
- Airport collaboration

Adaptability

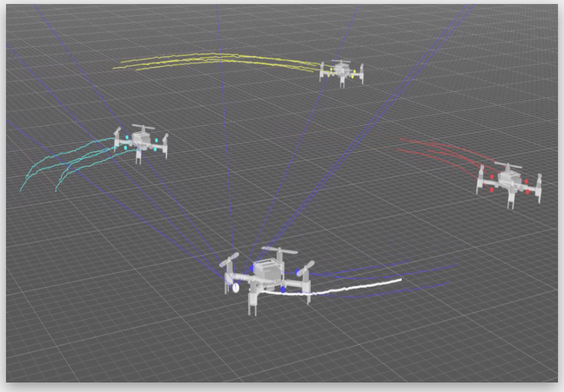
- Reconfigurable environments
- Tripod mounted cameras can be repositioned or used outside
- Large enough for small fixed-wing testing

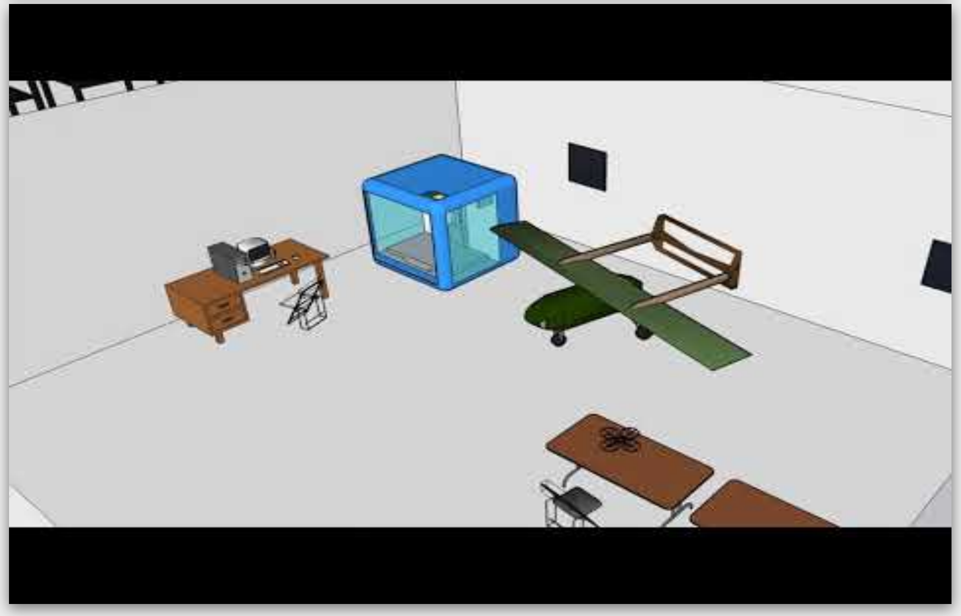
Environments

- Mixed- reality: More complex experiments can be conducted mixing virtual/physical elements
- Scaled urban: Testing for Urban Air Mobility (UAM) and multi-agent networks
- Harsh: Impact of weather (e.g. snow, water), or electronic jamming/cyberattacks

Control and Fabrication Rooms

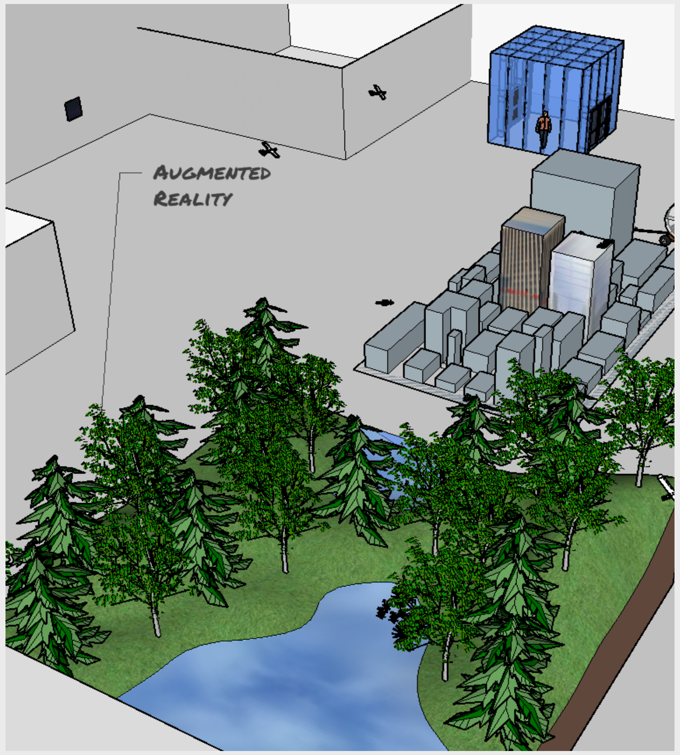
- Motion capture server
- Additive manufacturing, CNC





Mixed-Reality Environment

- Uses both **real-life sensor data** and **simulated sensor data.**
  - **For example,** UASs fly in a virtual forest or urban environment where simulated unreliable GPS signal is available but real wind from fans is used to generate real aerodynamic effects.
- Integrates real and virtual environments where UAS can perform a range of missions that are **impractical or impossible** in real environment alone.
- We are developing a system **similar to flight goggles.**



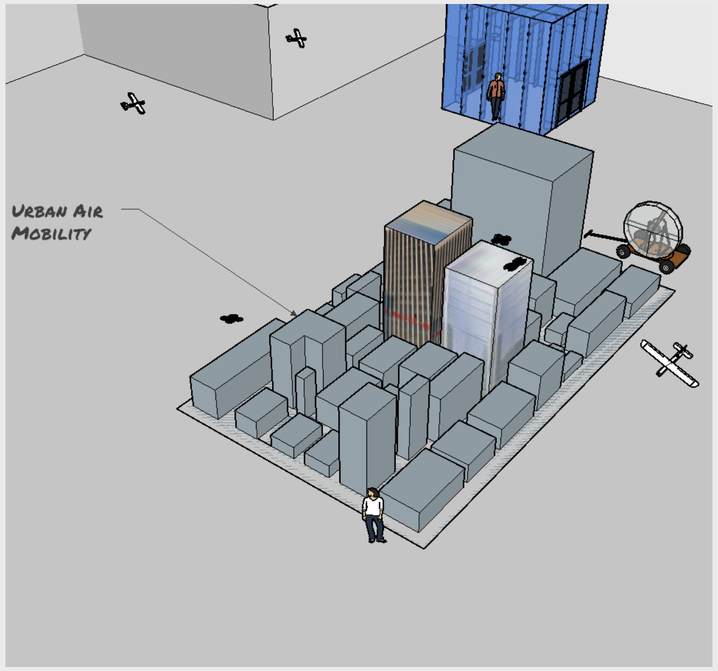
Scaled Urban Environment

- Various envisioned UAS applications are related to urban environment such as packet delivery, UAS Traffic Management (UTM) and Urban Air Mobility (UAM)

- Mission environment
  - Scale buildings are used to emulate urban environment
  - Micro UAS will be used to allow a large swarm of vehicle operating to simulate traffic in a city (enabled by high precision localization system)
  - Wind gusts can be provided by large fans

www.amazon.com/Amazon-Prime-Air


https://www.nasa.gov/aero/nasa-embraces-urban-air-mobility



Education Activities

Motivation: Our industrial partners have emphasized the benefit of teaching our students skills in autonomy that this facility fosters.

Hub for Education on Autonomy/Robotics

- Hands-on projects engage students and improve learning
- Use and calibration of motion capture systems
- Introduction to ROS, Python/C++ and Git version control which is used in software development
- Simulation with Gazebo (widely used by NASA, DARPA)
- Path planning for robotic vehicles
- Computer vision/ Visual mapping
- Machine learning
- Prepare for competitions like Alpha-Pilot, autonomous races

Education and Outreach

Overall strategy

Our education strategy is centered around the question of how we can expand and diversify the US workforce that will sustain the growth in autonomous operations enabled by our technical advances.

Three main components

(1) **A partnership with Morgan State University** to develop dual-degree programs, undergraduate research experiences, and mentoring opportunities for both students and faculty,

(2) **High school outreach programs** that particularly target underserved communities, and

(3) Outreach programs aimed at strengthening the pipeline of **women in aerospace engineering**.

Morgan State University

- A public, urban, HBCU, coeducational institution in a residential section of Baltimore, Maryland.
- By action of the Maryland Legislature, the University has been designated as Maryland's Preeminent Public Urban Research University, with the responsibility of addressing the needs of residents, schools, and organizations within the Baltimore Metropolitan Area.
- The future for MSU → #1 goal is to be first HBCU to be a Research-1 Institution.
- Please watch more about Morgan State here.

MSU Rocketry Club

Morgan State Faculty

Willie Rockward
Professor and Chair of Physics,
MSU PI for NASA ULI

Oscar Barton
Professor and Dean of
School of Engineering

Hongtao Yu
Provost & Sr. VP of
Academic Affairs

Craig Scott
Chair of Electrical and
Computer Engineering

Gerald Whitaker
Director of Base
Realignment

Jiang Li
Professor and Interim Chair
of Civil Engineering

Morgan State - Purdue Partnership

Newly formalized “3+2” dual degree partnership between the two institutions

First three years at MSU

- Year 1 at MSU
- Summer at Purdue
- Year 2 at MSU
- Summer at Purdue
- Year 3 at MSU

Final two years at Purdue

- Summer at Purdue
- Year 4 at Purdue
- Summer at Purdue
- Year 5 at Purdue

5 years

MSU BS
Civil or
Engineering Physics

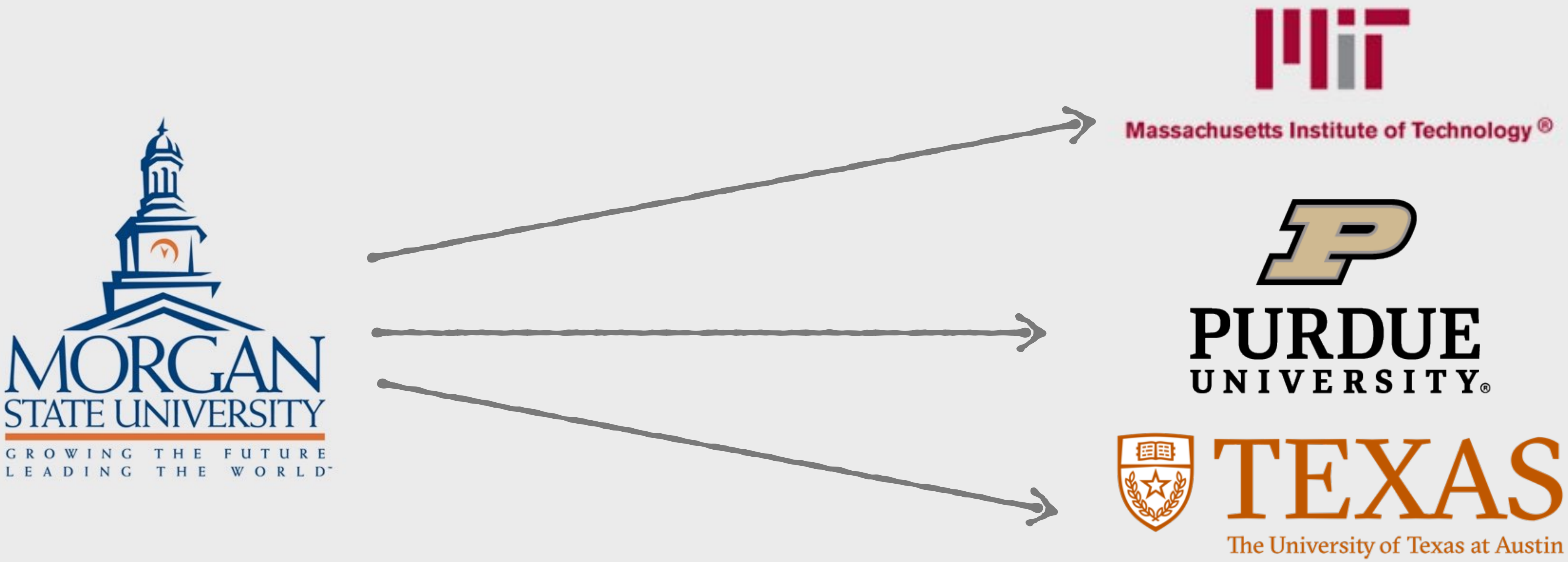
+

Purdue BSAAE

Details differ depending on the originating MSU School.

Summer Research Experiences

7 MSU students will participate in summer research each year at the partner universities



Additional opportunities

- MIT Summer Research Program
- Purdue Summer Undergraduate Research Fellowship
- UT Austin Moncrief Summer Internship Program

MSU had three students serving as Interns at the Purdue Zucrow Labs, one of the Nation’s premier academic rocketry facilities, during the 2019 Summer

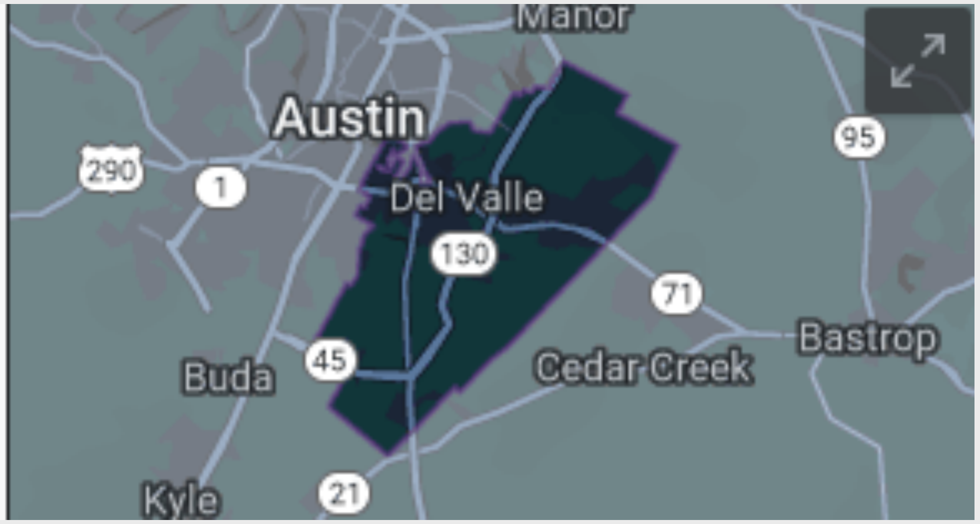
High School Outreach

Design and deploy **high school outreach programs** targeting underserved communities

- Expose students to career opportunities in aerospace engineering
- Provide students with meaningful research and mentoring experiences that grow their skill sets
- Primarily building on collaboration with the planned Career and Technical Education program in unmanned aerial systems at Del Valle Independent School District in Travis County, TX

Del Valle Independent School District

- Serves ~11,000 students
- 84.4% economically disadvantaged
- 84.1% Hispanic



We will work with Del Valle to

- Develop and deliver lecture modules for their Career and Technical Education classes
- Design and offer summer research experiences at UT Austin

J. Norris Sebastian III
Career and Technical Education Director
Del Valle Independent School District

Massachusetts Outreach

Contribute to the **Beaver Works Summer Institute** (BWSI)

- Co-organized by Lincoln Laboratory and MIT
- Hosted each summer for high school and middle school students.
- Four-week summer program teaches STEM skills through project-based, workshop-style courses
- Has drawn from 129 high schools across 27 states.
- Design projects for BWSI related to autonomy and advanced air mobility

Students and UAVs from 2012 2.007 Course, "Deployable Mini UAV"

https://beaverworks.ll.mit.edu/CMS/bw/bwsi

Women in Aerospace and Rising Stars Workshops

Build upon the successful “Rising Stars” workshops

Develop **a workshop series** focused on increasing the gender diversity of the workforce across the fields relevant to autonomy

Engage the members of our **technology recipients board** and other stakeholders

Summary

(1) **A partnership with Morgan State University** to develop dual-degree programs, undergraduate research experiences, and mentoring opportunities for both students and faculty,

(2) **High school outreach programs** that particularly target underserved communities, and

(3) Outreach programs aimed at strengthening the pipeline of **women in aerospace engineering**.

Non-advocate peer review board and process and discussion

Non-advocate peer review

Mike Ball

Carl Burleson

David Cunningham

Eric Feron

Gregg Fleming

Amy Pritchett

The role

- Evaluate the project (the results will be reported to NASA).
- Provide feedback and guidance to the team for course correction.

The method

- In average, meet twice annually.
- Feedback, e.g., in the form of "want to see more of," "improve," "better spend your time on something else," etc.
- After the meeting, compile a summary on which the team and the board agree and send to NASA.
- Start the next meeting with a statement on how the team acted on the board's recommendations.