Combining Formal and Probabilistic Modeling in Resilient Systems Design

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Outline

- 21st Century DoD Systems
- Engineered Resilience
- System Modeling
- Formal Probabilistic Approach
- Exemplar Problem
- Experimentation Testbed
- Initial Findings
- Summary

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21^{st} Century DoD Systems

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- High complexity (hyper-connectivity, dependencies)
- Long-lived (> 20 years)
- Likely to be extended / adapted for over lifetime
- Stringent physical and cyber security
- Need dependability + adaptability + proactive error prevention
- Need to operate safely in dynamic, uncertain environments subject to disruptions
- To address these challenges, we need new models, methods and tools

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Engineered Resilience is a Difficult and Messy Problem…Why?

- **Requirements:** can be imprecise (especially initially)
- **Actions:** can be unclear (especially initially)
- **Environment:** can be unknown or partially known (partial observability, unknown hostile and/or deceptive actors)
- **System states:** can be ambiguous (uncertainty)

These characteristics are incompatible with traditional, invariant modeling methods

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Systems Modeling

- Primary means for engineering systems including resilient systems
- A fragmented area for engineering resilient systems
- Most serious problems result from the gap between requirements and models that need to reflect requirements
  - contribute to poor flow down of system requirements to software requirements
- Different aspects of system behavior represented by different models
  - need to harmonize different models

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System Modeling Requirements

- Verifiability (correctness)
- Flexibility (to adapt to changing conditions)
- Bidirectional reasoning support (resilience-related decisions)
- Scalability and extensibility (no. of agents, interconnections)
- Exploit partial information to generate value (not “data hungry”)
- Learn from new observations (system and environment states)

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Formal Probabilistic Approach

- Combines formal and probabilistic modeling with heuristics
  - enables flexibility (resilience)-verifiability (safety) tradeoffs
  - heuristics: help contain combinatorial explosion in state space
- Exploits reinforcement learning
  - learning of system states and environment with new evidence
  - system states model: Partially Observable Markov Decision Process
  - provides value even with partial information
- Employs a layered architecture
  - planning and decision making (top level) and control (bottom level)
  - decisions and information flow from top level to bottom level
  - execution constraints flow from bottom level to top level
  - global objectives have precedence over local goals (if conflict)
- Defines new construct: Resilience Contract
  - balance system verifiability and system flexibility requirements

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Exemplar Problem: Multi-UAV Operations

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- UAVs used in missions in which environment is largely unknown and potential hostile with deceptive actors
- UAVs have to complete mission safely with original / descoped objectives
- UAVs can experience malfunctions and disruptions
- A mathematical model of environment is seldom available
- UAVs have collection assets to sense the environment
- UAVs can employ reinforcement learning to progressively learn the environment from sensed information
  - e.g., use RL to navigate through changing, partially observable environments

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What Resilience Means for Problem Domain

- **Operate safely** in dynamic, uncertain environments
  - tolerate / survive systemic faults and failures
  - adjust / adapt to environmental disruptions
  - protect / defend against physical and cyber threats
  - reconfigure / restructure to minimize impact of disruptions (e.g., security breaches, loss of sensing node or comm link)
- **Accomplish goals** with incomplete information
  - e.g., navigate safely to destination with partial observability

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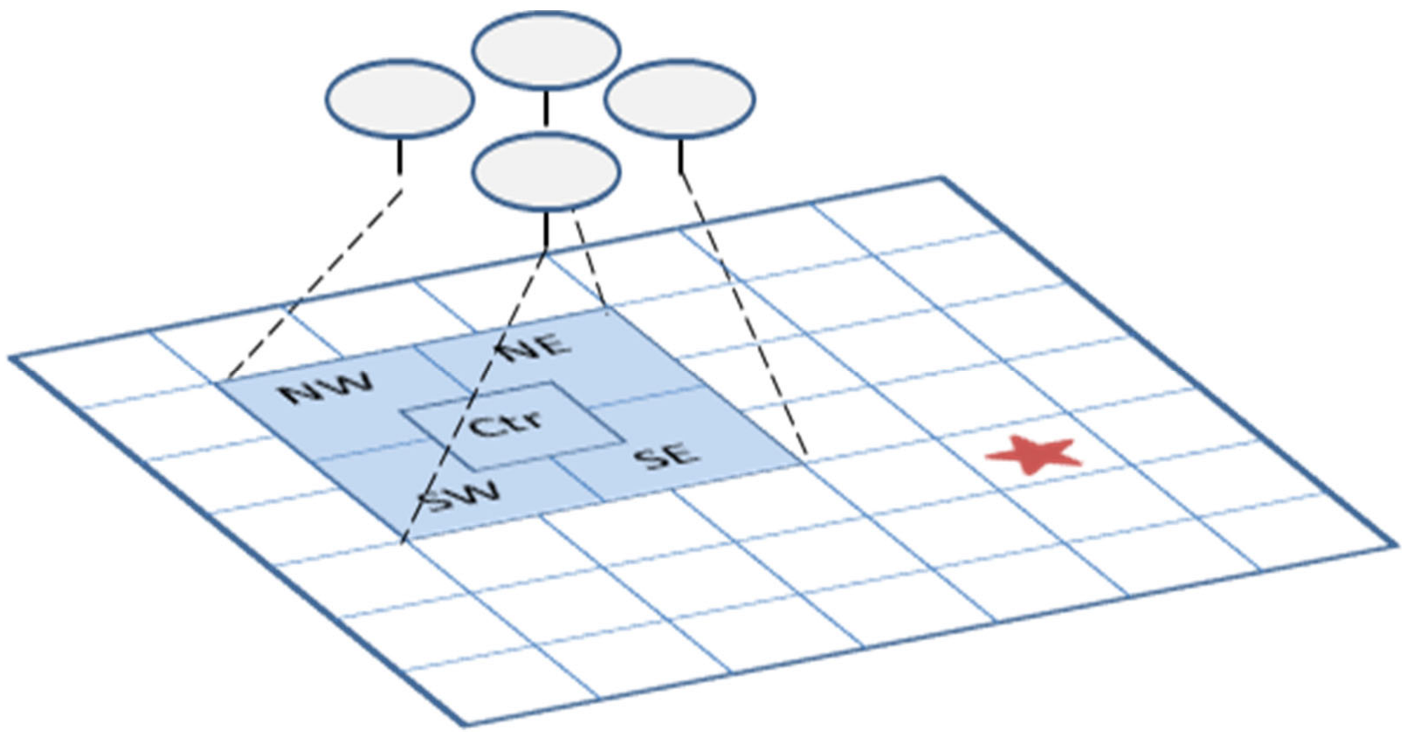
UAV position relative to a recon target (red star) and FOV (blue)



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Exemplar Contracts

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1. ¬overTarget && healthy && batteryGreen → move_to_target
2. ¬batteryRed && degraded || batteryYellow → move_to_base
3. batteryRed || failed → land
4. unknownHealth || unknownBattery → move_to_base
5. overTarget && CTR && healthy → takeImages & hover
6. overTarget && NW && healthy → takeImages & move SE
7. overTarget && NE && healthy → takeImages & move SW
8. overTarget && SW && healthy → takeImages & move NE
9. overTarget && SE && healthy → takeImages & move NW

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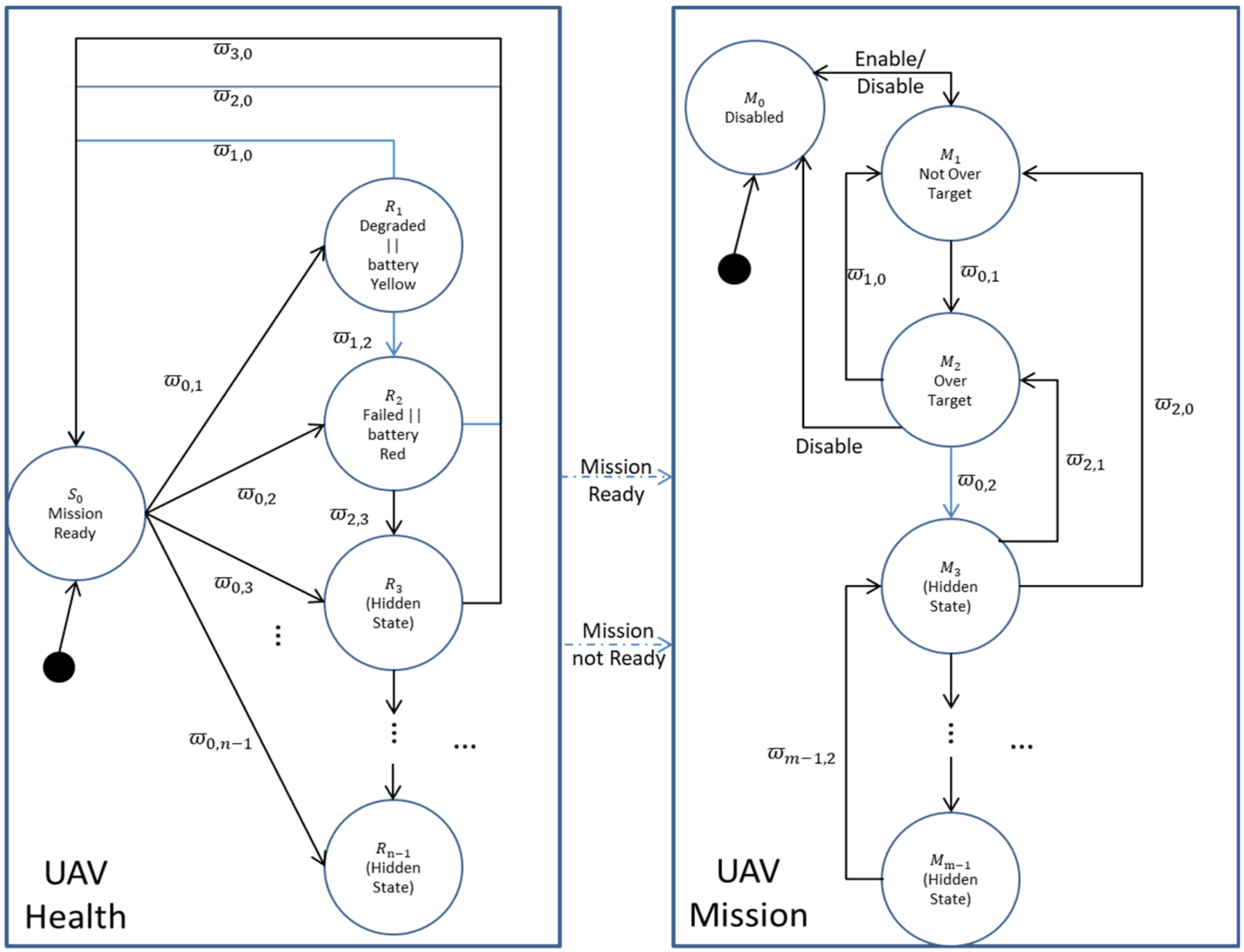
Simplified POMDP:
Health and Mission Models



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Multi-UAV Dashboard Prototype

- Capabilities
  - customizable dashboard for monitoring and control of simulated or physical vehicles
- Underlying technologies
  - dronekit platform with visualization facilities
  - quadcopters (hardware) and quadcopter simulation models
  - quadcopter planning and decision-making model
  - quadcopter controller
- Key capabilities
  - simulated vehicles exhibit behavior of physical vehicle
  - same commands used to control vehicle models and physical vehicles (quadcopters)
  - can switch from simulated vehicles to physical vehicles

Dashboard Showing Camera View of Flying Quadcopter

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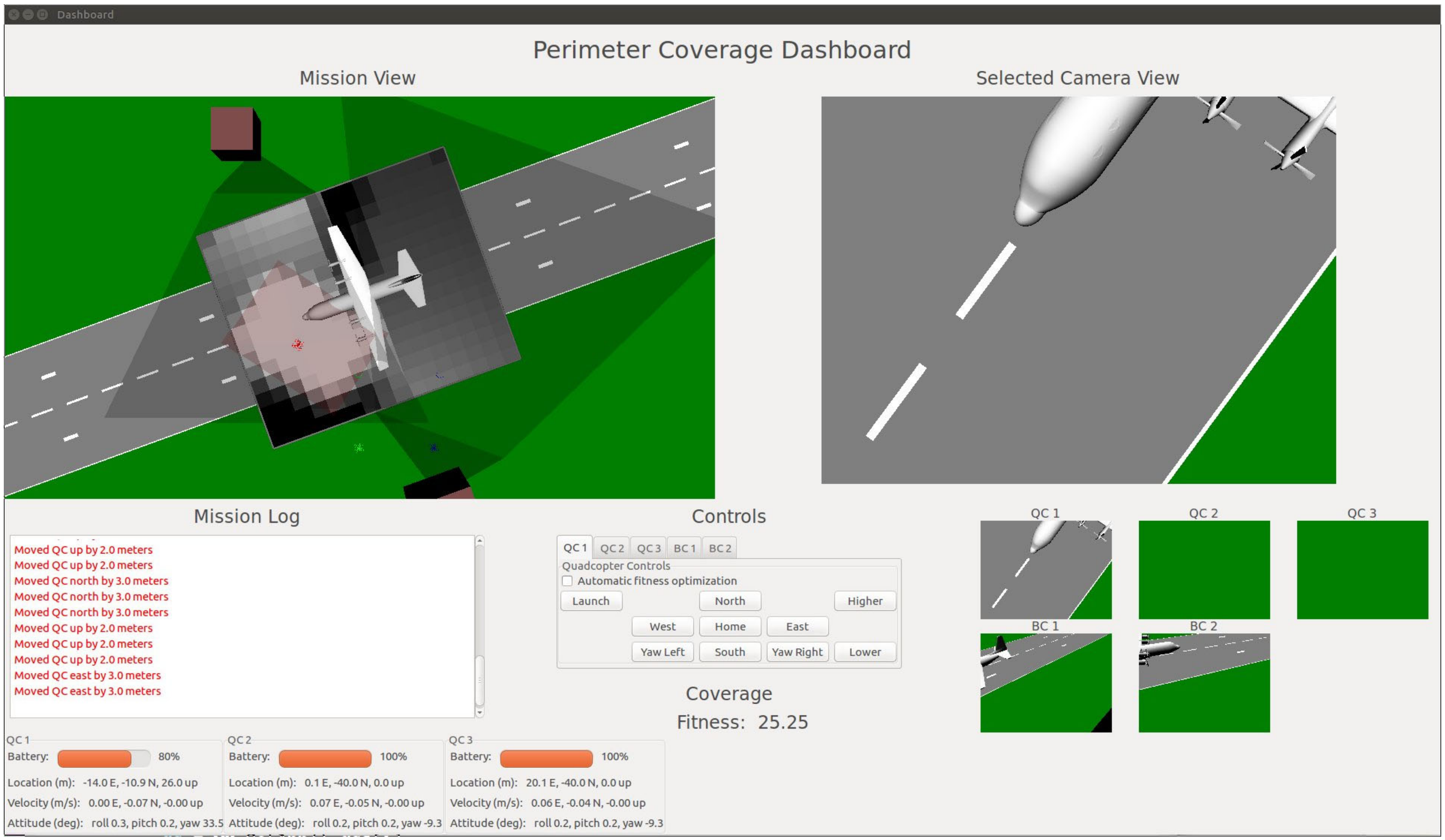

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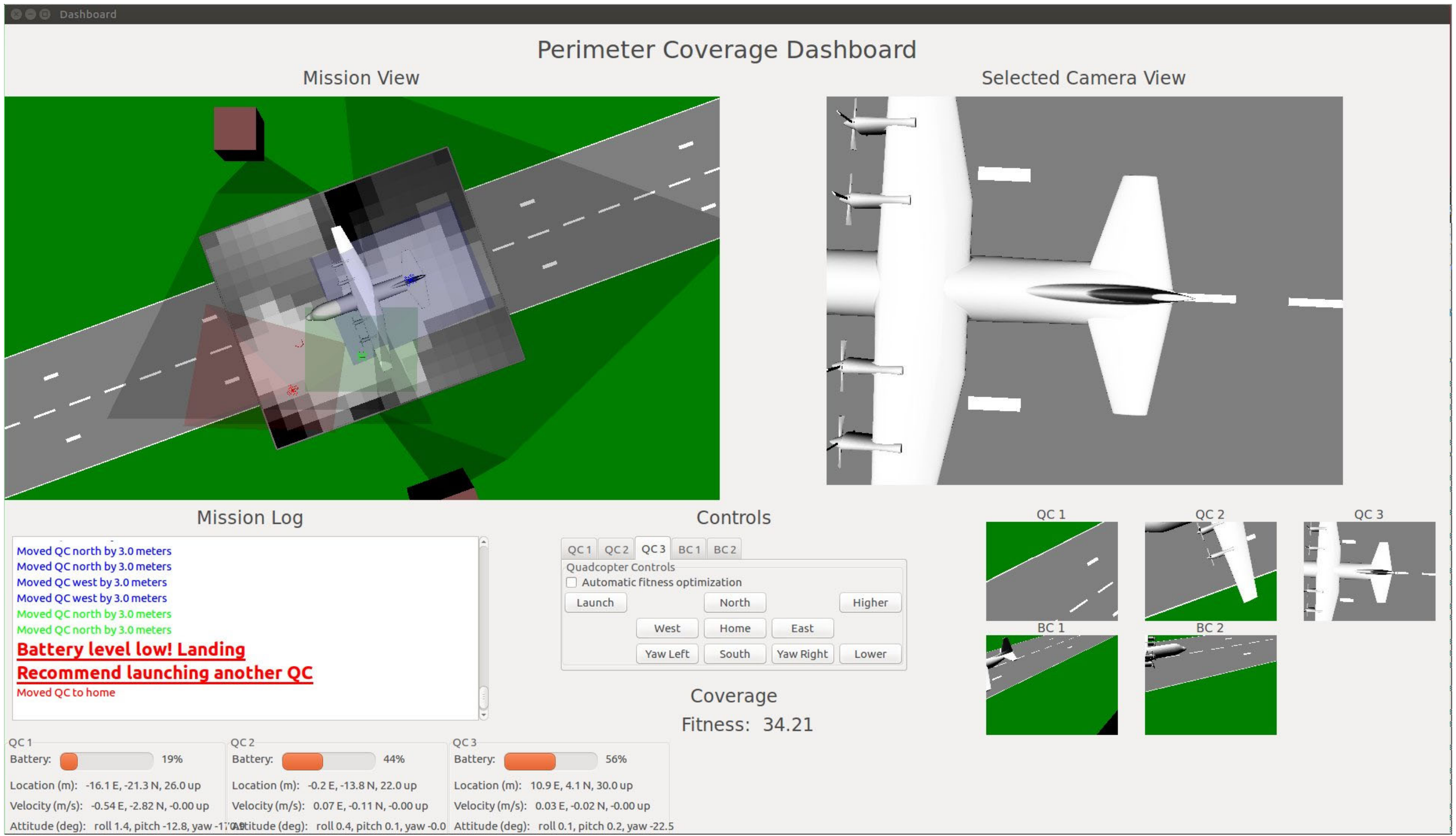
Dashboard Showing 3 Flying QCs With One Low on Battery and Landing



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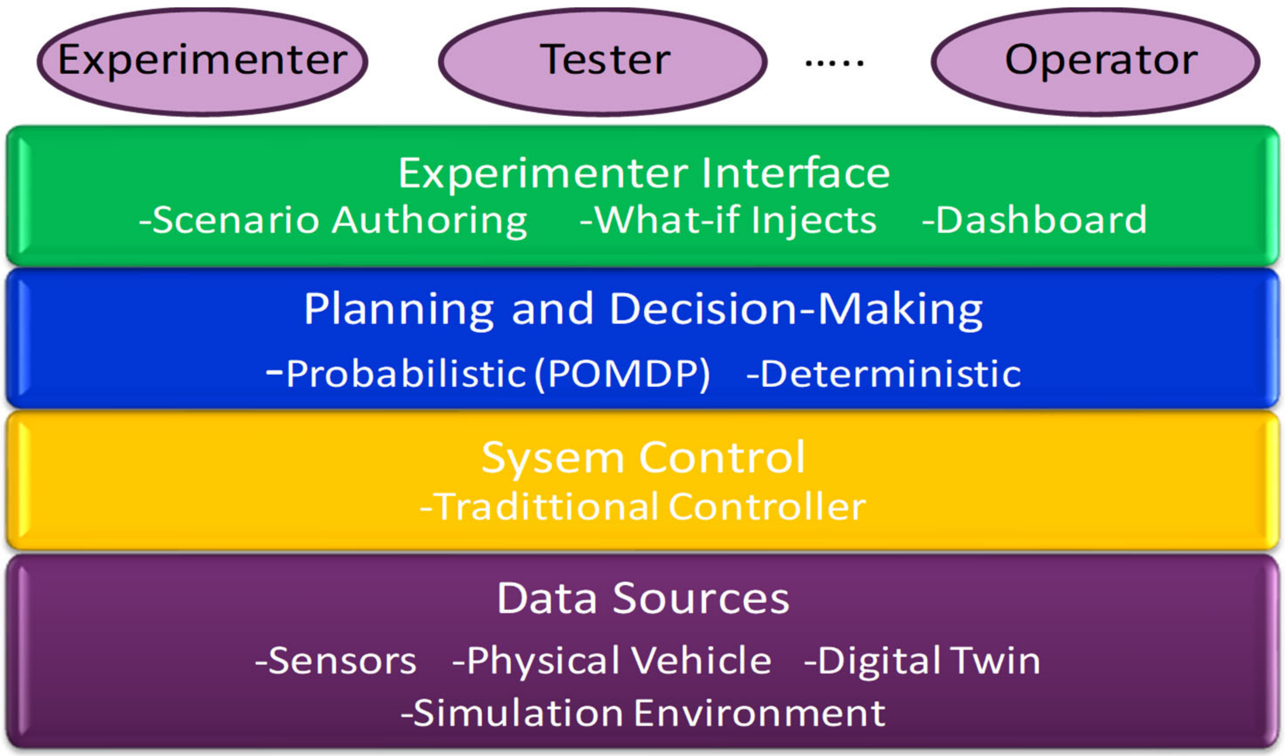
Experimentation Testbed Architecture



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Prototype Testbed

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- Quadcopters
  - driven by Raspberry Pi and Navio Flight Controller
  - full IMU: 3-axis accelerometers, rate gyros, magnetometer
  - inputs from laptop and/or remote controller
    - control values (throttle, roll-pitch-yaw)
    - perform autonomous flight
- Instrumented Testbed
  - layered architecture (UI, planning and DM, control, data sources)
  - customized Python scripts for vehicle control
    - dronekit framework and commands
  - semi-autonomous flights
    - launch, take-off, hover, and perform limited waypoint navigation
  - context-sensitive monitoring and control dashboard
    - monitor vehicle status and control vehicle
    - communicate with simulated vehicles and physical system

Prototype Testbed Hardware

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Findings To-Date

- Key problem in implementing hybrid models
  - resolving mismatch between planning & decision-making layer and vehicle control layer
- Mismatch resolution
  - ensure that propagated commands from PDM layer to controller do not violate physical and regulatory constraints
  - propagate execution constraints from control layer to PDM layer for PDM layer to take into account when issuing commands
  - incorporate heuristics (e.g., priorities, region of influence) to resolve conflicts and simplify computation

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Findings To-Date (cont'd)

- POMDP and vehicle controller work on different time scales
  - dynamics model runs every 0.01 seconds (accuracy)
  - POMDP runs slower (high level decisions/commands)
    - waypoint navigation problem with goal of minimizing response time to action
    - ideal sampling period for POMDP determined experimentally
- Simultaneous creation of prototype and testbed - good strategy
  - introduced rigor in experimentation
  - compatible with introducing Digital Twin
  - currently: able to switch between simulation model and physical system
  - future: incorporate operational data from physical twin into Digital Twin
- Monitoring and execution dashboard – a key capability
  - facilitated understanding and debugging of vehicle behaviors

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Summary

- 21st Century Systems need to be safe, resilient and affordable
- Have to operate in uncertain, hostile and deceptive environment with partial observability
- System model verifiability is needed for system safety
- System model flexibility is needed for resilient behavior
- Such capabilities beyond traditional systems modeling capabilities
- Resilience Contract, a probabilistic approach based on POMDP, when coupled with heuristics and reinforcement learning, can satisfy safety, resilience and improved performance needs
- Our research is demonstrating viability of this approach with different CONOPS and resilience mechanisms

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Thank You

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