Engaging Undergraduates in CPS Research:

from Freshman Explorations to Senior Design Projects

Saurabh Amin

Joint with Derek Chang, Mathieu Dahan, and Jeff Liu

MIT

NSF Review Meeting, January 25-26, 2017

NAE Report: **A 21st Century CPS Education**

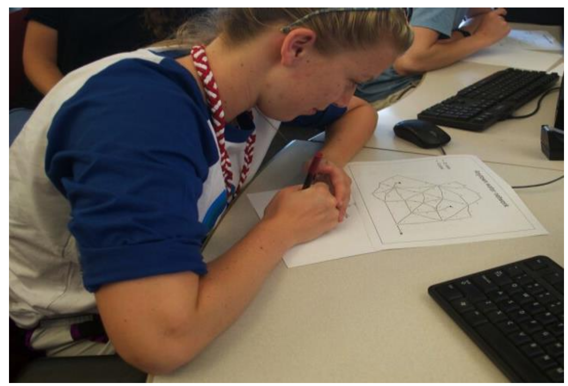
- CPS workforce will be *diverse*: (1) Foundational fields (EECS, MechE, Systems); (2) Applied fields (aerospace and civil); (3) CPS engineers
- Four broad areas: (i) Principles; (ii) Foundations of CPS; (iii) System Characteristics; (iv) Complementary skills
- Individual courses emphasize physical engineering or cyber design; but *most courses* fail to emphasize the interaction between physical and cyber aspects.
- Strong need to add CPS content to freshman-level intro courses
- Project-based courses should be extended to support CPS principles and foundations.
- CPS education programs for incoming UG students should leverage the visibility and interest in robotics, IoT, smart cities, & industrial internet.

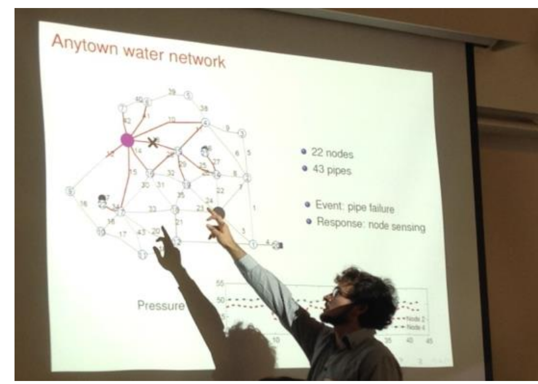
FORCES Driven UG Activities

1. **Online security games:**
   * Exploration / Orientation programs for Middle and high school students, and freshmen
2. **Quantitative sustainability subject:**
   * Core subject in UG curriculum for systems students
3. **Mini-UROP projects:**
   * Hands-on research experience for freshmen
4. **Capstone design projects on network resilience:**
   * One-two semester long integrative design project (joint with MIT Lincoln Laboratory and MTSI Inc.)

1. Education Module: Security Games

- **Objective:** A game theory module with focus on infrastructure security to teach UG students using interactive simulations of network games.
- **Website:** http://resilserv.mit.edu/game/
- **Lead Graduate Students:** Jeff Liu and Mathieu Dahan

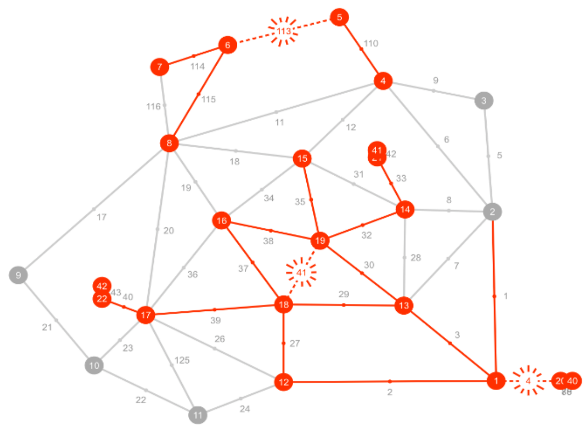




- **Key aspects:**
- Simulation of attack scenarios on water networks using EPANet
- Evaluation of defender (network operator) strategies
- Decision theory concepts: Game theory and Optimization

1. Education Module: Security Games

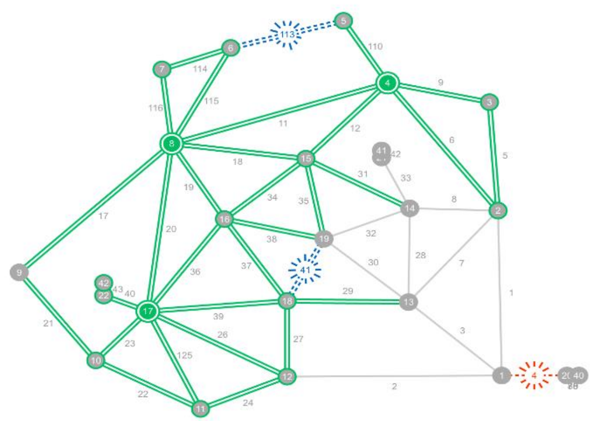
Playing round 1 of 12 on ‘Anytown’ vs. computer

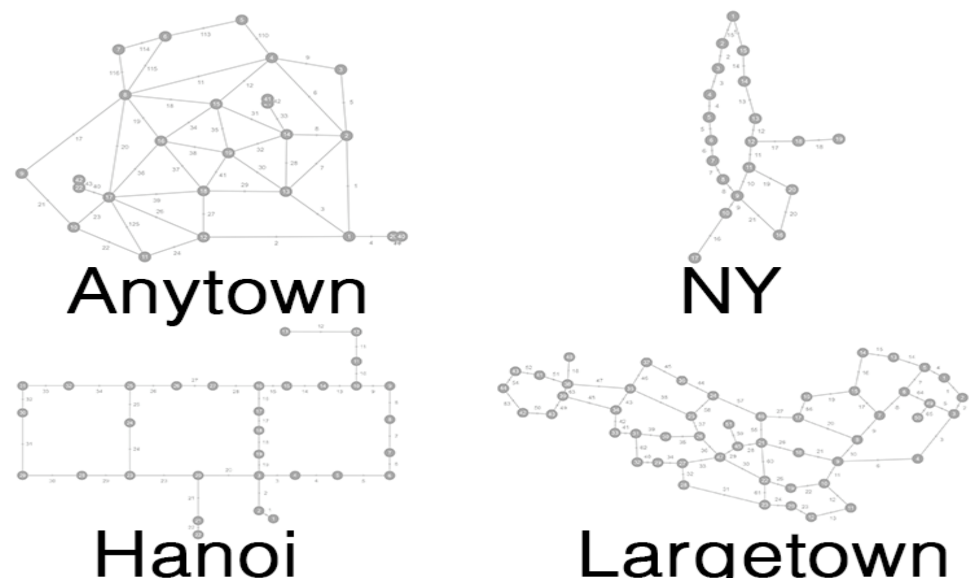


Game Structure

- Attacker disrupts links
- Defender places sensors on nodes
- Attacker wins round if majority of disruptions were undetected. Defender wins otherwise
- Players play several rounds to try and learn opponent’s strategy
- Human or computer opponent

Summary of round 1 on ‘Anytown’ vs. computer





1. Education Module: Security Games

Security Games Module at MIT 2016 Open House
Photo: Marilyn Siderwicz, MIT News

Outcomes / Knowledge gained:

* Network models of infrastructures
* Game theoretic models of strategic interaction
* Covering / facility location problems
* Insights on how cyber-aspects (sensor network design) influence physical network (leak detection)

Offered at:

* Pre-orientation 2015 (High School Seniors)
* IAP 2016 (Undergraduate Freshmen)
* MIT Open House 2016 (General public, including middle school students)

Data:

* 1044 rounds played across 87 games
* ~125 participants

FORCES
FOUNDATIONS OF RESILIENT CYBER-PHYSICAL SYSTEMS

2. Teaching: Engineering for Sustainability

1.020 "Energy & Water Sustainability"

- Undergraduate Junior-level core subject in CEE Systems curriculum
- Part of (proposed) MIT minor in Environment and Sustainability
- **Outline**:
  - Introduces a systems approach to modeling, analysis, and decision-making problems for water and energy sustainability, including the supporting cyber-physical infrastructure.
  - Formulation of models based on physical, environmental, social, and economic principles; and economic evaluation of design.
  - Uses numerical models to integrate concepts and to assess environmental impacts of human activities.

FORCES
FOUNDATIONS OF RESILIENT CYBER-PHYSICAL SYSTEMS

2. Teaching: Redesigning the course

Previous course offerings:

* Focused on analysis, with traditional problem sets and "correct" answers
* Topics presented in isolation, which made the course feel disjointed
* Limited emphasis on engineering design

Redesign Goals:

* Reorganize and integrate topics into cohesive and complementary units
* Retain analytical rigor of previous course iterations
* Introduce more open-ended design questions focusing on CPS aspects
* Increase emphasis on solving problems involving real-world/noisy data

FORCES
FOUNDATIONS OF RESILIENT CYBER-PHYSICAL SYSTEMS

2. Teaching: Redesigning the course

Redesigned Structure

Each unit has two components:

1. **Analysis & Modeling**
   * Fundamental techniques
   * Build tools and models
   * "Traditional" problem sets
2. **Design**

   -- Utilize tools and models to address open-ended design question

   -- Consider technological and regulatory aspects

   -- No "correct" answer: students must make & justify assumptions / trade-offs of their design

   -- Extra credit to innovative solutions

* Analysis/Modeling component retains majority of existing topics
* New design component unifies topics within and between units
* To accommodate the design component, we reduced emphasis on derivations that are better suited for in classes and quizzes dedicated specifically to these topics

FORCES
FOUNDATIONS OF RESILIENT CYBER-PHYSICAL SYSTEMS

2. Teaching: Redesigning the course

Units & Design Questions

1) Ecological systems

(ODEs, pollutants, chemical kinetics, predator/prey models)

-- Design regulations on fishing/farming/pollutants to ensure stable ecology

-- Coupled systems: farm runoff/industrial pollution affect algae and fish populations

-- Trade-offs: How much economic performance are you willing to sacrifice to ensure stable ecology?

2) Urban Networks

(Integer & linear programs, flow models, demand forecasting)

-- Design a water distribution network, including physical component, and sensing-control system

-- Optimization: various costs associated with facility and network installation that can be minimized

-- Uncertain demand/failures: designs must address and justify risks, failure modes, and associated costs

3) Energy Systems

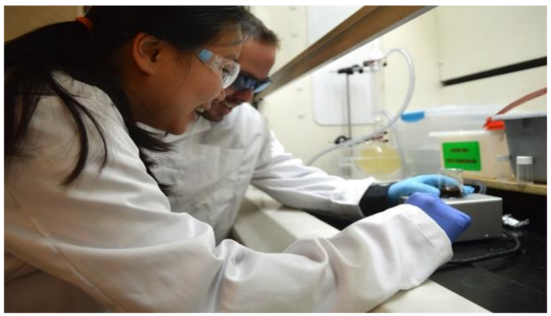
(Heat transfer, work, thermodynamics, renewables)

-- Design an energy efficient building from the ground up (both cyber and physical components)

-- Simulation: students build a working simulation of their building's temperature, water pressure, energy usage, tying many previous applications together

3. Freshman Research Projects (Mini-UROP)

* **Mini-UROP program:** Month-long freshman "crash course" and introduction to research in CEE (CPS, structures, or water resources).



* **Program features and history:**
  * Held every January over MIT Independent Activities Period
  * Freshmen are paired with CEE graduate student mentors and faculty to conduct projects with a mix theory, hands-on lab experience, and programming expertise
  * Held as a 6 unit Pass/Fail course, culminating in freshmen research presentations
  * We offered CPS projects to 2 students in 2016 (one is now a sophomore in CEE) and 1 student in 2017

FORCES
FOUNDATIONS OF RESILIENT CYBER-PHYSICAL SYSTEMS

3. Freshman Research Projects (Mini-UROP)

Example Projects in CPS

1) Water Networks

(2016: Visualization and analysis of distribution networks)

-- Model failure likelihood of water network pipes using visualization in ArcGIS

-- Use network pipe properties to calibrate a mathematical model

-- Model results dictate prioritization of pipe monitoring and inform state of network health

2) Transportation

(2016: Resilience of transportation networks)

-- Model the effect of random events (storms, accidents) on freeway traffic flow

-- Simulation: online traffic data from two San Francisco Bay Area freeways is used to calibrate a stochastic vehicle flow model written in MATLAB

3) Power Systems

(2017: Storm resilience of power networks: wind fields, cascades)

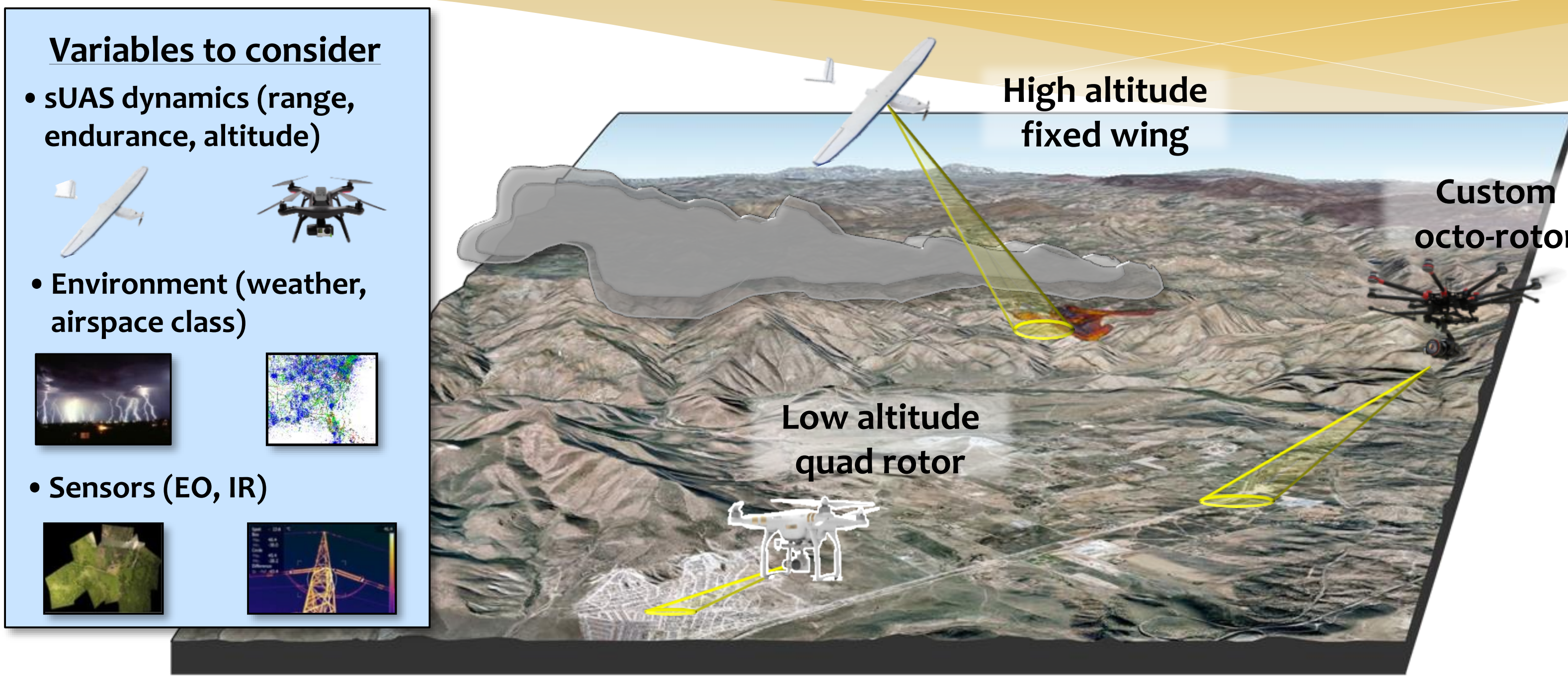
-- Test and implement machine learning algorithm that predicts storm surface wind fields

-- Design model of storm-induced power network component failures and cascading losses

-- Applications of stochastic processes, spatial statistics, and inference

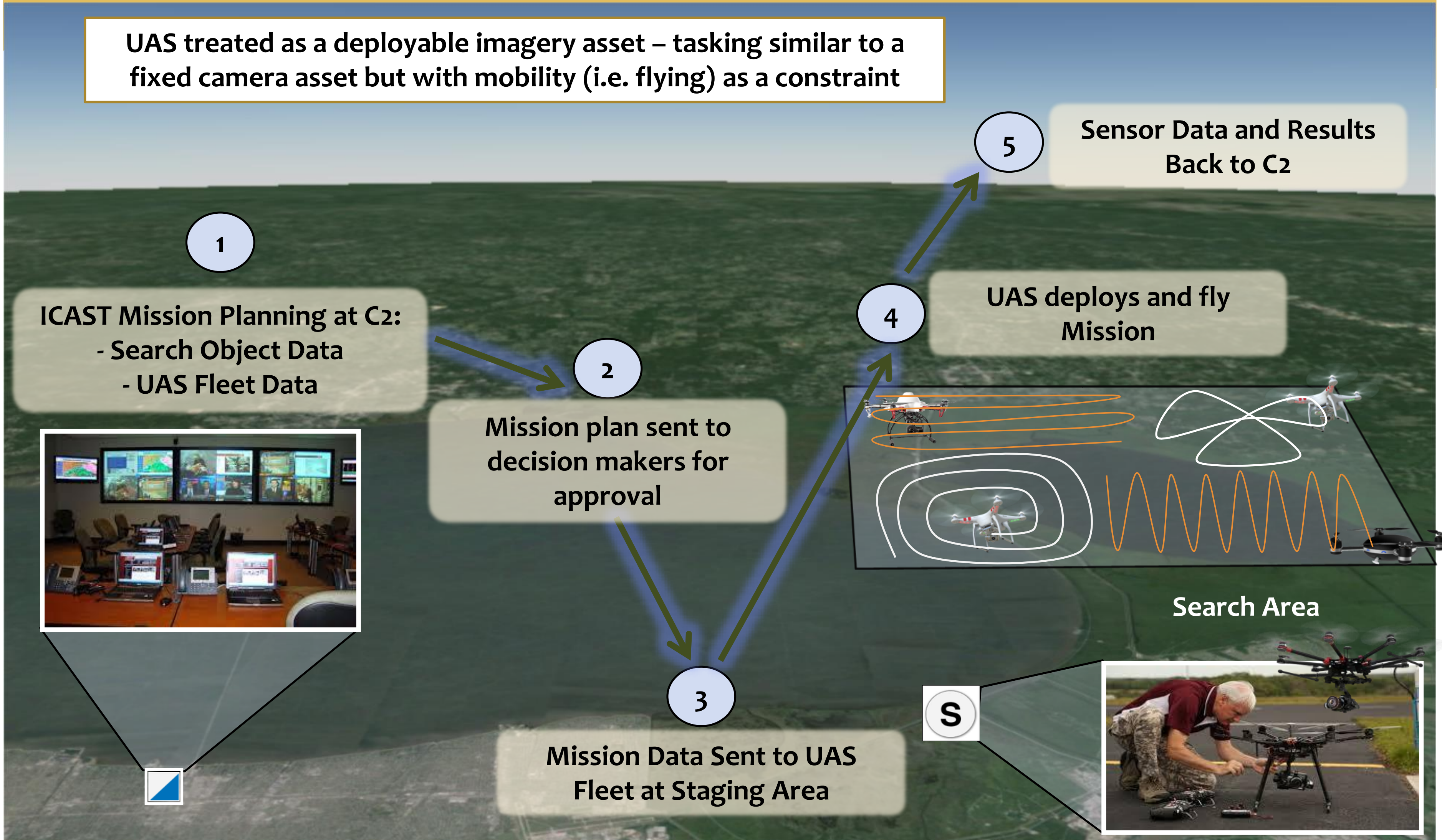
FORCES
FOUNDATIONS OF RESILIENT CYBER-PHYSICAL SYSTEMS

4. Capstone project: Intelligent Constrained Autonomous Strategic Tasking (ICAST)



- **“UAS Sensor On-Demand” capability**
  - **As an untrained user, I need sensors here ⇨ UAS enable data collect**
- **Prototype strategic tasker given the environment, sUAS, users, & sensors**
  - **Integrate sUAS system with mission specific algorithms & systems**
  - **Intelligent mission planning cognizant of sUAS size, weight, and constraints**
- **Beaver Work capstone project with MIT CEE Department**
  - **Graduate research; UROP projects; Course 1.013 CEE Design class to be offered in Spring 2017**
  - **Support: NSF FORCES project, Lincoln Laboratory and Modern Technologies Solutions, Inc.**

4. Capstone project: ICAST



Slide courtesy: Andrew Weinert

4. Capstone project: Goal and Team

Design challenge: What is the best way to deploy and task a fleet of small unmanned aircraft systems (sUAS) to perform strategic monitoring and diagnostics for large-scale critical infrastructure networks, while they are subject to component failures due to natural failures or malicious attacks?

Team:

- UG Students: Bridget Bassi and Morgan Goodson (double majors in CEE Systems and Management)
- Graduate student mentor: Mathieu Dahan
- Lincoln Laboratory mentor: Andrew Weinert (Humanitarian Assistance and Disaster Relief Systems Group)
- Industry support: Mike Munizzi (MTSI Inc.)

4. Capstone project: Statement

* To design, prototype, and evaluate a model-based decision support tool to task a fleet of small Unmanned Aircraft Systems (sUAS);
* To utilize this tool for distributed monitoring and real-time diagnostics of infrastructure networks.

* Two use cases: Detection and localization of
  * Pipeline/regulator failures in water systems, oil & gas networks
  * Distribution line failures and protection equipment malfunctions in electricity distribution networks

FORCES
FOUNDATIONS OF RESILIENT CYBER-PHYSICAL SYSTEMS

4. Capstone project: Objectives

1. Define the strategic mission of sUAS fleet
2. Decision variables:
   - Deployment patterns and sensing rates
   - Type of exploration maneuvers
3. Constraints:
   - Platform's size, weight and power; sensor range;
   - Network topology; obstacles and weather
4. Algorithms (design and implementation) for strategic tasking of fleet of sUAS for
   - Detection and isolation of failures (faults)
   - Strategic monitoring in the face of adversarial attacks
5. Evaluate and demonstrate strategic tasking capabilities
   - Simulation and bench-top tests
   - Field test (if possible)

FORCES
FOUNDATIONS OF RESILIENT CYBER-PHYSICAL SYSTEMS

Summary: Plans in moving forward

1. **Online security games:**
   * Extend to other CPS security questions / domains
2. **Quantitative sustainability subject:**
   * Use of real-world data in modeling; field visits
   * Emphasize interplay of regulatory and technological aspects
3. **Mini-UROP projects:**
   * Encourage research UROPs and mentoring about selection of CPS courses
4. **Capstone design projects on network resilience:**
   * Ongoing effort