SYSTEMS ENGINEERING RESEARCH CENTER

USC Viterbi School of Engineering
Systems Architecting and Engineering

Adaptive Cyber-Physical-Human System Testbed

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Sponsor: OUSD(R&E)

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ANNUAL SPONSOR **RESEARCH REVIEW**

OUTLINE

- Project Objective and Motivation
- Approach and Implementation
- Core Capabilities and Illustrative Scenario
- Successful Transitions
- Benefits and Payoffs

RESEARCH TEAM

- Principal Investigator: Dr. Azad Madni
- Co-Principal Investigator: Dr. Dan Erwin
- Project Manager: Dr. Ayesha Madni
- Graduate Research Assistants: Edwin Ordoukhanian, Parisa Pouya

PROJECT OBJECTIVE

To develop a cyber-physical-human system testbed for:

- Experimenting with different models and algorithms
- Demonstrating MBSE innovations (e.g., use of digital twins in MBSE)
- Facilitating transition of capabilities, models and algorithms to target sites

Domain: Unmanned Aerial Vehicle Team Operations

MOTIVATION

- Enable SERC researchers working on MBSE for autonomous systems to focus on research and experimentation, and not implementation details
- Provide a convenient platform to showcase research products on demand
- Facilitate comparison, integration, testing of virtual models / digital twins
- Simplify interoperability among models produced by SERC researchers
- Facilitate sharing of MBSE artifacts and lessons learned

CYBER-PHYSICAL-HUMAN SYSTEMS

(Madni et al., 2018)

- A class of safety-critical socio-technical systems in which interactions between *physical system* and *cyber elements* that control its operation are influenced by *human agent(s)*
- System objectives achieved through interactions between:
  - **Physical system** (or process) to be controlled
  - **Cyber elements** (i.e., communication links and software)
  - **Human agents** who monitor and influence cyber-physical system operation
- **Distinguishing Feature:** Human (agents) intervene to:
  - redirect cyber-physical elements or supply needed information
  - …..not just to exercise manual over-ride or assume full control

APPROACH HIGHLIGHTS

- Ontology-enabled testbed capability definition and integration
- End user-oriented scenario definition using graphical and scripting capabilities
- Context-aware dashboard for execution monitoring, visualization and control
- Well-maintained open source and low-cost commercial components
- Capability demonstration using an illustrative problem of DoD significance
- Starter-kit and user guide to allow users to hit the ground running
- Transition strategy from day one to enable smooth technology transfer

CORE TECHNOLOGIES

- Testbed ontology – testbed capabilities definition and integration
- Scenario builder – graphical modeling & scripting capabilities
- Context-sensitive dashboard – monitoring, visualization and control
- Context characterization – based on METT-TC mnemonic
- System modeling tools – SysML, decision trees, HMM, POMDP
- Dronekit platform with visualization and control facilities
- Quadcopter (QC) hardware and virtual QC model (digital twin)
- QC planning and decision-making algorithms

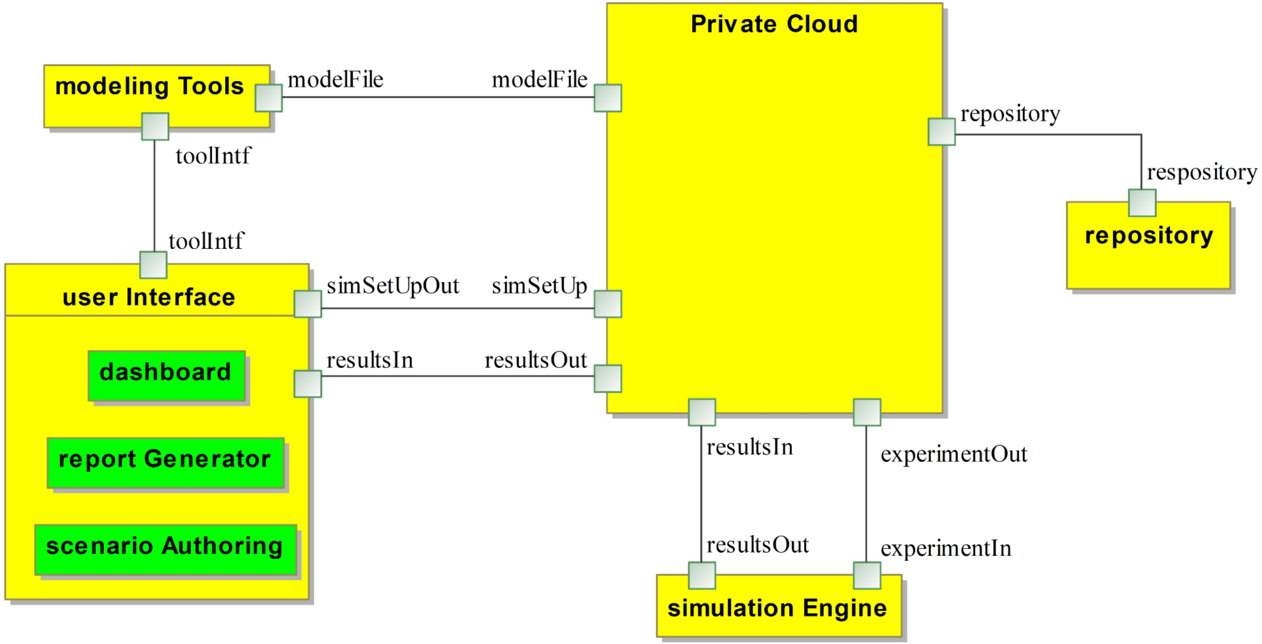
TESTBED ONTOLOGY

- *Scenario:* mission specification - provides context for experiments
- *World:* a geospatial region which support experiments.
- *Vehicle:* the proposed work will focus on models for quadcopter.
- *Agent:* an active element which may or may not be a vehicle.
- *Experiment:* scientific procedure to test hypothesis or demo capability
- *Laboratory:* elements used in experiments - communicate over wi-fi

TESTBED ONTOLOGY (CONT'D)

- *Project:* needs to be properly scoped to derive benefits
- *Scenario Builder:* facilitates creation and modification of scenarios
- *Smart Dashboard:* visualization, monitoring, control and scenario import
- *Standard Vehicle:* a standard physical quadcopter model
- *Predefined Scenarios:* "starter kit" to quickly start using testbed
- *Data Collector:* software to collect simulation execution data
- *Digital Twin:* software replica of physical system (including history)

TESTBED ARCHITECTURE



TESTBED HARDWARE

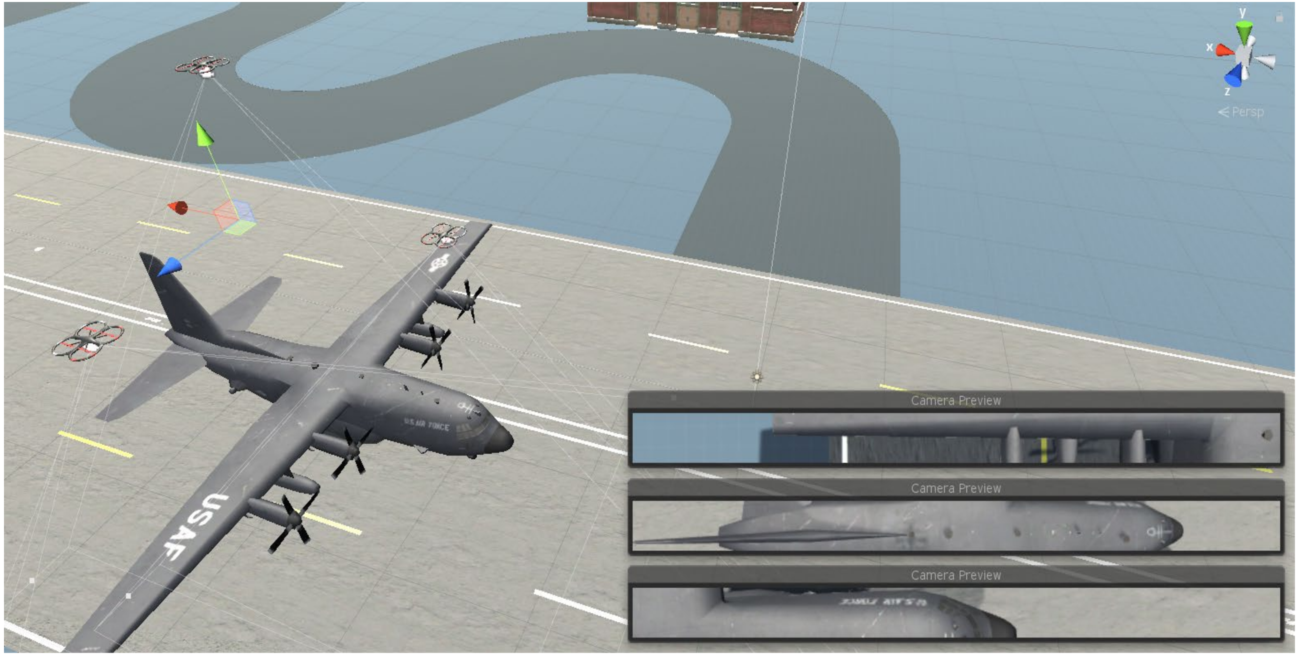
TESTBED CAPABILITIES

- *Scenario builder*: modeling, scripting, and import
- *Smart dashboard*: monitoring, visualization and control of simulation
- *Standard Vehicle:* quadcopter; software automates network communication
- *Digital twin*: creation and use of virtual model of system in simulation
- *Control*: using same commands for physical vehicle and virtual model
- *Data collection*: from vehicle mounted sensors for post hoc analysis
- *Execution trace*: scenario execution audit trail display on dashboard

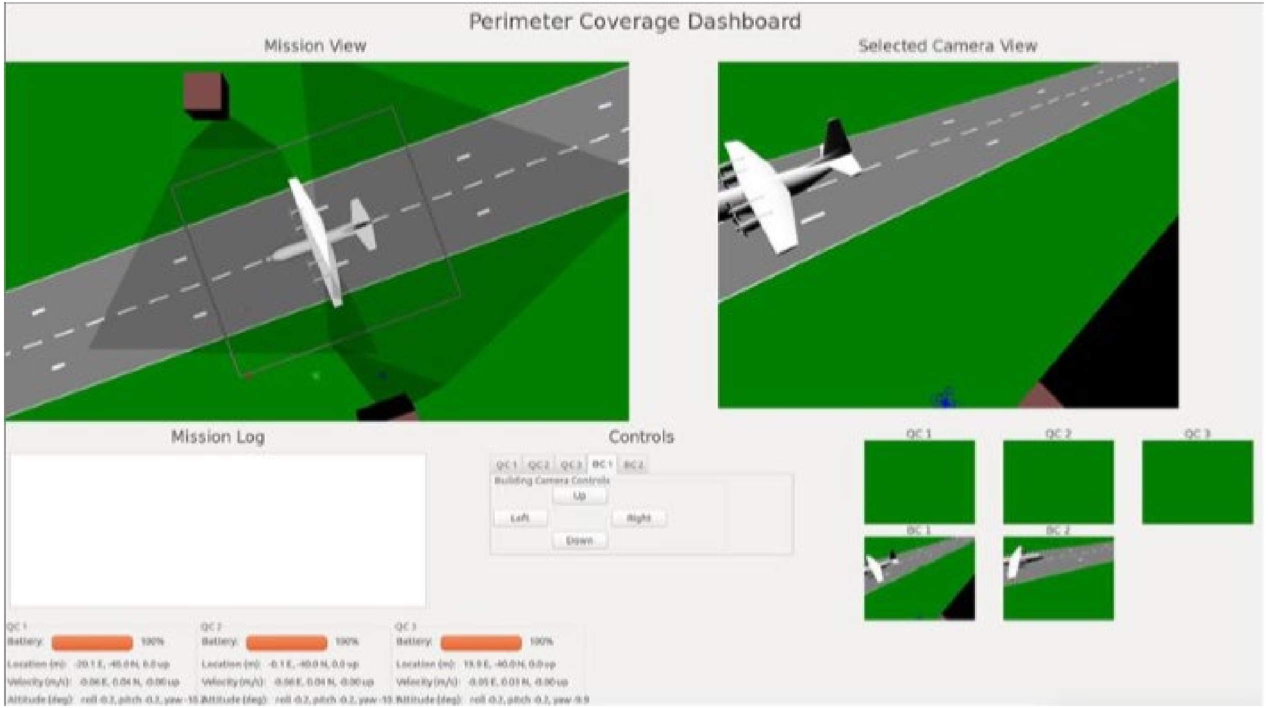
STARTER KIT/USER GUIDE

- Pre-defined scenarios
  - use scenarios "out-of-the-box" in a simulation environment, and later in the physical laboratory
- Multi-vehicle control algorithms
  - rule-based model(deterministic)
  - Partially Observable Markov Decision Process model (probabilistic)
- Scenarios and control algorithms documentation
  - how scenarios and algorithms can be created
  - how scenarios and algorithms can be modified

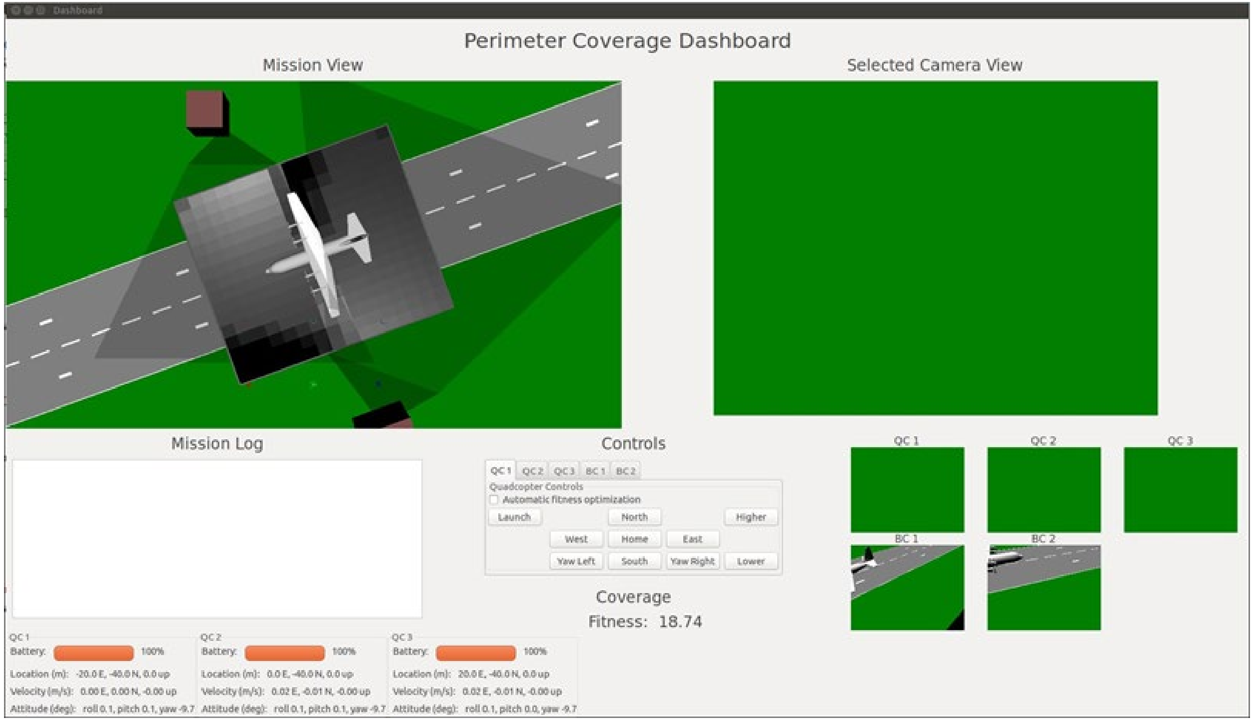
SCENARIO: AIRCRAFT PERIMETER SECURITY WITH MULTIPLE UAVS AND BUILDING-MOUNTED CAMERAS



DASHBOARD SHOWING SCENARIO SIMULATION

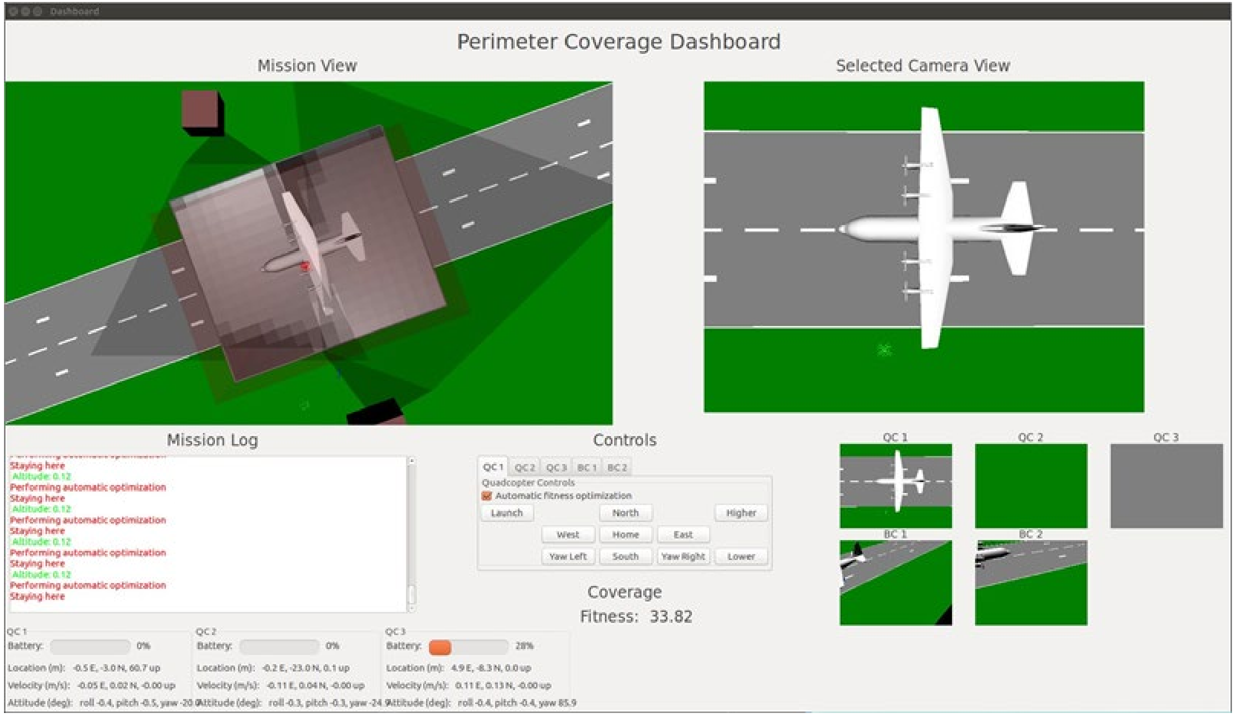


DASHBOARD SHOWING COVERAGE AREA

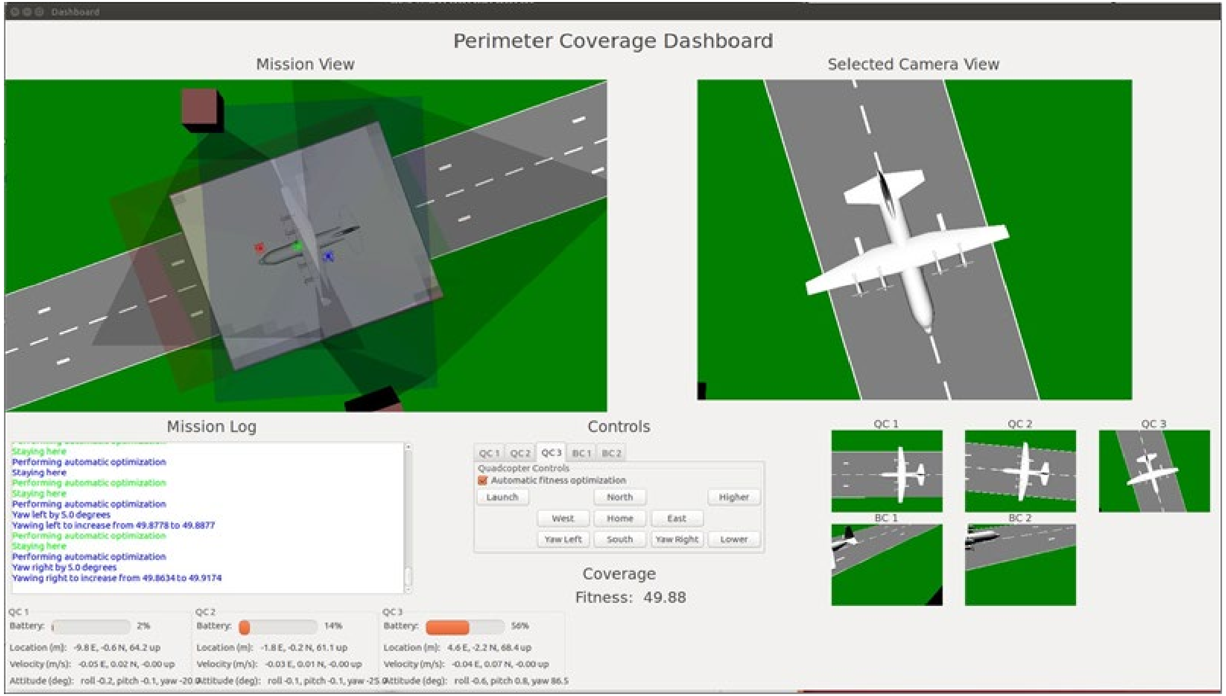


FITNESS FUNCTION OPTIMIZATION FOR ONE QC

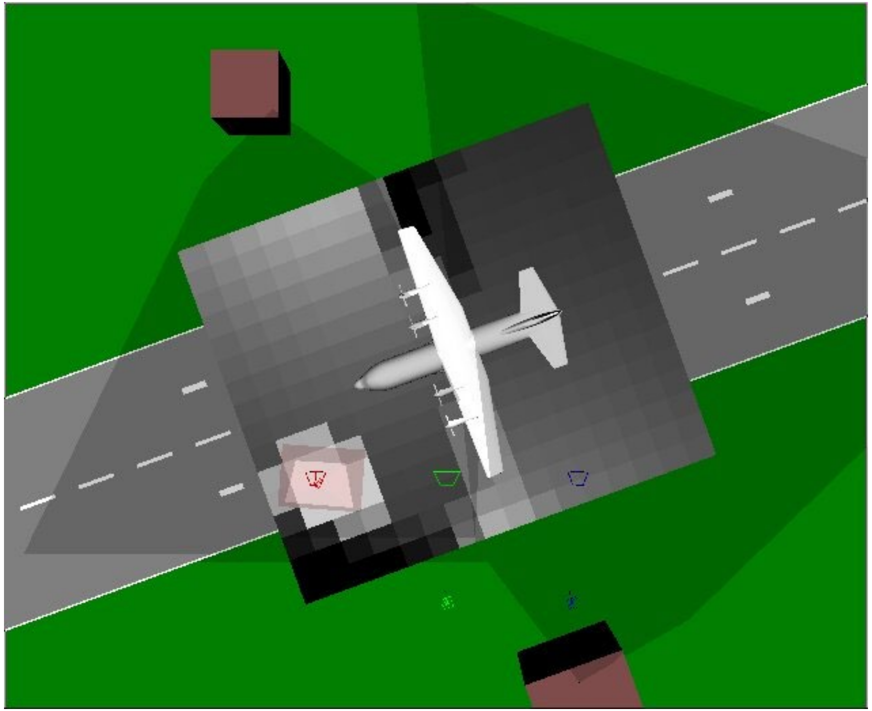
OPTIMAL LOCATION FOR SINGLE QC



OPTIMAL LOCATION FOR THREE QCs



PLAN VIEW OF TERRAIN: NADIR-POINTED (NP) VIEW WITH PERSPECTIVE



SUCCESSFUL TRANSITIONS

- University of Arizona (Dr. Alejandro Salado)
- Virginia Tech (Dr. Peter Beling)
- The Aerospace Corporation (Dr. Bob Minnichelli)

BENEFITS AND PAYOFFS

- Easy entry into field
  - start quickly with "zero dollar" investment by installing open-source software and running prebuilt simulation scenarios
  - high-vol inexpensive consumer COTS hardware
- Easy to assemble and replicate
  - library of standard hardware and components (e.g., QCs)
  - identical software interfaces (protocols) for virtual and physical
- Reduced risk in experimentation
  - experimental work can be initiated using known, proven designs, without need to design new vehicles and become expert "makers"
- Offload researchers from getting bogged down with implementation details
  - by providing libraries of models, connectors, infrastructure for interoperability

BENEFITS AND PAYOFFS (CONT'D)

- Easy comparison
  - effective visuals (multi-perspective, multilevel) to compare research results
- Best practices enablement
  - rapid dissemination of extensions (e.g., new / modified scenarios) to SE community
  - rapid realization of new, integrated capabilities
  - ongoing growth through contributions of SERC researchers
- Cost-effective experimentation
  - test models (e.g., vehicles, sensors) & algorithms (e.g., optimization, ML) in simulation
- Significant time and cost savings
  - freely available backbone, primary tools for creating experimentation environments
- On demand demonstrations
  - to internal/external customers

SUMMARY

- Prototype testbed increased MBSE value proposition for CPHS
  - end user scenario building
  - smart dashboard for scenario execution, visualization, monitoring and control
  - insertion of digital twin to enhance V&V
  - sensor instrumentation and data collection
  - MBSE libraries of models and connectors
- Testbed supporting SERC researchers (autonomous systems)
  - scenario definition and system modeling
  - what-if experimentation and data collection
  - MBSE artifacts creation and sharing
  - cost-effective experimentation
  - continuous improvement of system models and refinement of MBSE processes

RECENT TESTBED PUBLICATIONS

- Madni, A.M. MBSE Testbed for Rapid, Cost-Effective Prototyping and Evaluation of System Modeling Approaches, Special Issue "Model-Based Systems Engineering: Rigorous Foundations for Digital Transformations in Science and Engineering," *Applied Sciences*, 2021, 11(5), 2321.
- Madni, A.M., Sievers, M. Purohit, S. and Madni, C.C. Toward a MBSE Research Testbed: Prototype Implementation and Lessons Learned, IEEE SMC International Conference, October 10-14, 2020
- Madni, A.M., Erwin, D. and Madni, C.C. Digital-Twin-enabled MBSE Testbed for Prototyping and Evaluating Aerospace Systems: Lessons Learned, IEEE Aerospace Conference, March 6-13, 2021
- Madni, A.M., and Madni, C.C. Lucero, S.D. Leveraging Digital Twin Technology in Model-Based Systems Engineering. *Systems*. 2019; 7(1):7.
- Madni, A.M., Sievers, M. and Madni, C.C. Adaptive Cyber-Physical-Human Systems: Exploiting Cognitive Modeling and Machine Learning in the Control Loop, *INSIGHT*, 21,3, (87-93), 2018.

DR. AZAD M. MADNI, NAE

- Northrop Grumman Foundation Fred O'Green Chair in Engineering
- Professor, Astronautical Engineering and Civil and Environment Engineering
- Executive Director, Systems Architecting and Engineering Program
- Director, Distributed Autonomy and Intelligent Systems Laboratory
- Life Fellow/Fellow of IEEE, AAAS, AIAA, INCOSE, SDPS, IETE, Washington Academy of Science, AAIA
- Ph.D., M.S., B.S. in Engineering, UCLA

- **Notable Recent International/National Awards**
  - *2021 INCOSE/ASEE Outstanding Educator Award*
  - *2021 INCOSE Benefactor Award*
  - *2021 IEEE Aerospace and Electronic Systems Judith A. Resnik Space Award*
  - *2020 IEEE Systems, Man, and Cybernetics Norbert Wiener Outstanding Research Award*
  - *2020 NDIA Ferguson Award for Excellence in Systems Engineering*
  - *2019 IEEE Aerospace and Electronic Systems Pioneer Award*
  - *2019 AIAA/ASEE John Leland Atwood Award*
  - *2019 ASME CIE Leadership Award*
  - *2019 Society of Modeling and Simulation International Presidential Award*
  - *2019 INCOSE Founders Award*
  - *2011 INCOSE Pioneer Award*

- **Recent Authored Books**
  - Transdisciplinary Systems Engineering: Exploiting Convergence in a Hyper-Connected World (foreword by Norm Augustine) Springer, 2018
  - Tradeoff Decisions in System Design (foreword by John Slaughter), Springer, 2016

THANK YOU!