Provocative Talk:

Affordable, Adaptable and Effective: The Case for Engineered Resilient Systems

Dr. Azad M. Madni

Professor, Viterbi School of Engineering
Director, Systems Architecting & Engineering Program
Co-Director, Center for Systems and Software Engineering
Professor, Keck School of Medicine and Rossier School of Education

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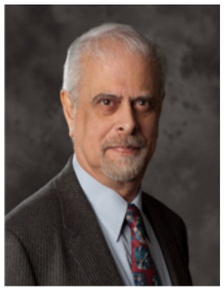
Azad M. Madni Biosketch



- Director, Systems Architecting and Engineering Program
- Co-Director, Center for Systems and Software Engineering
- Professor, Viterbi School of Engineering, Keck School of Medicine, Rossier School of Education, University of Southern California
- Founder and CEO, Intelligent Systems Technology, Inc.
- Life Fellow, IEEE & IETE; Fellow, AIAA; Fellow, INCOSE; Fellow, SDPS
- Ph.D., M.S., B.S. in Engineering from University of California, Los Angeles
- 2011 INCOSE Pioneer Award
- 2012 INCOSE-LA Exceptional Achievement Award
- 2008 President Award and 2006 C.V. Ramamoorthy Distinguished Scholar Award from SDPS
- 2004 and 2000 Developer of the Year Award from Software Council of Southern California
- 2004 DARPA IPTO Sustained Excellence by a Performer and Significant Technical Achievement Awards
- 2000 Blue Chip Enterprise Award from Mass Mutual & US Chamber of Commerce
- 1999 SBA's National Tibbetts Award for California
- Past President of Society for Design and Process Science
- **Research Interests: model-based engineering, engineered resilient systems, cyber physical systems, educational games, STEM education, big data analytics**

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Overview

- Motivation
- Resilience in Different Domains
- Resilience Engineering Challenges
- Engineering Ecosystem Vision
- Closed Loop Concept Engineering
- Strategic Research Directions
- Desired Outcomes
- References

Motivation

- Need to overcome:
  - drawbacks of current engineering practices
  - challenges of 21st century
- Drawbacks
  - linear, sequential, and slow (time-inefficient)
  - unnecessary rework and extraneous iterations (cost-inefficient)
  - premature elimination of alternatives (potential loss of competitive advantage)
  - information loss at every step (lack of traceability and inadequate design rationale)
  - inability to keep track of and manage risks
- Challenges
  - pace of technology advances
  - increasing scale and complexity of systems
  - uncertain sociopolitical futures
  - technology commoditization (technology widely available to global competitors)

Resilient systems engineering: a means to develop **affordably adaptable** and **effective** systems for **a range of operations** and **across multiple alternative futures**

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Resilience: An Evolving Concept

- Ability of a system to **adjust its functioning** prior to, during, or following changes and disturbances, so that it can **sustain required operations,** even **after a major mishap** or in the **presence of continuous stress** (Nemeth et al, 2009)
- Ability of a system to offer **broad utility** in a **wide range of operations** across many **potential alternative futures** despite experiencing disruptions (Neches & Madni, 2012)
- Ability of a system to **return to its original state** or **move to a new, more desirable state** after being disturbed (Christopher & Peck, 2004)
- Ability of a of a system to achieve envisioned (science) objectives even if the system (spacecraft**) performance, health, and/or environment** are **not as expected** (Murray, Ingham, Day, & Williams, 2012)

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Resilience

Ability of a system to **circumvent, survive, and recover from failures** to ultimately achieve mission objectives. A resilient system is able to **reason about own/environmental states** in the presence of environmental uncertainty

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Definitions Illuminate Various Characteristics of Resilience

- Adaptability (anticipation, responding, learning)
- Adaptive capacity
- Range of operational missions
- Variety of adverse conditions (unexpected/unforeseen)
- Range of possible futures
- Reaction (short-term) and adaptation (long-term)
- Graceful degradation outside operational performance envelope
- Environmental uncertainty
- Reasoning about own/environmental states
- Recovering fully/partially from disruption
- Real-time trade-offs
- Achievement of end objectives
- Learning from experience (successes, failures)

Resilience in Nature (Rapid Recovery)

The bamboo that bends is stronger than the oak that resists.

-- Japanese Proverb

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Resilience in Nature (Adaptation)

http://www.thisisourstory.net/2010/02/resilience/

Resilience in Networked Systems

- Resilience is an important property of networked systems
  - e.g., mobile ad-hoc networks, sensor networks, energy grids
- Large body of research in **compromise-resilient** systems
  - as opposed to failure-resilient systems
- In sensor networks, resilience is measured in terms of:
  - number of nodes that must be captured/compromised by an adversary before entire network is compromised
- In mobile ad hoc networks (e.g., UAV system or mobile vehicular networks), mobile nodes act not only as sources and sinks of information but also as relay to router nodes;
  - so, compromising a certain number of nodes beyond a threshold can result in total disruption of the entire network routing regime
- Can also study **resilience in the context of security/survivability**

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Resilience in Space Platforms

- Ability of spacecraft to achieve envisioned (science) objectives of space missions in the face of unexpected/unforeseen operational environment and off-nominal spacecraft performance
- Requires that spacecraft has **the ability to reason about its own & environmental states** in the face of **environmental uncertainty**, and **recover from failures**

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Resilience in Energy Grids

- To deal with power outages and adapt power distribution based on demand
  - goal of self-monitoring and self-healing
  - electronically diagnosing problems & rerouting power around them
  - merge energy grid with Internet so we can adjust our appliances with our iPhones when away from our homes
  - program our appliances so we can save energy
- Move from few large centralized plants to large network of distributed power plants
  - prevent disasters (e.g., recent Japan disaster)
  - acknowledge trend for increasing energy
  - overlapping microgrids to re-stabilize system after one goes down
  - communication and coordination are keys to a resilient network

Resilience in Health Care

- Resilience in health care (service sector)
  - how well sector responds to changes in output demand over time
  - demand for care varies widely in volume and type
  - resources needed to respond to demand tend to be limited and constrained in various ways (e.g., civilians, beds, machines, time)
- Resilience strategies vary with type of demand
  - temporary patient surge….add temporary resources
  - extended patient surge…extend work shifts, work double shifts
  - sustained patient surge (trend)…expand facility, recruit staff
- Making electronic medical records resilient is an important area
  - interoperability of patient data and portability of medical records

Resilience Engineering

- A proactive, risk-mitigated approach to building adaptability into systems that are complex, underspecified, and with multiple interdependent elements

- Resilience engineering is concerned with building systems that are able to circumvent accidents through anticipation, survive disruption through recovery, and grow through adaptation (Madni & Jackson, 2008)

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Resilience Engineering Challenges

- Calculating Leading Indicators
  - key to assessing consequence of risky decisions and controlling risks
- Conducting the right trade-offs in timely fashion
  - key to maintaining safety margins and control/avoidance of drift
- Developing an accurate model of drift
  - key to understanding risk factors and effective risk management
- Developing realizable resilience heuristics
  - key to informing and guiding resilient system design
- Developing appropriate resilience metrics
  - key to evaluating candidate resilience strategies

Toward a New Engineering Ecosystem

- Build on industry trends in **model-based engineering**
- Closed loop **concept engineering** with active stakeholder participation
- Automated tools and **decision aids** (analysis, evaluation, data collection)
- **Exploration** of mission scenario space to uncover “surprises”
- **Rapid insertion and evaluation** of key technologies/concepts that enable resilience
- **Resilience methods** to successfully counter surprises
- **Resilience heuristics** to inform and guide system design
- Continual **cross-feed of multiple data types** by stakeholders to each other to inform their respective activities

Key Technology Concepts

- Co-evolution of systems, missions, and ConOps
  - information sharing and decision aiding
- Rapid trade space exploration
  - alternatives kept longer, explored deeper
  - enhances ability to exploit new technologies and adapt to new circumstances
- Closed loop concept engineering
  - analyze/evaluate system concepts/designs wrt life cycle concerns
  - continually inform requirements and CONOPS (operational mission context)
- Accelerated Design and Testing
  - rapidly composable modeling and analysis tools
  - risk-sensitive engineering planning aids
  - model-based T & E

Need new Methods, Processes, and Tools to help engineers & users understand interactions, identify implications, and manage consequences

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Closed Loop Concept Engineering

- Co-evolution of system, mission & ConOps (stakeholder participation)
  - possible because of increased computational power and availability
  - greater flexibility in exploiting data and applying services
- Affords opportunity to evaluate and iterate on capabilities
  - in light of mission utility
  - avoids premature lock into requirements and key performance parameters
- Basis for developing trust in ConOps and architectural design
  - what-if exploration of capabilities with stakeholders in the loop

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Exemplar Resilience Heuristics
(Madni & Jackson, 2008)

- Functional Redundancy
  - alternative ways to perform a function without physical redundancy
- Drift Detection & Correction
  - monitor & correct drift toward brittleness through corrective action
- Graceful Degradation
  - self-aware gradual performance degradation in the face of unanticipated/unexpected events
- Learning & Adaptation
  - ongoing knowledge acquisition from environment to reconfigure, re-optimize, and grow

Strategic Research Directions
(Neches & Madni, 2012; Madni, 2012)

- System Representation and Modeling
- Characterizing Changing Operational Environments
- Cross-Domain Coupling
- Trade-Space Analysis
- Collaborative Design and Decision Support
- Quantitative Assessment of Technologies
- Resilience Games

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System Representation and Modeling

- Representation of multiple perspectives
  - physical and logical structures, and system behaviors
  - interactions with environment & interoperability with other systems/SoSs
- Multiple classes and types of models
  - classes: executable, depictional, statistical, non-parametric
  - types: device/environmental physics, comm, sensors, effectors, sw, systems
- New models need to be developed & made interoperable
  - rate at which they can be developed and validated is a key issue
- Models & simulations of live and virtual elements can fill gaps
  - cross-integration of physics-based and statistical models
  - integration of multidisciplinary, multi-scale physics models
  - automated/semi-automated techniques for model acquisition
  - techniques and tools to build adaptable models

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Characterizing Changing Operational Environments

- Complement system models with models of dynamic operational environments (drive system behavior)
  - to develop deeper understanding
- Gather and model operational data
  - to experiment with alternative designs and understand impact
- Go beyond how design and test are conducted today
  - e.g., achieve desired performance under specific conditions
  - optimizing in this fashion leads to brittle systems
- Need to understand a range of “likely” conditions
  - requires modeling of ConOps, environment, operational context
- Need:
  - **instrumentation** (collect data from live/virtual env., system tests)
  - **synthetic environments** for experimentation and learning

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Cross-Domain Coupling

- Many models that exist are not interoperable
  - model complex system across multiple domains & environments
  - example domains: materials, fluids, physics, chemistry
- Need new computing technologies and standards
  - models differ in type, detail, coverage, representation, data reqs
- Key challenges are:
  - achieving superior interchange between incommensurate models
  - resolving temporal, multiscale, multiphysics integration mismatches
- Promising solution approaches (examples)
  - creating libraries with reusable content
  - accelerating workflow definition and conversion between models
  - on-demand composition of modeling and analysis workflows
  - consistency maintenance across hybrid models (data abstraction)

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Trade-Space Analysis

- Enhanced trade-space analysis enabled by computing advances
  - generate a larger number of options
  - explore them in greater depth
  - keep them open longer
  - manage added complexity
  - test more extensively
- Need to:
  - automate exploration of multiple conditions
  - generate and test more alternative solutions
  - analyze results and rapidly deliver findings to decision makers
  - assist decision makers in exploring most important options

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Collaborative Design & Decision Support

- Ultimately, all technological advances lead to people
- Advances needed in:
  - collaboration technologies
  - information abstraction and summarization
  - multimedia presentation and visualization
  - human-computer interaction
- Need specific advances in:
  - usable multidimensional trade spaces
  - rationale capture
  - tradeoffs prioritization aids
  - explainable decisions
  - physics-based and behavioral models
  - information push-pull w/o exceeding cognitive limitations

Quantitative Assessment of Technologies

- Models to examine total performance and potential payoff of resilience technologies
- Tools to assess real benefits of resilience technologies and provide quantitative basis for strategic research decisions
- Methods to increase confidence that the technology trade space has been sufficiently explored, circumscribed and populated
- Techniques to visualize and interact with multidimensional trade spaces to assess sensitivities and draw implications
- Techniques to assess the sensitivities of design alternatives to changes in design parameters, requirements, and technologies
- Modeling and analysis capabilities to assess technology trade space and enhance understanding of the magnitude of impact on desired capabilities based on design tradeoffs

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Educational Games to Teach Resilience Concepts

- Resilience continues to be an evolving concept
- Each definition introduces a unique perspective on resilience
- People frequently confuse resilience with other quality attributes of systems
- An effective way to teach resilience concepts is within the framework of educational games
- Examples of concepts that can be taught through games are: adaptability, functional redundancy, and dynamic tradeoffs
- Concepts learned this way will persist in the sense that games with an underlying storyline tend to be memorable and can facilitate recall of the underlying concepts

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Castle Wall: Example Resilience Game
(Spraragen & Madni, 2012)

- **Storyline**: Invading army on horseback equipped with catapults seeking ingress into castle (medieval backdrop)
- **Learning Objective**: Understand number of invaders denied ingress and be able to perform key tradeoffs in building a resilient wall
- **Player Objective**: Prevent invaders from getting into castle by building a brick and mortar wall
- **Invader Tactic**: Catapult shots and horseback sorties
- **Wall Design Problem**: Choose stone, design a rectangular brick, then a pattern of bricks and mortar
- **Design Parameters**: Brick size, brick weight, and distance brick has to be carried
- **Design Tradeoffs**: Brick size vs. portability; brick size vs. vulnerability
- **Key Resilience Concepts**: Dynamic tradeoffs, absorption of disruption, recovery from disruption
- **Key Metrics**: Speed of wall repair; number of invaders denied ingress into castle

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Desired Outcomes / Envisioned End State

- Enhanced Capability Engineering
  - context-sensitive (environment, mission)
  - expanded option set (more alternatives developed, evaluated, maintained)
  - superior trade-offs analysis & management (interactions, choices, outcomes)
- Effective Systems
  - easy to adjust, adapt, reconfigure, replace (mission context)
  - graceful function degradation with high confidence
  - superior performance and mission effectiveness in face of contingencies
- Accelerated Engineering Processes
  - fewer rework cycles
  - faster cycle times
  - timely management of requirements shifts

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Recommendations

- Need to transform the engineering of complex systems
  - to make systems affordable, effective, and adaptable (i.e., resilient)
  - to control costs, make schedules, and proactively manage risks
- Resilient systems need to provide utility
  - in a wide range of missions/operations
  - across many potential alternative futures
- Closed loop concept engineering is key to enhancing trust in architectural design and system ConOps
- Need strategic research advances on several fronts
  - system representation and modeling
  - characterizing changing operational environments
  - cross-domain coupling
  - trade-space analysis
  - collaborative design and decision support

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Thank You