Cyber-Physical-Social Systems and Resilient Infrastructures – A Perspective from NSF

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Outline

• NSF Overview
• Context
• Key Programs and Project Highlights
• Conclusions
“to promote the progress of science; to advance the national health, prosperity, and welfare; to secure the national defense...” NSF Act, 1950

Science offers a largely unexplored hinterland for the pioneer who has the tools for his task. The rewards of such exploration both for the Nation and the individual are great. Scientific progress is one essential key to our security as a nation, to our better health, to more jobs, to a higher standard of living, and to our cultural progress.
Investing in engineering research and education and fostering innovations to benefit society
Fundamental

- CBET
  - Chemical & Biochemical Systems
  - Bioengineering and Engineering Healthcare
  - Environmental Engineering and Sustainability
  - Transport, Thermal, & Fluid Phenomena

- CMMI
  - Advanced Manufacturing
  - Mechanics and Engineering Materials
  - Resilient and Sustainable Infrastructure
  - Operations Design and Dynamical Systems

- ECCS
  - Electronics, Photonics, and Magnetic Devices
  - Communications, Circuits, and Sensing Systems
  - Energy, Power, Control and Networks

Translational

- EEC
  - Engineering Research Centers
  - Engineering Education
  - Engineering Workforce

- IIP
  - Academic Partnerships
  - Small Business Partnerships
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Context
Critical Infrastructures are a mainstay of the national economy, security and societal functioning
Critical Infrastructure Sectors

- Food and Agriculture
- Banking and Finance
- Chemical

- Commercial Facilities
- Communications
- Critical Manufacturing

- Dams
- Defense Industrial Base
- Emergency Services

- Energy
- Government Facilities
- Healthcare and Public Health

- Information Technology
- National Monuments and Icons
- Nuclear Reactors, Materials and Waste

- Postal and Shipping
- Transportation Systems
- Water

Source: DHS
Critical Infrastructure and Extreme Events

• In the U.S. and much of the world, these infrastructures are
  – Aging
  – Operating at capacity limits
  – Often vulnerable due to their locations, e.g. in floodplains, along fault lines, proximate to urban areas vulnerable to malicious attack

• Each hurricane or storm sends us a stark reminder of the vulnerability of these infrastructures to extreme events

• Also vulnerable to man-made events
Paradigm Shift:
Infrastructure as a (Cyber-Enabled) Service
The Service Economy

• The U.S. service sector is responsible for:
  – Employing approximately 80% of workers
  – Creating approximately 80% of GDP

• Manufacturing (product) industries are increasingly incorporating value-added service components

• We need high-quality, low-cost, and highly personalized solutions in education, healthcare, manufacturing, transportation, and agriculture.
Productivity and Economic Growth

Chart 1: Output per Hour in the United States, Total Economy and Selected Sectors, 1948-2011
(average annual rate of change, per cent)

Source: Gordon, International Productivity Monitor, Spring 2013


Source: Kocher and Sahni, N Engl J Med, October 2011
“Manufacturing is performing a magnificent ballet on a shrinking stage.”

- Robert Gordon
Service System – A Working Definition

A cyber-physical-social system

A system for human interactions with physical and informational environments mediated by advanced technologies to add value.
“In short, we’re at an inflection point—a point where the curve starts to bend a lot—because of computers. We are entering a second machine age.”
“The Internet of Things has already set in motion the idea of a fourth industrial revolution—a new wave of technological changes that will decentralize production control and trigger a paradigm shift in manufacturing.”

- Markus Löffler, McKinsey

“But in most of the firms in which we carried out our research the traditional line between “manufacturing” and “services” has become so blurred that it no longer serves to distinguish separable and distinct activities or end products.”

- MIT PIE Report
Retail Revolution under Way

"Given the business evolution of Amazon from a bookstore to the store for everything, we had to reinvent automation, following the lean principle of "autonomation": keep the humans for high-value, complex work and use machines to support those tasks."
Programs and Project Highlights
FY14: Resilient Interdependent Infrastructure Systems (RIPS)

• To enhance understanding and design of interdependent critical infrastructure systems and processes resilient in the face of disruptions and failures from any cause
• ENG, CISE, and SBE funded 10 projects for $17M in FY 2014

Image credit: Paul M. Torrens, Geography and UMIACS, University of Maryland, College Park


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FY15 CRISP: Critical Resilient Interdependent Infrastructure Systems & Processes

• FY15 funding for CRISP: $20 million
  – Type 1 Awards: 3-year projects, $500k max
  – Type 2 Awards: 3-4 year projects, $1M-$2.5M

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Emphasis on Multi-disciplinarity

• Engineering
• Computing
• Social and behavioral sciences
Interdependent Critical Infrastructure Systems (ICIs)

- Infrastructures are viewed as:
  - as networks of systems and processes
  - that function collaboratively and synergistically
  - that produce & distribute continuous flow of essential goods & services
  - as interdependent and connected
Interdependencies

- Dependencies
  - Direct, indirect, disjunctive (depends on >1 node) and conjunctive (depends on one of two nodes) dependencies

- Interdependencies
  - Physical (e.g. through materials flows)
  - Cyber
  - Geographic
  - Logical (e.g. substitutability, shared resources)

→ Existence of feedback loop distinguishes from dependencies

- Failures can propagate from one system to the next due to these interconnectivities
Resilience – the Concept

• Resilience as a term has taken on many meanings
• Common to most resilience definitions are two components (DHS):
  1) Ability to withstand disruption event with little loss in function
  2) Rapidly and efficiently restore functionality if loss incurred
• Many measures have been proposed:
  – Some focus on time to recovery
  – Others focus on loss: post-event performance over time, or after some elapsed time
CRISP Program Goals

1. Create new approaches/solutions for design/operation of infrastructures as processes/services

2. Enhance understanding/design of ICIs and processes under disruptions from any cause
   - natural, technological, organizational or malicious
   - various timescales and intensities

3. Create knowledge for innovation in ICIs to safely, securely, and effectively expand range of goods and services they enable

4. Improve ICI’s effectiveness, efficiency, dependability

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Targeted Infrastructures in the Awards

Number of Awards

- Energy: 14
- Transportation Systems: 10
- Communications: 8
- Water: 6
- Information Technology: 4
- Nuclear Reactors, Materials and Waste: 2
- Healthcare and Public Health: 0
- Government Facilities: 0
- Defense Industrial Base: 0
- Banking and Finance: 0
- Chemical: 0
- Commercial Facilities: 0
- Critical Manufacturing: 0
- Dams: 0
- Emergency Services: 0
- Food and Agriculture: 0
- National Monuments and Icons: 0
- Postal and Shipping: 0

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CRISP Proposed Research Topics

• Water-Energy-Food Nexus
• Urban/Rural Infrastructure Resilience
• Autonomous Transportation Systems
• Smart Grid
• Alternative Energy
• Crowd-sourcing
• Community Resilience
• Climate Change
• Attack Scenarios

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Methodological Approaches in the Awards

1) **Mathematical Modeling and Optimization**: graph theory; network models; stochastic and nonlinear optimization and modeling; Markov modeling; Bayesian networks; queueing theory; algorithms and heuristics; control theory; game theory; artificial intelligence

2) **Simulation**: agent-based approaches – both for discovery and validation
Methodological Approaches in the Awards

3) **Statistical**: statistical inference (correlation, regression, clustering, natural language processing); expert opinion; attitudinal studies; community surveys; time-geography theory; machine learning; network formation for social networks; behavioral studies of humans;...

4) Reliability and systems modeling

5) Systems of systems and explanatory sciences
Cyber-Physical Systems Program

- Abstract from sectors to more general principles
- Apply these to problems in new sectors
- Build a new CPS community
- Encourage other communities to join
CPS In Context

**IoT**
- Low-cost sensors, MEMs, low power, 5G, ...

**National Priorities**
- Energy, health care, advanced manufacturing, ...

**Industrial Interests**
- Commercialization, monetization, standards, consortia, ...

**S&T Advances**
- Machine learning, big data, control, sociotechnical systems, advanced materials...
IoT Core Technologies

• Security and Privacy
• Energy Management
• Real-time computing
• Sensors and Actuators
• Wireless Networking
• Signal Processing
• Sensing and Control
• Mobile Computing
• Big Data
Imagine a (cyber-physical-social) future …

Credit: Nicolle Rager Fuller, NSF
Cyber-Physical and Social - Bridging the Gap
EAGER: Challenging the Cognitive-Control Divide

**MAIN OBJECTIVES/IDEAS:**
Human observation, prediction and control of complex systems is based on *dynamic primitives* of motor behavior

**INTERDISCIPLINARITY:**
A model of cognition for complex system control requires experimental psychology and applied control theory

**WHAT DOES SUCCESS LOOK LIKE:**
Subjects predict structure in data better and faster when it is composed of dynamic primitives of motor behavior

**WHAT NEXT:**
Develop controller design methods to mimic human-based dynamic primitives in complex system behavior

**TRANSFORMATIVE OUTCOME:**
Identification of best ‘basis functions’ for quantitative engineering models of human observation, prediction and control of complex systems

A common theoretical framework for cognition and control based on motor system dynamic primitives
**MAIN OBJECTIVES/IDEAS:**
Introduce a new form of adaptive control that reduces risk of decompensation when anomalies cascade via more effective human-automation coordination.

**INTERDISCIPLINARITY:**
- Apply cognitive engineering/science to anomaly response for autonomous critical digital services.
- Extend the boundaries of automated services by utilizing adaptive control theory.

**WHAT DOES SUCCESS LOOK LIKE:**
Triggering timely and smooth human re-engagement in shared control to reduce risk of decompensation when anomalies cascade.

**WHAT NEXT:**
Generalize the results to safety-critical systems, cyber-security, energy, and transportation systems with highly autonomous

**TRANSFORMATIVE OUTCOME:**
- Extend models of human perception, cognition and action for supervision of highly autonomous processes during anomaly response.
- Combine above with adaptive control theory in a new architecture for dynamic shared control in human-automation systems that measurably reduces the risk of decompensation.
**OBJECTIVE:**
Explore reciprocal relationships in the communication of intent between humans and autonomous systems

**INTERDISCIPLINARITY:**
Combines research in computer vision, robot motion planning, human-computer interaction, cognitive psychology and kinesiology

**WHAT DOES SUCCESS LOOK LIKE:**
A set of methods to communicate system intent among the system and stakeholders, validated by models

Extend the models to other domains such as manufacturing that could benefit from increasing autonomy to identify generalizable interaction

**TRANSFORMATIVE OUTCOME:**
Using models of human and automation performance, identify new design guidelines for safe autonomous systems that have awareness of the intent of humans in and around the system, with reciprocal relationships for those same humans
**MAIN OBJECTIVE:**
Create a design method that uses morphing algorithms to generate customized product behavior in response to the user’s cognitive style and task at-hand.

**INTERDISCIPLINARITY:**
Combining research on:
- Cognitive Style (Psychology and Marketing)
- Morphing, Inverse Optimal Control (Machine Learning)
- Design Methods, Sensor Data (Engineering Design)

**WHAT DOES SUCCESS LOOK LIKE:**
Faucet (product) flow and temperature (behavior) set precisely as a person would have adjusted it themselves (cognitive style and task) in a simulation study.

**WHAT NEXT:**
Apply model in real-world experiments, reducing water use for daily tasks.

**TRANSFORMATIVE OUTCOME:**
Moving from “smart” products, that are in reality not very smart, to “telepathic” products that can seemingly read one’s mind. These telepathic products will be capable of predicting, testing, and potentially changing a user/product interaction, with help from a model that links product behavior and user’s cognitive style.
EAGER: Dynamics of collaboration between humans and engineered systems: system design for collective expertise

**MAIN OBJECTIVES/IDEAS:**
Humans learn and develop new skills (evolve), which can determine the performance of collaborative human-engineered systems.

**INTERDISCIPLINARITY:**
This effort will leverage social computing and dynamical systems theory to advance collaboration between humans and engineered systems.

**WHAT DOES SUCCESS LOOK LIKE:**
A validated network-based model of human collaboration for exploring interactions between humans and engineered systems.

**WHAT NEXT:**
These results will lay the foundation for informing the design of next-generation human-engineered systems, towards enhanced performance through engineered interactions.

**TRANSFORMATIVE OUTCOME:**
A framework for understanding, predicting, and ultimately, controlling the evolution of the collaboration between humans and engineered systems.
1548521: Babak Heydari and Susan Mohammed; Stevens Institute of Technology

EAGER: Hybrid Socio-Technical Teams: A Theoretical Framework for Modeling and Design of Hybrid Networks of Human and Autonomous Agents

**MAIN OBJECTIVES/IDEAS:**
Fundamental research for understanding dynamics, behavior, and coordination mechanisms of human-agent networks.

**INTERDISCIPLINARITY:**
Combine multi-agent computational methods such as complex network analysis and game theory with social psychology of team behavior.

**WHAT DOES SUCCESS LOOK LIKE:**
Parametric, context-dependent, analytical and computational models to understand how team-level coordination and cooperative behavior are affected by composition of team members, communication network structure, distribution of humans and machines on networks nodes, and the environment.

**WHAT NEXT:**
A long term research plan on:
1) Architecture of human-agent structure
2) Methods for analysing collective behaviour of human-agent systems

**TRANSFORMATIVE OUTCOME:**
This project will result in improved understanding of the behavior of human-agent networks, and hence more efficient design of future intelligent systems for disaster response, energy and transportation, all of which will in the future rely on efficient, dynamic coordination between a group of people and a network of autonomous agents.
EAGER: Studying the Dynamics of In Home Adoption of Socially Assistive Robot Companions for the Elderly

MAIN OBJECTIVES/IDEAS:
Robot that actively observes and facilitates family dynamics in the context of in-home elder care.

INTERDISCIPLINARITY:
Algorithm and engineered system development informed by user experience, gerontology, social psychology.

WHAT DOES SUCCESS LOOK LIKE:
Evaluation study users refuse to return the robot. Robot is able to maintain engaging interaction resulting in positive outcomes in objective and subjective measures.

TRANSFORMATIVE OUTCOME:
Develop engineered system and data driven quantitative models of human-machine interaction in the home that inform the design of next generation in-home robots that facilitate positive interactions among family members under otherwise stressful eldercare circumstances.
EAGER: A New Science of Visual Experience

**MAIN OBJECTIVES/IDEAS:**
Develop an analytical language to model visual experience in 3D environments

**INTERDISCIPLINARITY:**
- **Engineering:** Analytical modelling
- **Psychology:** Perception/action phenomenon
- **Computer Science:** Virtual environment for validation with human subjects

**WHAT DOES SUCCESS LOOK LIKE:**
Analytical quantification of measures of visual experience across one or more specific 3D environments, validated via human subjects testing in a virtual environment

**WHAT NEXT:**
Generalize our analytical framework to design a generic 3D environment, with consideration for bidirectional human-machine interaction

**TRANSFORMATIVE OUTCOME:**
Project will serve as the foundation towards developing a *universal set* of analytical models that emerge from analysis of a variety of context-specific human-environment interactions that form the basis for visual experience when designing 3D environments

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1548394: Parikh, Flach, and Wischgoll (Wright State) and Gue (University of Louisville)
EAGER: A Mathematical Framework for Increasing Trust in Human-Machine Interactions

MAIN OBJECTIVES/IDEAS:
To study the use of psychophysiological tools and eye tracking to measure human trust and derive dynamic mathematical models that capture how humans respond emotionally to machine user interfaces (UIs).

INTERDISCIPLINARITY:
Close collaboration between dynamic modelling, and application of psychological analyses of human judgement.

WHAT DOES SUCCESS LOOK LIKE:
• An empirically verified approach for measuring trust, particularly in human-machine contexts
• Mathematical models that can be used to develop closed-loop feedback between humans and machines

WHAT NEXT:
• Design a class of emotional intelligence algorithms that enable machines to build cooperative and trusting relationships with humans and these to real world applications and formulate new hypotheses for future studies

TRANSFORMATIVE OUTCOME:
Dynamic models of trust in terms of psychophysiological measurements and UI design features.

This will improve human-machine interactions through redesigning machine UIs to include an emotional intelligence system that enables the machine to respond to the human in real-time.
MAIN OBJECTIVES/IDEAS:
Design flying and ground robots based on how humans perceive them, in order to maximize humans’ comfort level.

INTERDISCIPLINARITY:
Computer science, cognitive psychology, robot design and control will be brought together with the goal of creating a virtual reality environment, which enables the study of human perception of robots.

WHAT DOES SUCCESS LOOK LIKE:
A virtual reality environment, in which humans, pilotless planes, driverless cars, and robots co-exist, and populate the same airspace, roads.

WHAT NEXT:
When successful, the team will proceed by designing, building, and controlling real robots.

TRANSFORMATIVE OUTCOME:
Design of ‘Non-Intrusive, Collaborative, Empathetic, Robust (NICER)’ robots.
EAGER: Developing a Mathematical Framework to Enable Bi-Directional Interactions of Humans with Smart Engineered Systems Using Relational Elements

MAIN OBJECTIVES/IDEAS:
Facilitate behavior change by incorporating relational elements into human-automation interaction

INTERDISCIPLINARITY:
Maries research on mathematical modelling, behavioral sciences, and human-computer interaction

WHAT DOES SUCCESS LOOK LIKE:
A mathematical framework that enables two-way interactions between people and buildings. The research will contribute to the goal of enabling cyber-physical systems to interact and collaborate with humans

WHAT NEXT:
Developing fully automated virtual agents working from computational models to facilitate behavior change

TRANSFORMATIVE OUTCOMES:
New knowledge of how theories of human interpersonal trust and influence can inform the design of automation. Increased fundamental understanding of human-machine teamwork, including elucidating theories of why and how people build connections with automated systems. Advanced understanding of how automation exhibiting relational features can facilitate behavior change in the population served by those systems.
A Thought Experiment

- Imagine designing a railway engine at the dawn of the 19th century
- No systematic mechanical engineering at that time
- Are we in an analogous situation in various service systems?
- What might we learn from the experience in the development of different engineering fields?
Models

• Models are fundamental building blocks in all engineering fields
• Leverage scientific knowledge in physics, chemistry, biology, and the power of mathematics
• What might constitute “models” as we think about engineering for service systems?
• What would be the role of social and behavioral sciences in this regard?
Analysis and Design Tools

• What analysis and design tools might be developed to systematize the process of engineering service systems?
• How do we leverage advances in cyber-physical systems and machine learning?
• What are cyber security implications and needs in this context?
• How do we put people in the center in framing design questions?
• What can we learn from early experiences in infrastructure and retail?
Example: Learning and Education

- Productivity of a teacher has not improved significantly in decades
- Major challenges in K-16 education
- Growing body of knowledge in learning science and education
- Modern information technology tools provide an unprecedented opportunity to transform education into just-in-time, personalized education
- Idea of a learning engineer

Plenary session presenters discussed advances in the fundamental science of learning—the underlying research base as to how individuals learn—and called for the development of a new applied discipline—termed learning engineering—which was intended to translate these fundamental insights into new learning environments and tools.

Advancing Technology-Enhanced Education: A Workshop Report, IDA STPI, December 2013
Example: Health Care

• Aging is one of the mega trends for the next many decades

• Cost, quality, access, and efficacy of health care are major societal issues of our time

• PCAST report on Systems Engineering for health care

• Health care engineers
Concluding Remarks

• Exploration at the boundaries of cyber-physical engineering and behavioral/social sciences
• Potential for significant new knowledge creation
• Great potential to positively impact large parts of society
Thank you!

Questions? Comments?

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