Energy, Power, Control and Networks (EPCN)

Cyber Physical Systems (CPS)

Research and Education Opportunities

Kishan Baheti

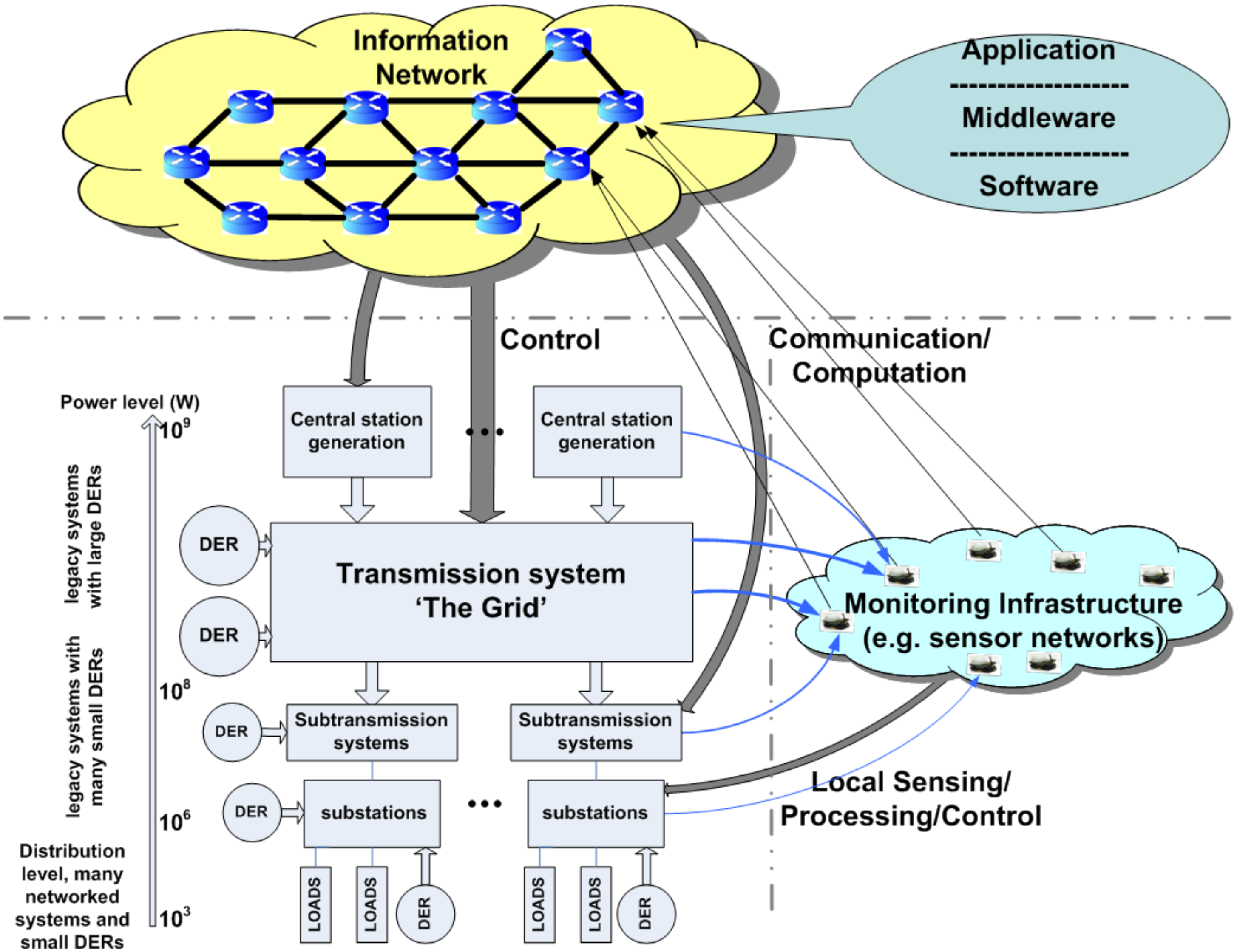
Outline

- The Current Environment: Issues Addressed by EPCN Funded Research
- Additional Program Roles
  - *Integrating Research and Education*
  - *Collaborations with Other Agencies and Directorates*
- Cyber Physical Systems (CPS)
- CPS Education – Power Grid
- Looking to the Future

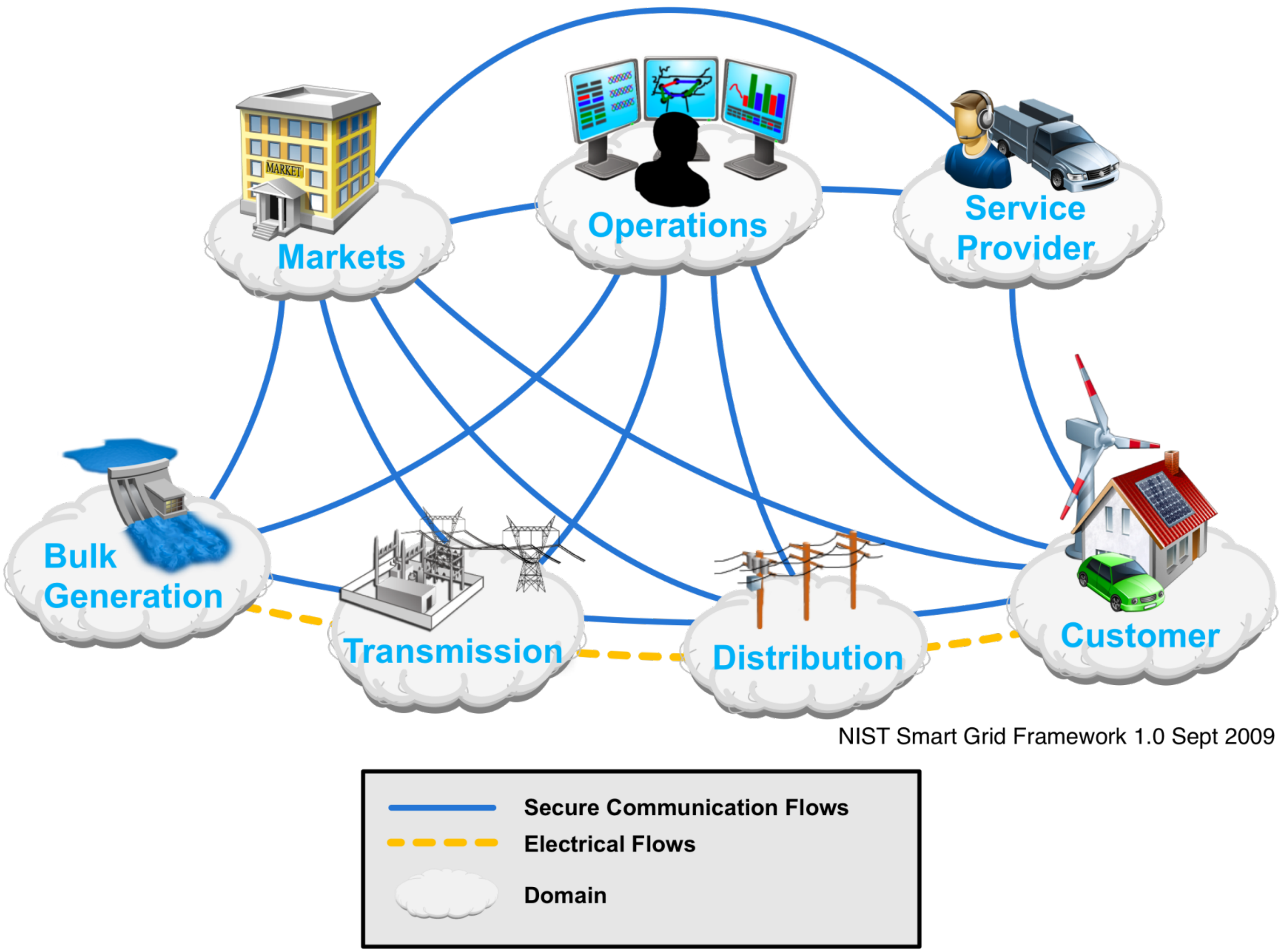
Something to think about..

- Making electricity contributes to 40% world carbon dioxide emission
- Electricity use in U.S. is expected to double by mid-century
- Electric Power grids going through major transformation
- Critical need for new curriculum in energy and power
- Impact of technology and the on-line learning
- Changing expectation of students

Vision of Cyber-Enabled Mega-scale Power Grid: Information Network Overlay Power System



Smart Grid Framework



NIST Smart Grid Framework 1.0 Sept 2009

Energy, Power, Control & Networks (EPCN)

- Design and analysis of complex dynamic systems including sensing, imaging, control and computational technologies
- Emphasis on electric power networks including generation, transmission, distribution
- High power electronics and drives
- Energy harvesting devices and systems
- Regulatory and economic structures

Energy, Power, Control and Networks (EPCN)

Eyad Abed, Kishan Baheti, Paul Werbos

- Control Theory and Hybrid Dynamical Systems
- Networked Multi-agent Systems
- Cyber Physical Systems Modeling and Control
- Systems Theory for Biology and Medicine: Modeling the Brain
- Control and Optimization in Buildings, Transportation and Robotics
- Adaptive and Intelligent Systems: Neural Networks

Energy, Power, Control & Networks (EPCN)

- Energy Harvesting, Storage Devices and Systems
- Solar and Wind Energy and Integration of renewables with Grid
- Monitoring, Protection and Cyber Security of Power Grid
- Advanced Power Electronics and Electrical Machines
- Electric and Hybrid Vehicles; Integration with Grid
- Policy, Economics, Consumer Behavior and the Power Grid

EPCN Program

- Types of Proposals
  - Faculty Early Career Development (CAREER)
  - Single Investigators / Small group
  - Industry Collaborations (GOALI)
  - Exploratory Research (EAGER)
  - Workshop in emerging areas
  - International collaborations
  - REU, RET (students, teachers)

CAREER: Cyber-security of controlled Systems

(ECCS-1151076, Langbort, University of Illinois at Urbana-Champaign)

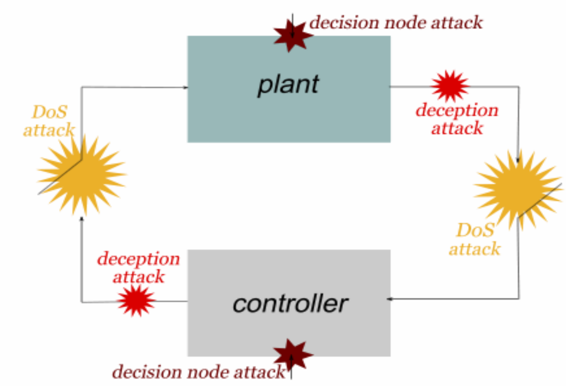
- **Context:** Cyber risks for Critical Infrastructures
  Supervisory Control and Data Acquisition (SCADA) systems are increasingly exposed to cyber threats.

- **Big Picture Vision**: Design cyber-secure control systems to guarantee at least some basic level of stability and safety in face of compromised/subverted components in feedback loop

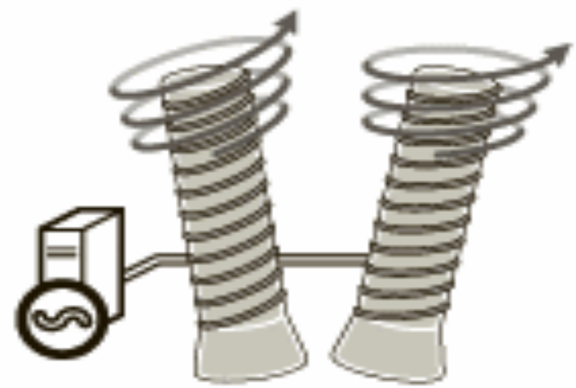
- **Approach:** dynamic games of incomplete information
  Strategic attacker may have partial knowledge of the control system. Use recent advances in robust control theory

- **Recent Achievement:** Characterized the trade-off between stealthiness (measured by a cost) and closed-loop damage using dynamic games and mechanism design.

Computer Scientists and Engineers needs to work together



Cyber-attack on communications channel



An artist's view of how a computer worm can spin turbines out of control...

Adapted from G.Gates' illustration for NYTimes (06/01/2012)

Advances in Power Electronics

100 kV, 60 Hz, 2 MW, 35 Tons, 30 kW loss

150 kV, ≥ 10 kHz, 1 MW, 450 Lbs, 3 kW loss

Fig. 1: Comparison of a HV 60-Hz transformer for a conventional Si-based power conditioner with a high-power and HF nanocrystalline transformer developed at Los Alamos National Laboratory [6] for a next-generation SiC-based power conditioner.

Novel High Frequency Electronic Converters for the Electric Power Grid

(ECCS- 1002369/GOALI, Mazumder , University of Illinois at Chicago)

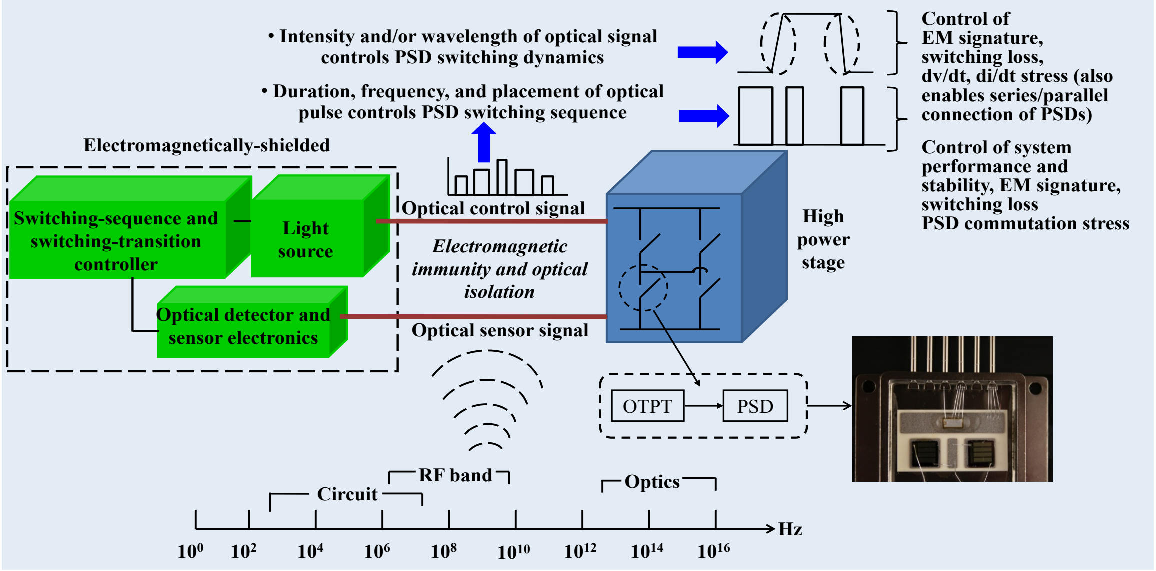
▪**Challenge:** Design next generation Optically modulated power electronics control

▪**Impact:** Improved performance, stability, efficiency and reliability at higher voltage and current

▪**<u>Outcomes:</u>**

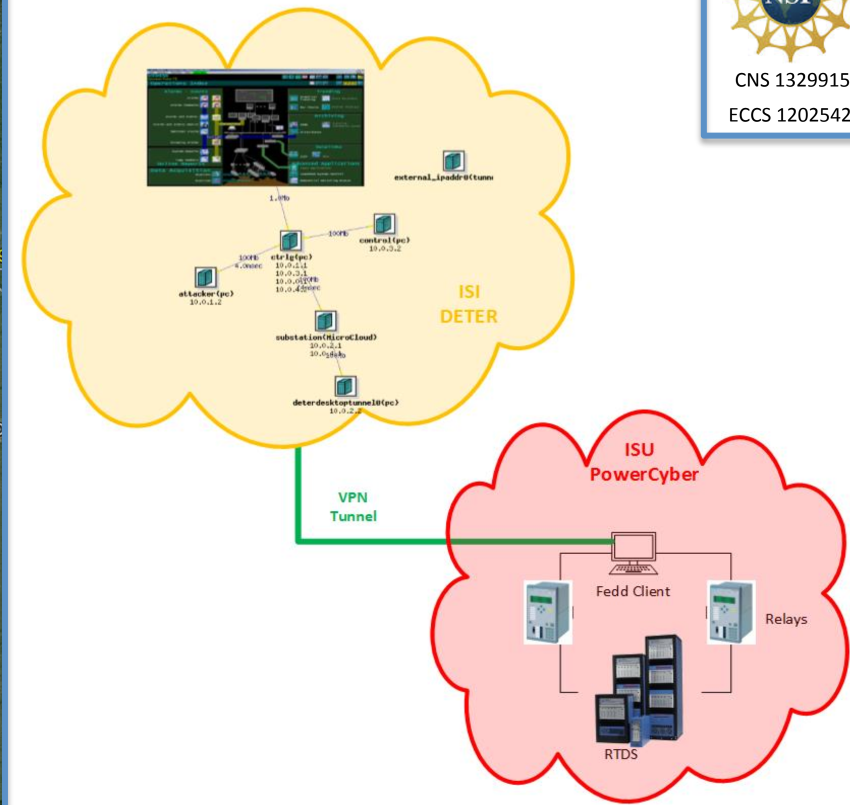
▪*Optical control and switching at > 2MHz operation demonstrated*

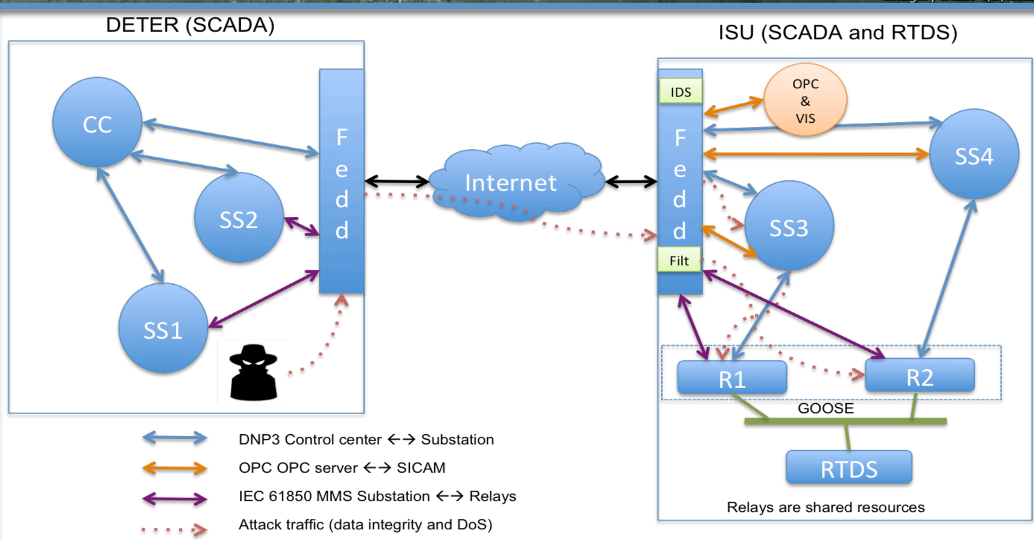
The PI is the inventor of this technology and has contributed to several spin off companies

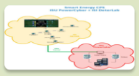


CPS Testbed Federation for Secure and Resilient Smart Grid - Demo at SmartAmerica Challenge

CNS 1329915, ECCS 1202542

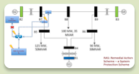






Federation setup (ISU and DETER)

- **SCADA Control Center** and **Energy Management Systems** (EMS) running inside DETER.
- **Substation Automation Systems** (SAS) running inside both DETER and ISU PowerCyber.
- Physical **relays** and **Real-Time Digital Simulator** (RTDS) running in ISU PowerCyber.



Coordinated attack on RAS (ISU and DETER)

- **Data integrity attack** from ISU PowerCyber
- **DoS attack** from DETER

Defense capabilities (ISU and DETER)

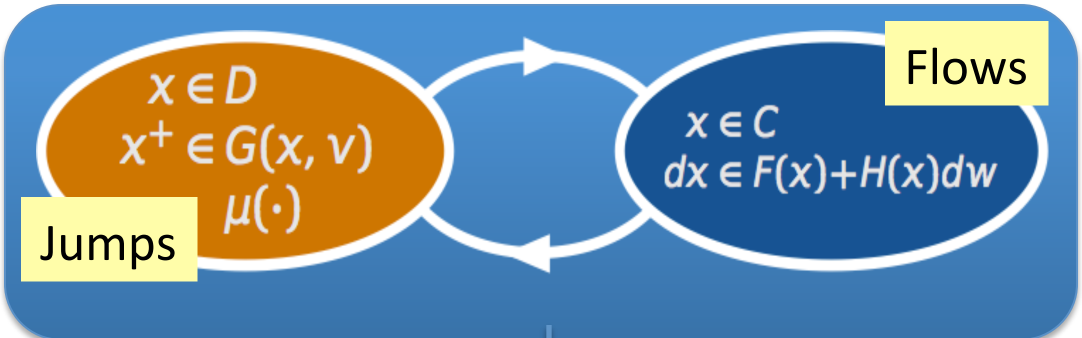
- **IDS/IPS** for Packet dropping @ Substations
- **Traffic filtering** @ Substations

Visualization (ISU)

- **OPC server** interface with SICAM
- **Google earth** interface

Stability Theory for Set-valued Stochastic Hybrid Systems

(ECCS-0925637, Teel , University of California- Santa Barbara)



Application domains

- Networked control systems
- Air traffic management
- Bio-chemical networks
- Financial engineering
- Novel stochastic control

Accomplishments

- Basic existence conditions
- Simple Lyapunov theory

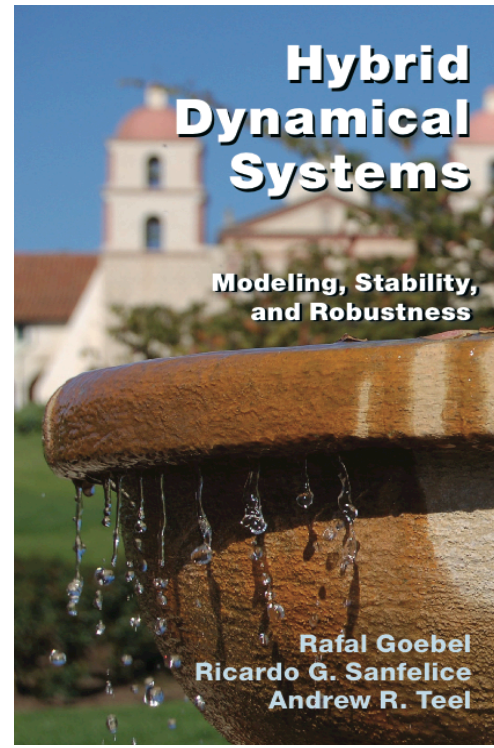
Novelty

- Random and adversarial interaction
- Streamlined framework capturing wide range of stochastic influences

To do

- Robustness
- Converse Lyapunov theorems
- Invariance principles
- Input-to-state stability
- Control applications
- Analysis applications

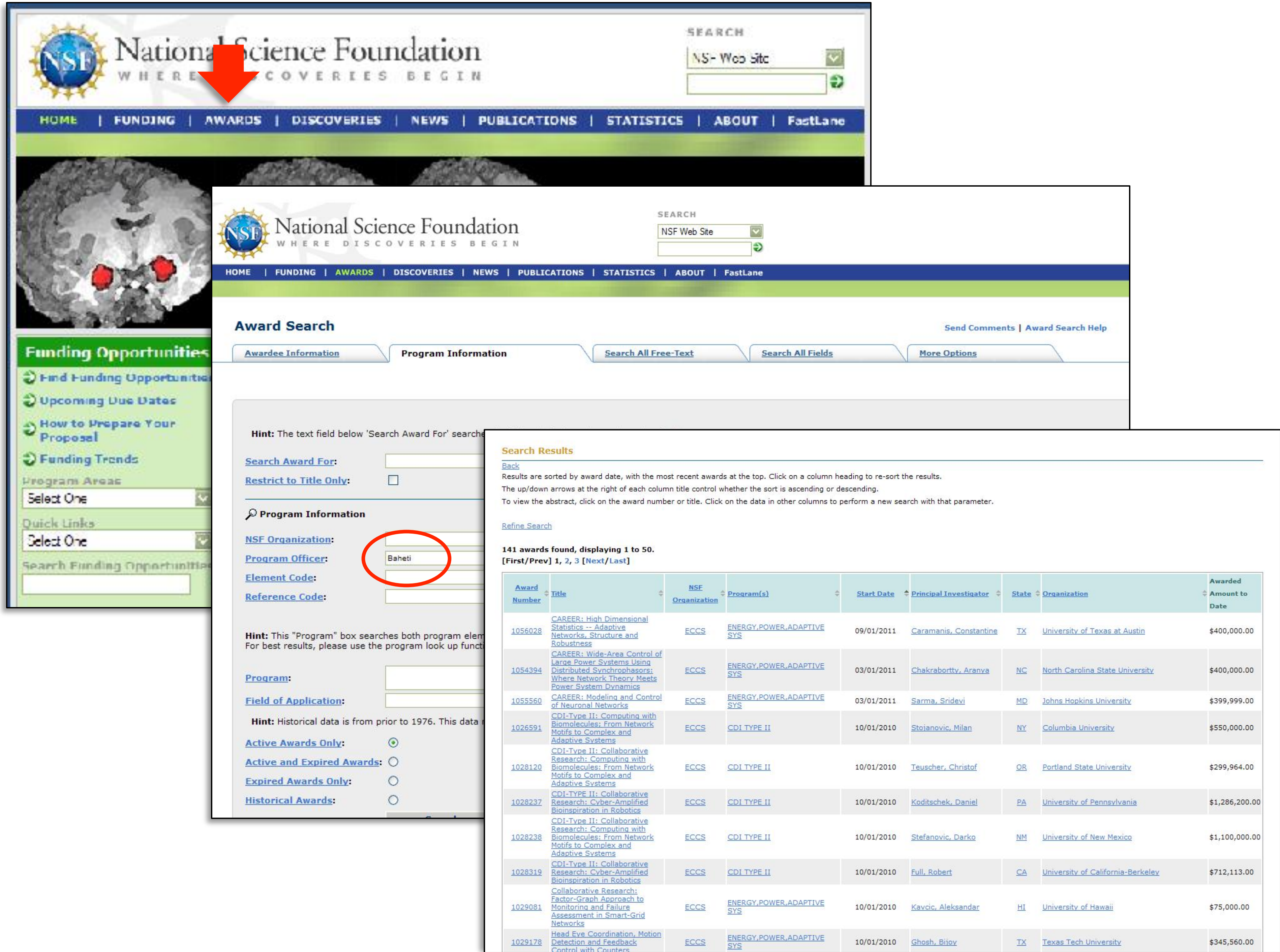
Track record



Source: Princeton Press 2012

NSF AWARD SEARCH

- www.nsf.gov
  - Search awards
    - Advanced search
      - Program officer
- Many search options available
  - CPS
  - Power Electronics
  - Institutions



Award Number	Title	NSF Organization	Program(s)	Start Date	Principal Investigator	State	Organization	Awarded Amount to Date
1056028	CAREER: High Dimensional Statistics -- Adaptive Networks, Structure and Robustness	ECCS	ENERGY,POWER,ADAPTIVE SYS	09/01/2011	Caramanis, Constantine	TX	University of Texas at Austin	$400,000.00
1054394	CAREER: Wide-Area Control of Large Power Systems Using Distributed Synchrophasors: Where Network Theory Meets Power System Dynamics	ECCS	ENERGY,POWER,ADAPTIVE SYS	03/01/2011	Chakrabortty, Aranya	NC	North Carolina State University	$400,000.00
1055560	CAREER: Modeling and Control of Neuronal Networks	ECCS	ENERGY,POWER,ADAPTIVE SYS	03/01/2011	Sarma, Sridevi	MD	Johns Hopkins University	$399,999.00
1026591	CDI-Type II: Computing with Biomolecules; From Network Motifs to Complex and Adaptive Systems	ECCS	CDI TYPE II	10/01/2010	Stojanovic, Milan	NY	Columbia University	$550,000.00
1028120	CDI-Type II: Collaborative Research: Computing with Biomolecules: From Network Motifs to Complex and Adaptive Systems	ECCS	CDI TYPE II	10/01/2010	Teuscher, Christof	OR	Portland State University	$299,964.00
1028237	CDI-TYPE II: Collaborative Research: Cyber-Amplified Bioinspiration in Robotics	ECCS	CDI TYPE II	10/01/2010	Koditschek, Daniel	PA	University of Pennsylvania	$1,286,200.00
1028238	CDI-Type II: Collaborative Research: Computing with Biomolecules: From Network Motifs to Complex and Adaptive Systems	ECCS	CDI TYPE II	10/01/2010	Stefanovic, Darko	NM	University of New Mexico	$1,100,000.00
1028319	CDI-Type II: Collaborative Research: Cyber-Amplified Bioinspiration in Robotics	ECCS	CDI TYPE II	10/01/2010	Full, Robert	CA	University of California-Berkeley	$712,113.00
1029081	Collaborative Research: Factor-Graph Approach to Monitoring and Failure Assessment in Smart-Grid Networks	ECCS	ENERGY,POWER,ADAPTIVE SYS	10/01/2010	Kavcic, Aleksandar	HI	University of Hawaii	$75,000.00
1029178	Head Eye Coordination, Motion Detection and Feedback Control with Counters	ECCS	ENERGY,POWER,ADAPTIVE SYS	10/01/2010	Ghosh, Bijoy	TX	Texas Tech University	$345,560.00

Cross Directorate Initiative
CISE/ENG

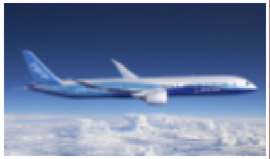
Cyber-Physical Systems

What are Cyber-Physical Systems?

- Cyber – computation, communication, and control that are discrete, logical, and switched
- Physical – natural and human-made systems governed by the laws of physics and operating in continuous time
- Cyber-Physical Systems – systems in which the cyber and physical systems are tightly integrated at all scales and levels

Why was the CPS program created?

National Priorities and Challenges outlined in several government reports including: health, wellbeing, and medicine; high-confidence critical infrastructures; safer transportation systems; collaborative intelligence; competitive economy and our manufacturing base; our aging population; ... networked information systems connected to our physical world.
Examples:

Transportation	▪ Faster and safer aircraft ▪ Improved use of airspace ▪ Safer, more efficient cars	
Energy and Industrial Automation	▪ Homes and offices that are more energy efficient and cheaper to operate ▪ Distributed micro-generation for the grid	
Healthcare and Biomedical	▪ Increased use of effective in-home care ▪ More capable devices for diagnosis ▪ New internal and external prosthetics	
Critical Infrastructure	▪ More reliable power grid ▪ Highways that allow denser traffic with increased safety	

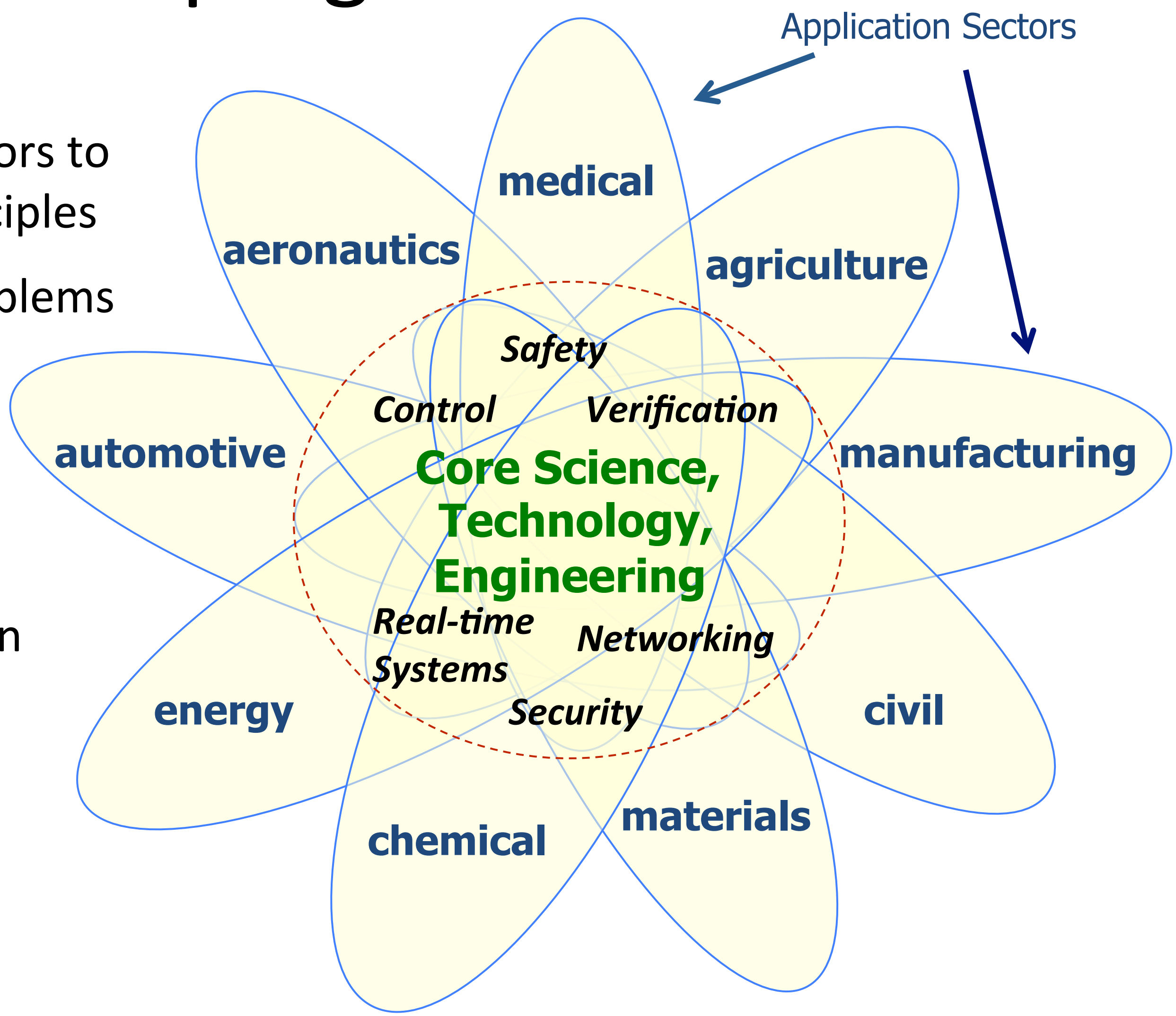
Some characteristics of CPS

- Not: isolated embedded real-time components, post-hoc bolt-on electronics, simulations or models of physical systems, scientific data acquisition/control of experiments...
- Is:
  - Cyber capability in every physical system component
  - Networked at multiple and extreme scales
  - Complex at multiple temporal and spatial scales
  - Dynamically reorganizing/reconfiguring
  - High degrees of automation, control loops must close at many scales
  - Operation must be dependable and often certified

Important factors: Highly networked, cooperative control, multiple spatial and temporal scales. Mixed initiative with varying time scales.

NSF model for expediting progress

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



Cyber-Physical Systems Program

Deeply integrating computation, communication, and control into physical systems

- Launched in 2009
- Aims to develop the core system science needed to engineer complex "smart" cyber-physical systems
- Serves key national priorities
- Coordinated across NSF and with other government agencies

114 active awards:

- $140M+ total investment
- 43 small, average $527K
- 66 medium, average $1.5M
- 5 large, average $4.7M

Transportation

Manufacturing and Industrial Automation

Energy

Healthcare and Biomedical

Critical Infrastructure

Cross-Directorate Solicitation: CISE and ENG

2014 CPS Program
Multi-agency Participation

- Department of Homeland Security (DHS)
  - Science and Technology Directorate (S&T)
    - Homeland Security Advanced Research Project Agency
- Department of Transportation (DOT)
  - Federal Highway Administration
    - Intelligent Transportation Systems Joint program office

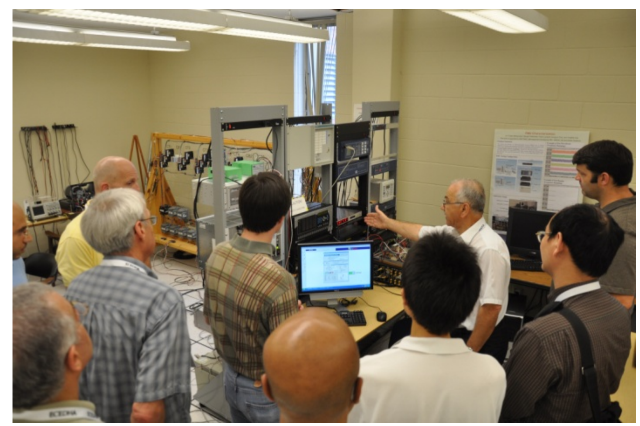
Cross-Directorate Initiatives

- Resilient Interdependent Infrastructure Processes and Systems (RIPS)
- Secure and Trustworthy Cyberspace (SaTC)
- National Robotics Initiative (NRI)

Integration of Research and Education

Shortage of Energy and Power Faculty in ECE Departments

- Electrical and Computer Engineering Departments Head Association (ECEDHA)
- NSF/ECEDHA faculty development workshop held at Georgia Tech on July 9-12, 2011



<u>Workshop Focus</u>:
Cyber Technologies for Electric Power Grid

International Collaborations

- JST-NSF-DFG Workshop on Distributed Energy Management Systems
  - Honolulu, Hawaii, January 2014
  - 100 participants from Japan, Germany and USA

Workshop Goal: discuss opportunities to leverage on-going efforts and identify new modalities for collaborations

Power Systems Education
What should NSF do?

- Shortage of Power Engineering Faculty in USA
- 300 Electrical Engineering Departments
- Major ECE Dept. vs Small ECE Dept.
- Combined Research-Curriculum Development
- Is there role for on-line education or MOOCS?
- Should NSF selectively fund pilot programs?

Energy, Power, Control and Networks (EPCN)

- EPCN Program supports innovative tools and test-beds, curriculum development integrating research and education
- Proposal Submission Window:
  - October 1 to November 1, 2014

Looking to the Future

- Enable research community and workforce to address challenges of next generation of systems
- Power industry recruiting needs and optimal (minimal) curriculum
- Learn from and collaborate with other research communities
- Identify near-term goals and action Plan