Active Heterogeneous Sensing for Fall Detection and Fall Risk Assessment

Skubic, Marjorie
CPS project that investigates the interplay of anomaly detection and the risk of anomaly events.

**Active Heterogeneous Sensing for Fall Detection and Fall Risk Assessment**

M. Skubic, J. Keller, D. Ho, Z. He, M. Popescu & M. Rantz

*ECE, HMI and Nursing, University of Missouri*

- Multi-camera vision (3D voxel model)
- 8-microphone circular array
- PIR array

**Detection history affects risk assessment**

**Fall Detection** ↔ **Fall Risk Assessment**

**Risk factors affect detection**

**CHALLENGES**

- Unstructured, dynamic environments
- Low light, variable lighting
- Adaptive fusion of multi-scale signals with qualitative data and risk factors
- Privacy restrictions

**CPS Grant CNS-0931607**
Collaborative Research: Monitoring Human Performance with Wearable Accelerometers

Hodgins, Jessica; Mark Redfern; De la Torre
Monitoring Human Performance with Wearable Accelerometers

**Motivation:**

Human-observer based methods for measuring human motion are labor intensive, and difficult to standardize across clinical settings or over time. Many medical conditions are monitored only via short visits to the clinician.

**Contributions:**

- Cyber physical systems for improved medical diagnosis and treatment monitoring
- Several data collections underway (lab, assisted living)
- New algorithms for time series classification

**Impact:**

Continuous and quantitative monitoring and evaluation of treatment at home.
Control Subject to Human Behavioral Disturbances

Patek, Stephen
Control Subject to Human Behavioral Disturbances:
Anticipating Behavioral Influences in the Control of Diabetes (CNS-0931633)
Stephen D. Patek (PI), University of Virginia

- This project addresses the design of control systems where the principle disturbances are the result of routine human behavior
  - Random, but not zero-mean white Gaussian
  - Statistical regular, but not periodic
- Goals:
  - To develop new mathematical models ("profiles") of human behavioral disturbances, focusing especially on appropriate statistical characterizations of routine behavior
  - To formulate and solve new control-theoretic problems that seek to anticipate human behavioral disturbances

**Principle Application:**
- *Artificial Pancreas* – feedback control of Type 1 Diabetes, where meals and exercise are the two main disturbances

(Wireless) Continuous Glucose Monitoring
Continuous Subcutaneous Insulin Infusion (Insulin Pump)
Cyber-physical system challenges in man-machine interfaces: context-dependent control of smart artificial hands through enhanced touch perception and mechatronic reflexes

Santos, Veronica; Stephen Helms Tillery
CPS challenges in human-machine interfaces:
Context-dependent control of smart artificial hands through enhanced touch perception and mechatronic reflexes

1) Establish relationships b/n biological and artificial systems (perception and control)
2) Induce perception of tactile feedback through cortical stimulation
3) Develop algorithms for smooth, context-dependent transfers of authority between biological and artificial systems

Co-PIs: Veronica J. Santos and Stephen I. Helms Tillery
NSF Award #0932389
Programmable Second Skin to Re-educate Injured Nervous Systems

Goldfield, Eugene
Programmable Second Skin for Re-Educating Injured Nervous Systems

Eugene C. Goldfield, Robert J. Wood, Dava Newman, Elliot Saltzman, Kenneth Holt
Marc Weinberg, Leia Stirling, Radhika Nagpal
Children’s Hospital Boston, Wyss Institute For Biologically Inspired Engineering, Harvard University

Use normally developing infant’s kicking to inform a sensing and actuating “skin” that helps brain-injured infants improve and expand kicking motions.
Towards Neural-controlled Artificial Legs using High-Performance Embedded Computers

Huang, He
Towards Neural-controlled Artificial Legs using High-Performance Embedded Computers

**Objective:** To develop a reliable and high-performance neural-machine interface (NMI) that accurately interprets the user’s intended movements in real-time for neural control of artificial legs.
A Real-Time Cognitive Operating System

Ballard, Dana
A Real-time Cognitive Operating System
The University of Texas at Austin, Computer Science and Center for Perceptual Systems
Dana Ballard, Joseph Cooper, Rahul Iyer, and Dmitry Kit

Embodied Cognition and biologically inspired computational models

- Multiple levels of sensory representation, learning, and prediction
- Spatial and temporal hierarchical abstractions of tasks and functionality
- Human subjects for model extraction and validation

Computer models and human subjects in natural vision tasks.

MPSoC based Control and Scheduling Co-design for Battery Powered Cyber-Physical Systems

Zhang, Fumin
Y1-Battery Powered CPS: Robustness

Establish a Unified Theoretical Foundation for Robustness of CPS

- Work Completed
  - Established a general hybrid systems model for any real-time scheduling algorithms.
  - Introduced a novel concept of dynamic schedulability.
  - Introduced a measure for robustness of scheduling algorithms.
  - Developed a new criteria for battery failure based on stability theory.
  - Introduced a measure for robustness of battery switching algorithms.
  - Our analytical methods have advantage over computation methods.
Non-Volatile Computing for Embedded Cyber-Physical Systems

Suh, Gookwon
Non-Volatile Computing

Wing-kei S. Yu, Shantanu Rajwade, Edwin C. Kan and G. Edward Suh
Cornell University

Embedded systems are everywhere

Autonomous wireless sensor networks

RFIDs and RFID readers

In-body sensors & Health monitoring

Challenges:
Unstable power sources
Limited battery lifetime

Voltage trace from an RFID
Receiving radiated energy

Can we eliminate dependence on batteries?

Non-volatile architecture enables:
Computation across power outages
Idle time power saving
Fast checkpointing and recall

Non-volatile microcontroller block diagram.
Hashed areas indicate NV modification.

SRAM hybridized with non-volatile flash.

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SRAM hybridized with non-volatile flash.
Programming Environment and Architecture for Situational Awareness and Response

Fowler, Robert
Goal: Research on improving programming productivity for sensing and sense/react systems.
- Productivity = Net present value of output.
- Efficient design and deployment
- Timely delivery of the right results.
- QoS/Relevance constraints.

Driving Problems: Environmental Sense/React.
- Rapidly deployable, Robust, Real-time Situational Awareness and Response (R³SAR Systems).
- Response to environmental emergencies: fire, flood, wind, ...
- DHS and DoD problems.
- Cost-effective sensing for field sciences.

General Approach: Explore/extend successful data-oriented, high-productivity methods.
- Spreadsheet (Table) idiom.
- Map/Reduce \(\rightarrow\) Sense/Reduce
- Databases and extensions.
- (Scripting languages.)

Specific Activities:
- Experimental platforms: TelosB and Sunspots, embedded (MAEMO, Android, ...) devices.
- Software prototyping and experimentation.
  - Sense/reduce prototype.
  - Campus WiFi base station signal strength capture
  - Control interface for “Tables” on Android phone.
  - Bird feeder monitoring.

- Internet base stations (PC104/Linux) connected to EMS with failover using wired service, cellular modems, AV.25 on trunked EMS radio.
- Results distributed via (Mobile) Web.
- Base-station to sensor node (SunSpot) connectivity via wire, Bluetooth, Zigbee.
- Sensors: flood level, robust weather stations.
- Ample battery capacity with PV chargers.
Ant-Like Microrobots - Fast, Small, and Under Control

Martins, Nuno Miguel
CPS: Medium: Ant-Like Microrobots – Fast, Small, and Under Control

Pamela Abshire, Sarah Bergbreiter, Nuno C. Martins, Elisabeth Smela
Award 0931878, (10/01/2009 --- 09/30/2012)

- Objective: to develop the first wireless network of cooperative mobile autonomous robots at a very small scale. Main challenge: severe power, size and weight constraints
- Co-design approach to develop:
  - **Locomotion:**
    - Thermal bimorphs (legged chip sent for fabrication)
    - Micro-scale dielectric elastomer actuators (DEA)
  - **Control:** new decentralized coordination algorithms based on stochastic model predictive control principles.
  - **Computation:** Use low power hybrid hardware configuration.
  - **Testbed:**
    - Visual tracking
    - Fleet of Zigbots
    - Localization techniques
Generation of natural movement for a multiple degrees-of-freedom robot driven by stochastic cellular actuators

Ueda, Jun
“Fingerprint” method for modeling and characterizing reconfigurable actuator array topologies

Jun Ueda, Georgia Institute of Technology  ECCS-0932208

Piezoelectric actuator array

Connection

Fingerprint

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</tbody>
</table>

Generation of “natural” robot movements

Stochastic actuator arrays

Force Variability Ellipsoid (FVE)

Actuator-level variability analysis
Image Guided Autonomous Optical Manipulation of Cell Groups

Gupta, Satyandra
Image Guided Autonomous Optical Manipulation of Cell Groups

Satyandra K. Gupta and Wolfgang Losert

- Create computational foundation, methods, and tools for efficient and autonomous optical micromanipulation using microsphere ensembles as grippers.

Initial scene

Four microspheres are moved to trap the cell

Trapped cell is moved to the desired location
Image Guided Robot-Assisted Medical Interventions

Tsekos, Nikolaos
The scientific directions, and the associated specific research objectives, of the Multimodal Image-guided RObot-assisted Surgeries (MIROS) project is its reliance on true sensing of the physical world with multi-contrast imaging and distributed force/bending-sensors, in order to maneuver a steerable surgical robotic manipulator inside the continuously changing environment of a patient while offering a comprehensive perception of the Area of Operation (AoO) to the operator via a visuo-haptic interface.
Learning for Control of Synthetic and Cyborg Insects in Uncertain Dynamic Environments

Abbeel, Pieter
## Learning for Control of Synthetic and Cyborg Insects in Uncertain Dynamic Environments

Pieter Abbeel (PI), Ron Fearing, Michel Maharbiz --- UC Berkeley

<table>
<thead>
<tr>
<th>Cyborg beetle</th>
<th>Synthetic crawler</th>
<th>Objective</th>
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<tbody>
<tr>
<td><img src="image" alt="Cyborg beetle" /></td>
<td><img src="image" alt="Synthetic crawler" /></td>
<td>Development of learning and adaptation capabilities that will enable operation of synthetic and cyborg insects in complicated environments, such as collapsed buildings.</td>
</tr>
</tbody>
</table>

### Technical Approach

1. Online performance improvement from minimal experience.
2. Learn control policies and dynamics models through sharing across platforms and environments.
3. Control learning algorithms on low-cost, low-power platforms.

### Year 1 Results

**Cyborg beetle:**
- Hardware/software setup, initial flight data

**Synthetic crawler:**
- On-board electronics: video, gyro, accel.
- **Learning and adaptation:**
  - Model-free policy gradient like method that leverages past experience for improved learning performance.
Tightly Integrated Perception and Planning in Intelligent Robotics

Mark Campbell, Dan Huttenlocher, Hadas Kress-Gazit
Tightly Integrated Perception and Planning in Intelligent Robotics
Mark Campbell, Dan Huttenlocher, Hadas Kress-Gazit
Cornell University

Objective: Tightly integrates probabilistic perception and deterministic planning in a formal, verifiable framework

- **Representations** – new techniques for constructing and maintaining representations of dynamic environments.
- **Anticipation and Motion Planning** - methods to anticipate changes in the environment and use them as part of the planning process.
- **Verifiable Task Planning** - providing probabilistic guarantees for high-level behaviors.
Collaborative Research: Localization and System Services for SpatioTemporal Actions in Cyber-Physical Systems

Arora, Anish; Gupta, Rajesh
Localization and System Services for SpatioTemporal Actions in Cyber-Physical Systems

Prof. Anish Arora (Co-PI: Ohio State University), Prof. Rajesh Gupta (Co-PI: UC San Diego), Dr. Ryo Sugihara (UC San Diego)

A Focus on Deterministic Properties
Sensed data is typically profiled in terms of statistical properties
- Focus is on efficiency of learning/testing of statistics

But for CPS applications, safe/critical operation often demands deterministic properties
- Our focus is on worst-case bounds on spatiotemporal properties
  i.e., network time, node location, state latency/error rate

Example: Pursuer-Evader Control System

- Clock Synchronization
  - Use causality in messaging to obtain constraints on global time
  - Synchronization error bounds derived from multiple constraints

  \[ f(s_0) = t_0 < t_1, f(s_3) = t_3 > t_3 \]

Control Properties Depend on Deterministic Guarantees
For single-pursuer single-evader catch-me game,
Nash equilibrium strategy exists provided deterministic guarantees exist on snapshot latency, error, and rate

Theorem:
Given
- distance \( d_p(t) \) between pursuer \( p \) & evader \( e \)
- speed ratio \( \alpha = s_p/s_e \)
- error \( e(t) \) in distance estimate
- staleness \( \delta(t) \) in the state snapshot
- synchronization interval \( r(t) \) between snapshots

Eventual catch guaranteed if there exists \( k > \frac{\alpha + 1}{\alpha - 1} \) s.t.
- distance sensitive latency: \( \delta(t) < \frac{d_p(t)}{u_e} \left( \frac{1 - \alpha + k + 1}{\alpha k} \right) \)
- distance sensitive error: \( e(t) < \frac{d_p(t)}{s_e} \frac{k + 1}{k} \)
- distance sensitive rate: \( r(t) < \frac{d_p(t)}{u_p} \frac{k + 1}{k} \)

Algorithms and Techniques for System Services with Deterministic Accuracy Guarantee
- Distance Sensitive Snapshot Service
  - Clustering
    + Solid disk clustering with or without localization
    + Stretch factor gives local healing
    + - Extended to log(N) levels

  - Scheduling
    + Aggregate and disperse data along trees in clusters
    + At each level
      - Clusterhead compresses data into m bits
      - Summary dispersed to all nodes in cluster & its neighboring clusters
    + Pipelined implementation
      - Nodes generate fresh data as soon as previous data out of level-1 clusters

- Sensor Localization
  - Sensor localization as (nonconvex) optimization problem
  - Upper bound of localization error by SDP relaxation

Formulation idea: Distance of nodes in two different realizations of a graph

Maximize \( \|x'_i - x_i\| = d_{iA} \)
subject to
  - distance between nodes: \( \|x_i - x_j\| = d_{ij}, \forall (i,j) \in E \)
  - distance between node and anchor: \( \|x_i - a_i\| = d_{ia}, \forall (i,j) \in E \)

Iterative algorithm for large networks
- Further relaxation: Solve SDP for subgraphs
- Increase the size of subgraph to improve error bounds
Dynamically Managing the Real-time Fabric of a Wireless Sensor-Actuator Network

Lemmon, Michael
Dynamically Managing the Real-time Fabric of a Wireless Sensor-Actuator Network

• CNS-09-31195  September 1, 2009 – August 31, 2012
• University of Notre Dame: M. Lemmon (PI), X.S. Hu (Co-PI)

• Objective: develop algorithms for wireless sensor-actuator networks (WSAN) supporting control applications that with hard/firm real-time quality-of-service (QoS) constraints.

• Approach: To meet real-time constraints required in networked control applications, one must manage the communication network’s “real-time fabric” to enable reliable prediction of end-to-end delays. This will be done by stabilizing the network’s interference environment through adaptive power/channel control, by managing data dropouts through rate control, and the use of anytime controllers. This approach balances the relationship between application (physical) performance and a network’s (cyber) end-to-end QoS. This requires a scalable integration of methods used in control, wireless networking, and real-time systems.

• Progress to Date:
  - Reducing jitter in real-time control tasks (RTSS09, ECRTS10)
  - Bounded Burst QoS constraints on dropouts (ACC 10, TAC 2010)
  - Adaptive bandwidth reservation schemes in wireless networks (TMC 2010)
  - Distributed Algorithms for Network Optimization (Ph.D. Dissertation 2010)
Sensor Network Information Flow Dynamics

Khandani, Mehdi
Optimum information flow in wireless sensor networks become computationally prohibitive when the number of nodes grows large.

Instead of modeling the network as a discrete nodes, the wireless sensor network can be modeled as a continuum of nodes covering an area (namely $A$) in $\mathbb{R}^2$ plane.

In a dense wireless network, information can be treated like a fluid. **Information flow vector field**, $D$, satisfies the following equations:

- $\nabla \cdot D = \rho(z) \quad z \in A$
- $D \cdot n = 0 \quad z \in \partial A$
- $D^* = \arg \min_A \int \| D(x, y) \|^2 \, dx \, dy$

- $\nabla \times D^* = 0 \quad \Rightarrow \quad D^* = \nabla u$

Potential function $u$ satisfies Poisson’s equation:

$$\nabla^2 u = \rho(z) \quad z \in A$$

$$\frac{\partial u}{\partial n} = 0 \quad z \in \partial A$$

Using Gauss Harmonic Theorem a distributed solution of this PDE on a stochastic grid is calculated using:

$$\hat{u}(z) = \frac{1}{M} \sum_{i=0}^{M-1} u(z_i) - \frac{E[r^2]}{4} \rho(z)$$
A Unified Distributed Spatiotemporal Signal Processing Framework for Structural Health Monitoring

Cheng, Qi
Motivation:

- This research is motivated by the current inability to accurately detect, diagnose or prognose structural anomalies/damages at an early stage.
- The critical gap from prior domain knowledge of physical systems and large amount/diverse sensor observations to the improved accuracy and confidence in health state assessment should be addressed.

Objective:

To develop a collaborative signal processing framework by coupling sensing data with physics-based and data-driven models to detect and diagnose degradation and damages.

Technical Approach:

- Model identification based on the domain information and Markov random field modeling;
- Distributed and localized inference by taking advantage of spatiotemporal information represented by the model;
- Design of a cyber-physical system for structural health monitoring through optimizing the sensing system, including what/where/how to sense.
Embedded Fault Detection for Low-Cost, Safety-Critical Systems

Balas, Gary
Embedded Redundancy Management for Low-Cost, Safety-Critical Systems
Seiler, Balas, Heimdahl, Srivastava, and Zhai

**Issue**: Current safety critical systems rely mainly on physical redundancy, increases system size, complexity and power.

**Objective**: Develop algorithms and computing architectures which enable fault detection without relying on physical redundancy.

**Fault Detection Approach**
1. *Model-based monitors* to detect faults in physical domain
2. *Monitors derived from software requirements* to detect faults in cyber (hardware/software) domain
3. *Data-driven anomaly detection* to cyber/physical faults

**Computing Architectures**:
- Multi-core architectures

**Applications**:
- UAVs, medical devices, road vehicles
A Framework for Enabling Energy-Aware Smart Facilities

Soibelman, Lucio
Problem Description

The demand is mostly ignored. Feedback helps reduce.

Difficult to obtain appliance-level data

Can we leverage low-cost data sources?

Solution and Results

Validation Results

<table>
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<tr>
<th>Method</th>
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<th>Whole</th>
<th>Transient</th>
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<td>Polynomial Coefficients</td>
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<td>51%</td>
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<td>Fourier Coefficients</td>
<td>64%</td>
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<td>RBF Coefficients</td>
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<td><strong>64%</strong></td>
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Laboratory (A)

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House (B)

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</table>

Of U.S. electricity consumption
Cyber-Enabled Efficient Energy Management of Structures (CEEMS)

Vincent, Tyrone
CEEMS – Cyber Enabled Energy Management of Structures
Tyrone Vincent, Robert Braun, Dinesh Mehta, Kevin Moore, Sid Suryanarayanan, Marcelo Simoes, William Hoff

Supported by NSF Grant CNS-0931748

Application area: Buildings as cyber-physical systems with multiple, interacting networks

- Simulation and Optimization for Buildings and Integrated Energy Systems
- Cyber Enabled Building Energy Management Systems
- Activity Recognition
- Interconnected Dynamic Systems – Identification and Control
Anomaly Detection

Han, Jiawei
Anomaly Detection: A Filtering-and-Refinement Approach

- **Method**
  - Filtering: Eliminate obvious normal data (Roughly separate normal from abnormal, by *Deterministic Space Partition*, and generate a small set of anomaly candidates)
  - Refinement: then focus on possible anomalies

- **Efficient detection of abnormal events!**

  - Scan dataset once, with linear time, generate a small set of anomaly candidates

  - Outliers are identified (marked red) in the data
Discovery of Periodic Patterns of Moving Object Clusters

- A system that mines moving object patterns: Z. Li, et al., “MoveMine: Mining Moving Object Databases”, SIGMOD’10 (system demo)
- Z. Li, B. Ding, J. Han, and R. Kays, “Mining Hidden Periodic Behaviors for Moving Objects”, KDD’10 (sub)
- Z. Li, B. Ding, J. Han, and R. Kays, “Swarm: Mining Relaxed Temporal Moving Object Clusters”, VLDB’10 (sub)

Bird flying paths shown on Google Earth

Mined periodic patterns by our new method

Swarm discovers more patterns

Convoy discovers only restricted patterns
Foundation of Heterogeneous Information Networks (KDD’09, PKDD’10)

Global Ranking? VS. Clustering in heterogeneous network?

What feature can I use?

Cluster and rank people or events
Find highly suspicious groups/events

Flickr: query “Raleigh”

Table 5: Top-10 Conferences in 5 Clusters Using RankClus

<table>
<thead>
<tr>
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<th>Network</th>
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</table>

- RankClus/NetClus: Integrating Clustering with Ranking for Heterogeneous Information Network Analysis (KDD’09)
- GNetMine: Classification of Heterogeneous Information Networks (PKDD’10)
Towards Foundations of Cyber-Physical Networks

- Principles for mining moving objects and spatiotemporal data
- Principles for mining heterogeneous information networks
- Towards foundations of cyber-physical networks