Body Sensor Networks: An Application-Centric Approach

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Wireless Health Vision

- Data
  - Continuous
  - Longitudinal
  - Remote
  - Non-invasive
  - Inexpensive
  - High quality

- Health Apps
  - Personalization
  - Event detection
  - Diagnosis
  - Rehabilitation
  - Care taking
  - Wellness self-efficacy
Wireless Health Infrastructure

- **Hardware**
  Collecting the data and getting it where it needs to go

- **Software**
  Converting data into medically relevant information

- **Database**
  Enabling access to information for diverse stakeholders

- **Interfaces**
  between them
Big Wireless Health Questions

• What value does Wireless Health promise?
  – Improve health outcomes
  – Enhance wellness
  – Enable aging-in-place
  – Lower healthcare costs
  – ...

• How can this value be demonstrated?
  – Need application domain expertise
    • Collaborate, collaborate, collaborate
  – Deploy platforms in real human subjects studies
  – Convert data to medically relevant information
  – Identify and use metrics appropriate for target application(s)
  – Science-based research
• “An interdisciplinary team of researchers focusing on technology to improve healthcare... and healthcare to improve technology”

• Co-directors: John Lach (ECE), Steve Patek (SIE), Jack Stankovic (CS)

• Members from Neurology, Neurosurgery, Neuropsychology, Nephrology, Biomechanics, Orthopedic Surgery, Cardiology, Geriatric Nursing, Psychiatry, etc.
• Application-driven engineering research
  – Embedded systems, circuits, and signal processing expertise
  – Strong relationships with medical personnel and patients
  – Real systems deployed in real clinical applications, including rapid prototyping

• Historical application focus is on movement disorders, requiring high precision motion capture and analysis to
  – Study movement disorder etiology and progression
  – Increase movement disorder diagnostic sensitivity
  – Evaluate efficacy of therapeutic intervention

• Exploring other sensing modalities and application areas

• Technology goal: maximize wearability and battery life of body sensor networks (BSNs) while delivering required motion analysis fidelity

• Overall goal: improve healthcare and medical research to ultimately improve patient outcomes and quality of life while reducing healthcare costs
BSN Research Cycle

1. Platform Development
2. Clinical Application
3. System Optimization
4. Signal and Information Processing

The cycle is designed to iteratively develop and apply platform technologies, optimizing systems and signal processing techniques for clinical applications.
DBS-based Management of Tremor

- Tremor can impair quality of life for advanced Parkinson’s Disease (PD) and Essential Tremor (ET) patients
- Deep brain stimulation (DBS) offers tremor relief for recalcitrant, advanced tremor
- Drs. Jeffrey Elias and Robert Frysinger (UVA Neurosurgery Department) desired to study impact of different DBS settings on PD and ET with quantitative tremor analysis
  - Occurrence
  - Frequency
  - Magnitude
  - Classification
BSN Research Cycle

- Platform Development
- Prototype
- Wearable Inertial Sensor Nodes
- System Optimization
- Clinical Application
- Joint Time-Frequency Analysis of Motion
- Signal and Information Processing
- Continuous, Non-Invasive Tremor Measurement
TEMPO Over Time (Cycles)

from Ben Calhoun:
• 2-lead ECG with atrial fibrillation detection and wireless streaming
• 19 uW – runs off of body heat!
BSN Research Cycle

- Platform Development
- System Optimization
- Clinical Application
- Signal and Information Processing

TEMPO 1, TEMPO 2, TEMPO 3
TEMPO in Human Subject Studies

- Parkinson’s disease – study efficacy of deep brain stimulation
  - Jeffrey Elias, Robert Frysinger (UVA Neurosurgery)
- Parkinson’s disease – study impact of cognitive stress
  - Scott Wylie (UVA Neurology)
- Normal pressure hydrocephalus – improve diagnosis
  - Jeffrey Barth, Donna Broshek, Jason Freeman (UVA Neuropsychology)
- Geriatrics – enable fall risk assessment in naturalistic settings
  - Thurmon Lockhart (Virginia Tech Locomotion Laboratory)
  - Mark Williams (UVA Geriatric Medicine)
  - Amy Papadopoulos, Cindy Crump (AFrame Digital)
- Dialysis – study cause of higher fall rates
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- Cerebral palsy – study efficacy of orthopedics for children
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- Dementia – assess physical agitation
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Tremor Assessment

Raw 3-axis Tremor Acceleration Waveforms

Teager Tremor Waveform
BSN Research Cycle

Platform Development

System Optimization

Clinical Application

Signal and Information Processing

TEMPO 1, TEMPO 2, TEMPO 3

Teager & STFT Energy, ANN, SVM, KNN, Real-time variance, Haar DWT

Tremor, Gait Disorders, Fall Risk, Agitation, ...
BSN Optimization

• To make health assessment of human movement a reality, platforms will need:
  – **Smaller form factor** (invisible to the user) for unobtrusive, naturalistic use
  – **Longer battery life** (from hours now to days and weeks in the near future) for continuous, longitudinal monitoring
  – **Necessary application fidelity** (data that reliably yields clinically-meaningful, non-obvious information) for delivering **value**
TEMPO Empirical Observations

- Transmit compressed data
- Transmit only when necessary
- Transmit information instead of data
- Power off gyros when possible

On-node signal processing is key to energy efficiency
Effects of Lossy Compression

- Assume an application accepts a maximum MSE distortion of 100 (from raw 12-bit ADC acceleration)
- For fixed compression ratio:
  - Distortion above this threshold violates the requirement, so data rate must increase
  - Operating well below the threshold is energy inefficient since data-rate can be further reduced

For a given data rate, distortion will change over time, so dynamic management of data rate is desirable
BSN Control Architecture

- A data controller and a destination controller
- Runtime optimization of tradeoffs between power consumption, computational complexity, and signal fidelity
- Adjust to system dynamics
  - Data characteristics
  - Wireless channel characteristics
  - Application priorities

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Data Acquisition

DSP | Data Controller

Destination Controller

Wireless Transceiver

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DAQ

Feature Detection

Pattern Classification & Compression

DSP Toolkit

Data Controller

FIFO Queue

Destination Controller

Physical Layer

MAC Layer

Wireless Transceiver
Energy-Fidelity Framework

BSN Hardware → Measured Time → Energy Model

C Source → CR → Fidelity Measurer

Data Rate Reduction Techniques → LabVIEW Source → Raw Data → Fidelity

Energy-Fidelity Tradeoff Space

BSN Data
Dynamic Energy-Fidelity Management

What is the right measure of “fidelity”? Almost certainly *NOT* MSE!!!
Trade-offs

• Engineering is all about managing trade-offs

• Traditional technical metrics
  – Power, cost, delay, throughput, ...

• Emerging Wireless Health metrics
  – Wearability, safety, quality of information (QoI), ...

• Optimizations must simultaneously consider all metrics
QoI: Quality of Information

- **System\(_0\)**: Highest QoI
- **System\(_1\)**: Compress Data
- **System\(_2\)**: Fewer Sensors

Power: | Cost: | Wearability: | QoI: 
---|---|---|---
System\(_0\): | | | 
System\(_1\): | | | 
System\(_2\): | | | 

Questions: ???

The diagram illustrates the trade-offs between Power, Cost, Wearability, and QoI for different system configurations.
QoI: Quality of Information

**System\(_0\)**
- Highest QoI
- Health Decision

**System\(_1\)**
- Compress Data
- Health Decision

**System\(_2\)**
- Fewer Sensors
- Health Decision

QoI Assessment
BSN Research Cycle

- **Platform Development**: TEMPO 1, TEMPO 2, TEMPO 3
- **System Optimization**: Energy-Fidelity Scalability, Application Profiling, DVFS, BCC
- **Clinical Application**: Tremor, Gait Disorders, Fall Risk, Agitation, ...
- **Signal and Information Processing**: Teager & STFT Energy, ANN, SVM, KNN, Real-time variance, Haar DWT

Energy-Fidelity Scalability, Application Profiling, DVFS, BCC
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Aiding Diagnosis of Normal Pressure Hydrocephalus with Enhanced Gait Feature Separability
J.T. Barth, B.C. Bennett, M. Brandt-Pearce, D.K. Broshek, J.R. Freeman, J. Lach

Before HVLP
  Brain imaging
  Cognitive skills assessments
  Gait performance

High Volume Lumbar Puncture (HVLP) procedure

After HVLP
  Cognitive skills assessments
  Gait performance
Gait Feature Extraction

- Visually Observable Features
  - Average Speed, Step Length, Step Time

- BSN-Enabled Linear Features
  - Stride Time Standard Deviation, Average Double Stance Time

- No Linear Feature Separates NPH Group from Non-NPH Group
Results: Nonlinear Gait Feature

Lyapunov Exponent

- Before HVLP
- After HVLP

Lyapunov Exponent ➔ Gait Stability
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Enabling Longitudinal Assessment of Ankle-Foot Orthosis Efficacy for Children with Cerebral Palsy

Bradford C. Bennett, John Lach

- AFO goals
  - Facilitate walking by controlling the position of the ankle and providing a base of support
  - Prevent contractures by putting muscles in a lengthened position and providing variable ranges of motion
  - Prevent deformity by controlling the position of the foot/ankle

- Joint angles, gait moments, and gait velocity assessments in VICON laboratories
AFO-Embedded Inertial Sensing

- Validation against VICON
- 4 CP children to date
- Preparation for in-field data collection
- Working with prosthetics manufacturers

![Graphs showing ankle joint angle and shank angular velocity](image)

**Right Ankle Angle of CP Subject 1 with AFO**

- **RMSE = 1.34**

**Angular Velocity of Right Shank of CP Subject 1 with AFO**

- **Pearson Correlation = 0.9714**

**Heel Strike**
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Continuous, Non-Invasive Assessment of Agitation in Dementia Using Inertial Body Sensors
Azziza Bankole, Martha Anderson, Aubrey Knight, Tonya Smith-Jackson, John Lach

• Agitation is common in dementia patients
  – Major caregiver burden
  – Changes over time and in response to stimuli
• Approaches to mitigate agitation require evaluation
• Cohen-Mansfield Agitation Inventory (CMAI) requires sampled expert observation
• Need for continuous, longitudinal monitoring
Inertial BSNs for Agitation Assessment

- Explored use of inertial BSNs for physical agitation assessment
- Jerky, repetitive movements correlate with physical agitation
  - Requires joint time-frequency analysis
- Pilot study: six dementia subjects in long term care facility
  - Three 3-hour sessions over six weeks (different times of day)
  - Three TEMPO nods (dominant wrist, waist, and opposite leg) with triaxial accelerometers
  - Suggested Teager energy a good measure of physical agitation
Planned Human Subject Studies

• Epilepsy – detect and study seizures
• Obesity – behavior modifying feedback
• Traumatic brain injury – measure head forces
• **Dementia – caregiver empowerment for agitation mitigation**
• Posture – provide real-time feedback to users
• Prosthetics – develop smarter controls
• Stroke – track stroke rehabilitation progress via telemedicine
• Asthma – track environmental exposure and predict/prevent asthma attacks
BESI: Behavioral and Environmental Sensing and Intervention
NSF SCH-INT: 1418622

• Empower caregivers dealing with dementia-related agitation
• Detect and predict agitation to prompt pro-active interventions
  – Detect with validated agitation detection sensors (Bankole – WH 2011)
  – Predict with dyad-specific models
• Transdisciplinary team
  – John Lach (Embedded Sensor Systems, UVa)
  – Azziza Bankole (Geriatric Psychiatry, Carilion Clinic)
  – Martha Anderson (Geriatric Nursing, Carilion Clinic)
  – Tonya Smith-Jackson (Human Factors Engineering, NC A&T)
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U.Va., NSF Partner on Nanosystems Engineering Research Center on Self-Powered Health Monitoring

SEPTEMBER 5, 2012
FARISS SAMARRAI

The University of Virginia and three other universities will partner on a national nanotechnology research effort to create self-powered devices to help people monitor their health and better understand how their environment affects it, the National Science Foundation announced today.

The NSF Nanosystems Engineering Research Center for Advanced Self-Powered Systems of Integrated Sensors and Technologies, or ASSIST, to be headquartered on North Carolina State University’s Centennial Campus, includes the four partner schools – U.Va., North
ASSIST Nano-Enabled Systems

ASSIST Technologies
1. Energy harvesting and storage
2. Nanodevices
3. Nanosensors
4. Integration and prototyping
5. Packaging and deployment

Center System-Driven Vision & Test Platforms
- Energy harvesters
- Low-power Electronics
- Wearable materials
- Non-Adhesive Wristband (environmental, skin-G, PH, pulse-ox)
- Adhesive Patch (EKG, skin-G, heart/lung sounds, cortisol biomarkers)
- Mouth-based Platform (saliva biomarkers, breath)

Slide courtesy: Veena Misra (NCSU)
Interdisciplinary Collaboration

• Synergistic research must have bi-directional impact
• Understand each others’ interests and objectives – each person must regularly answer:
  1. What must I do to achieve my objectives?
  2. What am I willing to do to achieve my objectives?
  3. What is my timeline?
  4. Based on each of our answers to 1-3, are we compatible? Can we at least take turns\textsuperscript{1}?

\textsuperscript{1}Deborah Estrin’s key to interdisciplinary collaboration
Ask “why?” at least as often as “what?”

\[ \vec{v}(t) = \int \vec{a}(t) \, dt \]
Other Grand Wireless Health Research Challenges

• **Behavior modification!**
• Optimizing systems using the proper metrics
• Reasoning about safety and “good enough”
• Unintended Wireless Health system/app interactions
• Prediction – not just detection
• Data sharing to improve study power
• Data sharing to demonstrate progress of field
• Non-invasive bio-chemical sensing
• Data to knowledge
• Human factors and user adoption
• Convincing demonstrations of improved outcomes
• Translation to industry
• MANY MANY others...
Big Wireless Health Questions

• **What value does Wireless Health promise?**
  – Improve patient care
  – Enhance wellness
  – Enable aging-in-place
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• **How can this value be *demonstrated*?**
  – Need application domain expertise
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  – Science-based research
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