Wireless Sensor Networks for Home Medical Care

John A. Stankovic
BP America Professor
Department of Computer Science
University of Virginia

http://www.cs.virginia.edu/wnsn/medical/
http://wirelesshealth.virginia.edu/
What’s Wrong With Wires

And we don’t want a patient tethered to a bed or fixed medical device
Outline

• Problems and Vision

• Univ. of Virginia AlarmNet System
  – Architecture
  – Main Ideas/Results

• Current Work and Summary
The Problems

- Aging Populations
- High Cost of Medical Care
- Lack of Facilities
- Quality of Life Issues

- **Solution**: Home Health Care
  CCRC
  Assisted Living
Vision - Smart Living Space

- Humans-in-Loop
- Heterogeneous
- Evolution
- Open
- Privacy
Large Scale Deployments

Assisted-Living Campus

- Person
- Person with Body Network
- Backbone Node
- Sensor Node
State of Art

- UCLA, Harvard, Yale, GaTech, MIT, Univ of Washington, Johns Hopkins, Imperial College, U. of Geneva, UPenn, UVA, etc.

- GE Health, Intel, Philips, Verizon, IBM, etc.
- West Wireless Health Center
- Wireless Life Sciences Alliance

- Europe, Asia, US
"3" Open Questions

• Scale
  – Numbers of sensors
  – Number of smart home units
  – Number of facilities
  – Number of functions on body networks
  – Numbers of body networks

• Activity Recognition (AR) not accurate enough

• Safety
Goals - A System View

- Tailored to patient
- Evolves over time
- Seamlessly integrate heterogeneous technology
- Largely Passive
- 24/7 Monitoring and Care
Benefits

• Identify normal behaviors
• Identify anomalous behaviors
• Detect medical problems (depression) early
• Improve quality of life
• Monitor adherence to and effectiveness of treatments
• Detect dangerous situations
• Maintain privacy
• Longitudinal studies
AlarmNet

- Assisted Living and Residential Monitoring Network
- In-Lab Testbed
- Privacy – deployed in 8 homes
- Detecting Falls – students
- CAR – 22 patients in Assisted Living
- Sleep Study - 10 subjects
- Body Sensor Networks
- Deployment Plans – Depression in the Elderly
  - Deployed in one home
AlarmNet Architecture

PDAs
Patient Interface
Body Networks
Emplaced Sensor Network
Backbone
Back-End Database
Internet
Nurses Stations
Human Interfaces
With Harvard
With Harvard
Sleep Monitoring

- Sleep motion (restlessness and agitation)
- Sleep quality
Using Physiological Signals

- EEG: measures brain waves
- EOG: measures eye movements
- EMG: measures electrical activity of muscles

Disadvantages
- Expensive
- Uncomfortable
- Measure once/twice
Wearable Devices in Home Environments

- Actiwatch
- Headband - Zeo

- Disadvantage
  - Users need to wear the devices
Non-Wearable Solutions

- **Pressure Pads**
  - Disadvantage
    - Not entirely comfortable
    - Do not infer body positions

- **Cell Phone Apps**
  - Built-in accelerometers are used
  - Disadvantage
    - Not robust
WISP

- Combines RFID technology with sensors
- Used to sense light, temperature and acceleration
- Powered and read by RFID readers
WISP Instrumented Mattress
Body Position Inference

- For different body positions, orientations of one or more axes of the accelerometers with respect to gravity are different.
- We combine the readings from all three tags to infer body position.
Body Position Inference

• During training, for each body position of the subject, we construct a 9-tuple from the readings of the three tags

• We train a Bayesian classifier with these tuples

• We use this classifier to infer body positions during sleep
Controlled Experiments for Body Position Inference

- 10 subjects
- 3 different mattresses

- Each subject lies in each of the 4 body positions for 2.5 minutes each

- For each position, we use the data from the first 2 minutes for training and next 30 seconds for evaluating accuracy of body position inference
• 3 settings:
  – set1: differentiate between the bed being empty or occupied
  – set2: differentiate between empty, lying and sitting
  – set3: differentiate between all lying positions, empty and sitting
Realistic Overnight Experiments

- 6 nights
- DDR pads (sense pressure) used as baseline system
- Also compare with an iPhone application: Sleep Cycle
- We also recorded the video of the 6 nights’ sleep
Evaluation by Cross Validation

• 6 Evaluation sets
• In each set, we train our system based on 5 nights of data and evaluate the performance of the remaining night
• Ground Truth
  – Validated the performance of DDR pads by comparing with 3 hours video
  – DDR pads are considered ground truth
Body Position Inference

- **Ground Truth**
  - Collected from the recorded video
  - Accurate within 5%
Medical Studies

• Correlation between sleep movement and agitation with incontinence in dementia patients
  – Combine with acoustic and wetness sensors
AlarmNet Architecture

Dust
Light
Pollen
Humidity
Temperature
Motion
Activities

PDAs

Human Interfaces

Nurses Stations

Patient Interface

Body Networks

Emplaced Sensor Network

Backbone

Back-End Database

Internet

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Key Points

• Self-configuring - Highly flexible (radio shack model)

• New sensor types can be added later

• Contributes to Activity Recognition (AR)
AlarmNet Architecture

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Privacy Security

Nurses Stations

Human Interfaces
AlarmGate

- Netbridge device (Stargate)
  - single board computer
  - embedded Linux
  - 400MHz Xscale
  - mote daughterboard
  - wireless ethernet
Privacy - Many Stakeholders

- Patients
- Patients family and friends
- Doctor – what advantages for them in treating patients
- Nurse
- Technician
- Orderly
- Admin
- Social Worker
Privacy - Many Data Types

- Personal medical data
- Personal activity data
- Environmental data
- Contextual data
- Longitudinal data
- System Performance data
Authorization Framework

- User's Request
- Reply
- Device
- Database
- Request Authorizer
- Policy Manager
  - Inconsistency Check
  - Privacy Policy
- Context Manager
- Context
- Data mining analysis
- Request History
- LOG Audit Trail
- Analyze Audit Trail

Violate Privacy On Heart Attack
Fingerprint And Timing-based Snoop attack

**ADL**

- **ADLs inferred:**
  - Sleeping, Home Occupancy
  - Bathroom and Kitchen Visits
  - Bathroom Activities: Showering, Toileting, Washing
  - Kitchen Activities: Cooking

- High level medical information inference possible

- HIPAA requires healthcare providers to protect this information

<table>
<thead>
<tr>
<th>Timestamps</th>
<th>Fingerprints</th>
<th>Locations and Sensor Types</th>
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</thead>
<tbody>
<tr>
<td>T1</td>
<td>Red</td>
<td>?</td>
</tr>
<tr>
<td>T2</td>
<td>Green</td>
<td>?</td>
</tr>
<tr>
<td>T3</td>
<td>Blue</td>
<td>?</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>
Performance

• 8 homes (X10) - different floor plans
  – Each home had 12 to 22 sensors
• 1 week deployments
• 1, 2, 3 person homes
• Violate Privacy - Techniques Created
  – 80-95% accuracy of AR via 4 Tier Inference
• FATS solutions
  – Reduces accuracy of AR to 0-15%
Key Points

• Privacy is critical (many types)

• Overridden on alarms

• Use dynamic context and request history

• Inconsistency checking algorithms required
AlarmNet Architecture

- Dust
- Pollen
- Humidity
- Temperature
- Motion
- Activities

PDAs

Patient Interface

Body Networks

Emplaced Sensor Network

Privacy Security

Internet

Back-End Database

Nurses Stations

Human Interfaces

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Graphical Interfaces

- PDA real-time query issuer – template based
- Circadian Activity Rhythms
- Nurse’s station monitoring
- Embedded displays
Depression Detection and Monitoring

- Multi-modal
- Passive
- Combines Objective and Subjective Measures
Depression Monitoring

Patient Display

Caregivers Display

Depression Inference

Eating
Sleep Quality
Movement
Mood
Weight Gain/Loss

DB

Motion and Contact
Sleep Data
PHQ-9
Acoustic
Weight

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Patient Health Questionnaire

In the past 2 weeks have you had any of the following problems:

Begin
Little interest or pleasure in doing things

Not at all  More than half the days  Nearly every day
Patient: Lois Peters, 83
Medical History:
Chronic Major Depression

<table>
<thead>
<tr>
<th>Service</th>
<th>Status</th>
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<tbody>
<tr>
<td>Sleeping Quality</td>
<td>terminal insomnia</td>
</tr>
<tr>
<td>Hygiene Level</td>
<td>clean</td>
</tr>
<tr>
<td>PHQ Score</td>
<td>moderate</td>
</tr>
<tr>
<td>Weight</td>
<td>stable</td>
</tr>
<tr>
<td>Eating</td>
<td>good</td>
</tr>
<tr>
<td>Social Level</td>
<td>active</td>
</tr>
</tbody>
</table>

*last taken 2 weeks ago*
PDA Real-Time Queries

AlarmGate SW on stargate

DB
SenQ

- Interactive, Embedded Query System
  - Peer to peer
- Streams – define, discover and share
- Virtual sensors – discover and share
- Devices added/deleted
- Optional Modules
- Location Transparency
- UI - Developers, Domain Experts, Users
- Privacy and Security

SenQ Layers

- Loosely coupled layers
Sensor Data Sampling & Processing

1. Sensor Sampling and Processing
2. Query Processing and Network Messaging
3. Query Management and Data Storage
4. SenQL Declarative Query Language

Sensor Sampling & Processing
- Predicate
- Report
- Aggregate
- MovingAvg
- Collect

Dynamic Wiring

Samples
- SensorSample

Sensor Drivers
- EventSensor
- SplitPhaseSensor
- PollableSensor

Key: Internal flow Network messages

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Sensor Data Sampling & Processing

• Virtual Sensors
  – users fuse streams to make new sensors
  – sensor drivers can recursively invoke SenQ
Query Management

1. Sensor Sampling and Processing
2. Query Processing and Network Messaging
3. Query Management and Data Storage
4. SenQL Declarative Query Language

- Query Manager
- Privacy Manager
- Power Manager
- Database Interface
- AMSecure
- Audit Log
- Authentication
- PhoenixSource
- Routing
- Client Manager
- Sensor Network
- IP Network

Sensor Data
Queries
Circadian Activity Rhythms

- 22 patients
- 3 months to 1 year
- 7 males; 15 females
- Ages 49-93
- All ambulatory
- Weekday; weekend; seasonal
- Eliminate times when not in facility
- Learning - 2-3 weeks of normal behavior
Circadian Rhythms

Circadian activity rhythm per room for 70 days
Anomalies

• Examples
  – Retroactively analyzed the anomalies
    • Detected “depression” – much more time in bed
    • Detected increased urination at night
    • Detected different behavior upon return from hospitalization

Summary

• Wireless Health
  – Body Sensor Networks
  – Environmental and AR Networks

• Easy to Modify over Time
  – Incorporate new technology as it becomes available
  – Adapt as medical conditions change

• Protects Privacy
“It appears to be some kind of wireless technology.”
Current Research

- Data Association (multi-person homes) – new height sensor
- Run Time Assurance – safety
- Robust AR
- Scaling
- Fall Detection
- BSN