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Outline

• Motivation
  – Assisted Living
  – Vision as a Sensor
• FireFly Mosaic
• System Performance
• Home Activity Clustering
Aging Population

- 2000 US Census: 10 Million People over 65 Live Alone
  - Expected to more than double by 2050

- $70,912 per year for a private room in a nursing home ($194 per day)

- $25.32 per hour for in-home aid

- Quality of Life
  - People want to stay at home and enjoy their normal routine

- Similar trends in Europe (e.g. Italy) and Asia (e.g. Japan)
Where Can Technology Assist?

- Monitor Daily Patterns
  - Generate Sanitized Reports for Doctors and Caretakers

- Monitor Home Environment
  - Is the oven on? Is the temperature okay?

- Track Medication and Use

- Fall Detection

- Continual Medical Monitoring
Vision-Enabled Wireless Sensor Networks (WSN)

• Images Provide Extremely Rich Information
  – Local processing provides more than just an image

• Multiple Cameras Provide:
  – Greater Sensing Area Coverage
  – Increase Decision Confidence based on mutual information
  – Helps Address Occlusion (View Obstruction) Problems
Vision-Enabled WSN Challenges

- **Vision Challenges**
  - Color Constancy, Dynamic Lighting, Object Recognition, etc

- **System Challenges**
  - Limited Bandwidth
  - Limited Power
  - Group Coordination
  - Fusing Multiple Sensor Inputs
Outline

- Motivation
- FireFly Mosaic
  - Hardware Components
  - System Primitives
- System Performance
- Home Activity Clustering
FireFly Mosaic Architecture

- Wearable Mobile Device
- Software Services
- External Network
- Gateway Device
- Image Sensor Node
- FireFly Sensor Node

Real-Time and Multimedia Systems Laboratory
Sensor Network Description

• FireFly Sensor Node
  – ATmega1281, 8K Ram, 128K Rom
  – CC2420, 802.15.4 Radio

• Nano-RK RTOS (www.nano-rk.org)
  – Priority-based Fully Preemptive Operating System
  – Reservations
  – Open Source / Plain Vanilla C

• RT-Link
  – TDMA Link Layer Protocol
    • Collision Free TX and RX slots
  – Software Time Synchronization
FireFly Mosaic Node

CMUcam3 Image Sensor

Antenna

FireFly Sensor Node

Battery Pack
CMUcam3 Image Sensor

- 60 MHz ARM7TDMI Processor
- 64K RAM, 128K Flash
- 352 x 288 RGB Images
- Open-Source Image Processing Library
  - Color Blob Tracking, Frame Differencing, Convolutions, Histograms, Color Space Conversion, Down Sampling, Template Matching, JPEG compression
- Commercially Available
  - USA, Canada, France, Germany, Italy, England, Sweden, Finland, Czech Republic, Singapore and Spain
Software Stack

FireFly Node
- Activity Reporting
- Sensing
- Network Mgmt.

RT-Link Layer
Nano-RK RTOS
- ATmega1281 8-bit MCU
- 802.15.4

CMUcam3
- Activity Clustering
- CC3 Image Libs
- 60 MHz ARM7 MCU
- FIFO
- CMOS Camera
FireFly Mosaic Primitives

• Camera Connectivity Graphs

• Camera-Centric TDMA Scheduling Heuristics
  – Based on Camera Connectivity Graphs

• Time Synchronization Primitives

• Image Processing Tools
  – Image Transfer
  – Multiple Camera Image Region Correlation
Camera Network Graphs (CNG)

Physical View

Non-Overlapping CNG

Shared View CNG
Communication Scheduling

Communication Graph

Camera Network Graph

Camera Cluster Communication

Upstream Result Communication
Outline

- Motivation
- FireFly Mosaic
- System Performance
  - Timing Jitter
  - Image Transfer Quality and Frame Rate
  - Energy Distribution
- Home Activity Clustering
Timing Jitter

Camera View #1

Y (pixels)

X (pixels)

Camera View #2

Y (pixels)

X (pixels)

Combined View

Z (pixels)

Y (pixels)

X (pixels)

Error (Total Pix. Dist.)

Jitter (ms)
Sending Images

• If I want to send an image, what is the best resolution, compression level and network rate?

1 sec 2.5 sec
CPU vs Network Bandwidth

Network Transmit Time
(Assuming No MAC Overhead)

JPEG Compression Time
Image Transfer Given CPU and Network Timing Parameters

Given a quality level, a compression and resolution can be found for minimal image transmit time.
## Energy Distribution

<table>
<thead>
<tr>
<th>Component</th>
<th>Active (mW)</th>
<th>Idle (mW)</th>
<th>Sleep (mW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARM7 Core</td>
<td>108</td>
<td>10</td>
<td>0.25</td>
</tr>
<tr>
<td>ARM7 Peripherals</td>
<td>49.5</td>
<td>2</td>
<td>0.01</td>
</tr>
<tr>
<td>Frame Buffer</td>
<td>171</td>
<td>52</td>
<td>n/a</td>
</tr>
<tr>
<td>CMOS Camera</td>
<td>125</td>
<td>5</td>
<td>n/a</td>
</tr>
<tr>
<td>MMC</td>
<td>13.2</td>
<td>1</td>
<td>n/a</td>
</tr>
<tr>
<td>ATmega1281</td>
<td>6.6</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>CC2420</td>
<td>66.0</td>
<td>15</td>
<td>0.01</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>572.3</strong></td>
<td><strong>132.52</strong></td>
<td><strong>0.29</strong></td>
</tr>
</tbody>
</table>

Camera sensor consumes *2x the radio active power*
Outline

• Motivation
• FireFly Mosaic
• System Performance
• Home Activity Clustering
Home Activity Clustering

• Automatically Learn Activities
  – Cooking, Cleaning, Sleeping, Watching TV, Working, etc

• Monitor Transitions between Activities

• Easy Setup and Training
  – Cameras Placed “Arbitrarily”
Home Activity Clustering

1) Generate Camera Network Graph with Correlated Image Regions

2) Gaussian Mixture Model (GMM) Motion Detection

3) Local Activity Clustering

4) Global Activity Cluster Merging

5) Generate Model
Deployment in an Apartment

Data Collection:
- 8 nodes
- 1 Day of Training
- 3 Days of Data Collection
Correlate Camera Regions
Communication Scheduling

<table>
<thead>
<tr>
<th>Node</th>
<th>TX</th>
<th>RX</th>
</tr>
</thead>
<tbody>
<tr>
<td>Node 1</td>
<td>1</td>
<td>17</td>
</tr>
<tr>
<td>Node 2</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Node 3</td>
<td>2</td>
<td>16</td>
</tr>
<tr>
<td>Node 4</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>Node 5</td>
<td>7</td>
<td>11</td>
</tr>
<tr>
<td>Node 6</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Node 7</td>
<td>5</td>
<td>13</td>
</tr>
<tr>
<td>Node 8</td>
<td>3, 4, 6, 8</td>
<td>12, 14, 15</td>
</tr>
</tbody>
</table>
Activity Detection

- Gaussian Mixture Model
- Background Subtraction
- Down Sampling and Connected Component Analysis
Activity Clustering Sample Results

<table>
<thead>
<tr>
<th>State</th>
<th>Labeled Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>a1</td>
<td>Sitting on Couch</td>
</tr>
<tr>
<td>a2</td>
<td>Working at Table</td>
</tr>
<tr>
<td>a3</td>
<td>Television</td>
</tr>
<tr>
<td>a4</td>
<td>Working at Sink</td>
</tr>
<tr>
<td>a5</td>
<td>Bag Moving on Door</td>
</tr>
<tr>
<td>a6</td>
<td>Sleeping in Bed</td>
</tr>
<tr>
<td>a7</td>
<td>Checking Gateway CPU</td>
</tr>
</tbody>
</table>
Conclusions

- CMOS Camera Sensors are Becoming Cheaper and Consume Less Power

- Low-Cost Microcontrollers are Getting Powerful Enough to Perform Useful Local Image Processing

- Tightly Coordinated Application-Specific Sensor Network Communication Can Enable More Sophisticated Sensing

- Sensor Networking Systems Hold Great Potential for Assisted-Living Applications
  - Demonstrated using FireFly Mosaic
Questions?