Low Power Sensors for Urban Water System Applications

Prof. Amine Bermak

Workshop on “Smart Urban Water Systems” HKUST 2015
Architectural, material, and circuit level solutions for smart and low-cost Microsystems (sensors)
“Autonomous Intelligent Microsystems”

Autonomous integrated smart sensing systems capable of “sensing, processing and communicating”

- Wireless Sensing Platforms
  - RFID with sensors, wireless sensor Network (WSN) etc.

Challenges to be Addressed
Challenges in WSN

- 4 main challenging requirements in “install and Forget” Electronics
  - Requirement 1: Low-cost $\rightarrow$ Mainstream CMOS technology (system integration)
  - Requirement 2: Battery-less: replacement hinders massive deployment in remote locations, cost issue $\rightarrow$ Self-powered + ultra-low power operation
  - Requirement 3: No human intervention for maintenance $\rightarrow$ Self-calibration.
  - Requirement 4: Low-Power communication: Information rather than data communications $\rightarrow$ Intelligent converters & Compress before communication
Talk Agenda – Towards Autonomous sensors

- State-of-the-Art Water Pipe Sensing
- Time-Domain Imaging – Low power alternative
- Time-Domain Image Processing – Smart Vision Sensor
  - Compression, Histogram Equalization, Adaptive quantization
- Alternative ADCs: Analog-to-information AIC converters.
- Energy harvesting Image Sensors
- Conclusion
Challenges of pipe inspection: Turbulence, deployment, cost, power, Wireless Communication

Flow created by sinking current into Storm Sewer

- Deployment cost must be low, it is preferable to use existing tapping sites (2 – 6 inch) as insertion, extraction, and measurement sites.
- Low-cost → Miniaturization → Low-power and integration
- Wireless communication
The Pressure Pipe Inspection Company (PPIC)

Both acoustic and video measurement are available.

CCTV provides the best in terms of accuracy.

Video Head

- Both acoustic and video measurement are available.
- CCTV provides the best in terms of accuracy

Sahara Inspection System

Wall thickness measurement
Video Samples from Sahara System

Close-Up of a Joint Cap at the Insertion
Example of an outlet
Extraction Point, 24x24x12" Tee
Example of Large Air Pocket
SmartBall System

- Calibration is needed
- Data is not available for real-time diagnosis.
- The most expensive technology (USD$9/ft).
- Accuracy and range (limited by battery lifetime).
- Ball (1000-2000 US$) can be lost
Echologics Engineering Inc.

Wireless Transmitter | Hydrophone Installation

- Installed at the surface of the pipe (limitation).
- Poor sensitivity and limited dynamic range.
- Worst accuracy.
- Lowest in cost (USD $2/ft) and easiest to deploy.
Summary on the State-of-the-art

<table>
<thead>
<tr>
<th></th>
<th>PPIC Sahara</th>
<th>Pure Tech. SmartBall</th>
<th>Echologic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure resolution (gpm)</td>
<td>0.06</td>
<td>0.06</td>
<td>0.6</td>
</tr>
<tr>
<td>Range (km)</td>
<td>2</td>
<td>25</td>
<td>-</td>
</tr>
<tr>
<td>Installation</td>
<td>Tethered</td>
<td>Swimming</td>
<td>External</td>
</tr>
<tr>
<td>Cost (USD$/ft)</td>
<td>2-4</td>
<td>4-9</td>
<td>2-3</td>
</tr>
</tbody>
</table>

- Echologic system is the most cost efficient but present many issues: Accuracy, Deployment issues (surface of the pipe),
- Smart Ball offers very interesting features but “offline” approach, expensive
- Acoustic medium is prone to interference from: traffic, construction, and air pocket.
Objective: Multi-sensing platform

- Water In-Pipe Roving Sensors (WIRS) rove inside the pipe.
- Open-Flow Sensor Networks (OFSN) for monitoring open-flow areas.
Challenges for open flow video sensors

- Existing open flow sensors include Water Level Sensors and video camera.
- Very expensive, costly maintenance and hence deployed at very small scale and only downstream (Urban areas).
- Need a separate energy harvesting unit (costly).
- Transmit only few frames/day.
“Wireless Camera Network”
Can we deploy cameras at large scale?

Challenges:
- Vision sensors are power-hungry
- Transmit a lot of data (1.1Mpixel translates to 1GB/s)

Key questions:
- Can we use the light to self-power the sensor?
- Can we transmit information rather than data?

Objectives:
1. Ultra-low power vision sensors
2. Self-powered sensors (Sensors that can be reconfigured as energy harvesters)
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Conventional Image Sensor

- **Space-charge region grows**
- **Photons discharge photodiode**
- **Measure final photodiode voltage**
- **Reset photodiode - charge to $V_{\text{supply}}$**
- **Monitor photodiode voltage**
- **Reset - repeat**
Conventional Image Sensor

- The three phases operation (basic of APS, by E. Fossum at JPL).
  1. **Reset**: The switch is closed and the voltage $V_n$ is reset to $V_{dd}$
  2. **Integration**: The switch is open and charges are collected during $t_{int}$
  3. **Read-out**: At the end of integration the accumulated charges or voltage is read-out.

\[ Q = (i_{ph} + i_{dc})t_{int} \]

\[ V_n = V_{dd} - \frac{i_{ph} + i_{dc}}{C_l} t_{int} \]

- Read-out a voltage
- Fixed time

Slide 17  Workshop on “Smart Urban Water Systems” HKUST 2015
Can we learn from Biology?

Gain adjustment mechanism in the turtle cones (T.Delb.)

Information is coded in the time domain (pulse train)

Biological Inspirations

Alternative Solution
Fixed voltage

Time based sensor

High illumination

Low illumination

\[ V \]

\[ V_{int} \]

\[ t_{int1} \]

\[ t_{int2} \]

\[ t \]
Time-Based Vision Sensor

- Begin with charged photodiode
- Light reduces photodiode charge
- $V_n$ reaches $V_{ref}$: Comparator triggers pulse can be seen as a time information
- Feedback pulse restores charge
PWM Sensor: Principle

- The comparator pulse is used as a write pulse to the memory which will then write in from the global data bus.
- The comparator pulse is also used to reset the voltage of the photodiode to Vdd → Feedback circuit.
## Prototype Chip

### Control circuitry:
- NUQ circuit
- Blanking circuit

<table>
<thead>
<tr>
<th>Feature</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resolution</td>
<td>64 x 64</td>
</tr>
<tr>
<td>Pixel size</td>
<td>45 x 45 (\mu\text{m}^2)</td>
</tr>
<tr>
<td>Fill-factor</td>
<td>12%</td>
</tr>
<tr>
<td>Image array area</td>
<td>95% of the chip area</td>
</tr>
<tr>
<td>Die size</td>
<td>15 mm(^2)</td>
</tr>
<tr>
<td>Dynamic range</td>
<td>100 dB</td>
</tr>
<tr>
<td>Process</td>
<td>0.35 um CMOS tech</td>
</tr>
</tbody>
</table>
Sample Images and results
Quantization boundaries are adjusted as the pixels’ spikes are received.
The quantization levels are adapted to the image statistics.
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Analog to Information Imager

- Key idea: Compression is performed prior to ADC
- Analog read-out attempts to remove redundancy.
- Image is divided into blocks
- Useful information within the block is extracted in analog domain.
- ADC only operates on useful data
Analog to Information Imager

- If the gradient is within a threshold: **uniform pattern** (UP), only the $u$ is sent
- Otherwise it’s an **edge pattern** (EP) and the mean, $G$, and the bit-image are sent
- Analog switch cap techniques are used to compute $u$, $G$ and **ADC is ON only when needed** (EP) (10% of the time).

$$u(4k, 4l) = \frac{1}{4} \times (L1 + L0 + R1 + R0)$$

$$G(4k, 4l) = \frac{1}{4} \times (|L0 - R1| + |L1 - R0|)$$

A single quadrant is processed in one read-out cycle.

Switched Cap techniques are used to compute the mean and quadrants.

SAR-SS is used for best trade-off between power and area.

ADC is On only for Edge Block → power saving.
### Prototype Measurement

<table>
<thead>
<tr>
<th>Compressed</th>
<th>Raw</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process</td>
<td>0.18 μm 1P6M Mixed-signal CMOS</td>
</tr>
<tr>
<td>Supply voltage</td>
<td>3.3 V, 1.8 V</td>
</tr>
<tr>
<td>Chip clock</td>
<td>4 Mhz</td>
</tr>
<tr>
<td>Imager size</td>
<td>816 × 640</td>
</tr>
<tr>
<td>Frame rate</td>
<td>111 fps</td>
</tr>
<tr>
<td>Pixel size</td>
<td>1.85 μm × 1.85 μm</td>
</tr>
<tr>
<td>Fill factor</td>
<td>13 %</td>
</tr>
<tr>
<td>Dark current</td>
<td>&lt;4307 e⁻/sec</td>
</tr>
<tr>
<td>Saturation level</td>
<td>7718 e⁻</td>
</tr>
<tr>
<td>Conv. gain</td>
<td>35.76 μV/e⁻</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>309 e⁻/Lux,sec @ 1167 Lux</td>
</tr>
<tr>
<td>Dynamic range</td>
<td>46 dB</td>
</tr>
<tr>
<td>ADC resolution</td>
<td>8b</td>
</tr>
<tr>
<td>Temporal noise</td>
<td>2 LSB&lt;sub&gt;rms&lt;/sub&gt;</td>
</tr>
<tr>
<td>Power</td>
<td>0.69 mW</td>
</tr>
<tr>
<td>Energy</td>
<td>12 pJ/pixel</td>
</tr>
<tr>
<td>Data rate</td>
<td>3 bpp (1 bpp after FPGA)</td>
</tr>
<tr>
<td>PSNR</td>
<td>20 dB</td>
</tr>
</tbody>
</table>

We can achieve 0.7BPP and 30dB SNR

Power level of less than 1mW (12pJ/p)

(lowest ever reported power for imager)

We can achieve about 111fps

<table>
<thead>
<tr>
<th>Reference</th>
<th>[19]</th>
<th>[25]</th>
<th>[26]</th>
<th>[10]</th>
<th>[17]</th>
<th>[16]</th>
<th>This work</th>
</tr>
</thead>
<tbody>
<tr>
<td>Algorithm</td>
<td>CS</td>
<td>Lossless</td>
<td>Haar wavelet</td>
<td>QTD</td>
<td>SPIHT</td>
<td>DCT</td>
<td>VPIC</td>
</tr>
<tr>
<td>Architecture</td>
<td>Column level</td>
<td>Column level</td>
<td>Column level</td>
<td>Chip level</td>
<td>Pixel level</td>
<td>Pixel level</td>
<td>Column level</td>
</tr>
<tr>
<td>ADC</td>
<td>$\Delta \Sigma$</td>
<td>Single slope</td>
<td>$\Delta \Sigma$</td>
<td>Single slope</td>
<td>none</td>
<td>none</td>
<td>SAR</td>
</tr>
<tr>
<td>ADC resolution</td>
<td>12b</td>
<td>8b</td>
<td>8b</td>
<td>8b</td>
<td>-</td>
<td>-</td>
<td>9b</td>
</tr>
<tr>
<td>Technology ($\mu$m)</td>
<td>0.15</td>
<td>0.35</td>
<td>0.35</td>
<td>0.35</td>
<td>0.5</td>
<td>0.5</td>
<td>0.18</td>
</tr>
<tr>
<td>Supply (V)</td>
<td>3.3, 2.0, 1.8</td>
<td>3.3</td>
<td>3.3</td>
<td>3.3</td>
<td>-</td>
<td>3.3</td>
<td>3.3, 1.8, 1.2</td>
</tr>
<tr>
<td>Area (mm$^2$)</td>
<td>2.9×3.5</td>
<td>2.6×6.0</td>
<td>4.4×2.9</td>
<td>3.3×3.2</td>
<td>2.3×2.3</td>
<td>2.4×1.8</td>
<td>2.16×1.36</td>
</tr>
<tr>
<td>Resolution</td>
<td>256×256</td>
<td>80×44</td>
<td>128×128</td>
<td>64×64</td>
<td>33×25</td>
<td>104×128</td>
<td>816 × 640</td>
</tr>
<tr>
<td>Pixel pitch ($\mu$m)</td>
<td>5.5</td>
<td>32</td>
<td>15.4</td>
<td>39</td>
<td>69</td>
<td>13.5</td>
<td>1.85</td>
</tr>
<tr>
<td>Fill factor (%)</td>
<td>-</td>
<td>18</td>
<td>28</td>
<td>12</td>
<td>21</td>
<td>46</td>
<td>13</td>
</tr>
<tr>
<td>Pixel circuit</td>
<td>4T pinned PD</td>
<td>8T</td>
<td>7T</td>
<td>PWM DPS</td>
<td>Heterogenous</td>
<td>Floating gate</td>
<td>3T APS</td>
</tr>
<tr>
<td>DR (dB)</td>
<td>78</td>
<td>-</td>
<td>-</td>
<td>&gt;100</td>
<td>-</td>
<td>-</td>
<td>34, 46</td>
</tr>
<tr>
<td>Frame rate (fps)</td>
<td>120</td>
<td>1920</td>
<td>435</td>
<td>30</td>
<td>-</td>
<td>10000</td>
<td>25</td>
</tr>
<tr>
<td>Throughput (Mp/s)</td>
<td>7.9</td>
<td>125.8</td>
<td>1.5</td>
<td>0.5</td>
<td>-</td>
<td>8.3</td>
<td>0.3</td>
</tr>
<tr>
<td>Power (mW)</td>
<td>93.1</td>
<td>96.2</td>
<td>150</td>
<td>26.2</td>
<td>17</td>
<td>0.25 @ 30fps</td>
<td>2</td>
</tr>
<tr>
<td>Energy (pJ/pixel)</td>
<td>11838</td>
<td>765</td>
<td>21973</td>
<td>53304</td>
<td>-</td>
<td>10101</td>
<td>6010</td>
</tr>
<tr>
<td>Compression ratio</td>
<td>1</td>
<td>16</td>
<td>&lt;1.5</td>
<td>3.5</td>
<td>8</td>
<td>9.1</td>
<td>80</td>
</tr>
<tr>
<td>PSNR (dB)</td>
<td>-</td>
<td>32.5</td>
<td>-</td>
<td>32</td>
<td>15</td>
<td>23</td>
<td>24.5</td>
</tr>
</tbody>
</table>

- Lowest energy/power consumption ever reported due to AIC and novel circuit techniques (dynamic circuits).
Polarization Imaging

Fully integrated real-time CMOS polarization image sensor


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Power is still the main issue

- Portable system and wireless sensing platforms lifetime is usually limited battery capacity
- Considerations for cost and system lifetime
  - Low power/energy consumption
  - Passively powered/energy harvesting capability
Using the same photodetector for Sensing/Energy harvesting: Improved FF and pixel size

=> Key Idea – Time domain imaging
Proposed concept


Avalanche Energy generation
Reconfigurable array: Performance summary

- Incorporate sensing and harvesting capabilities is feasible
- Power generated vs. power consumed: duty cycle of about 1%

<table>
<thead>
<tr>
<th></th>
<th>[24]</th>
<th>[25]</th>
<th>This work</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process</td>
<td>0.35$\mu$m</td>
<td>0.35$\mu$m</td>
<td>0.35$\mu$m</td>
</tr>
<tr>
<td>Array Size</td>
<td>160$\times$240</td>
<td>128$\times$96</td>
<td>32$\times$32</td>
</tr>
<tr>
<td>Supply Voltage</td>
<td>3.3V/1.5V</td>
<td>1.35V</td>
<td>1.5V</td>
</tr>
<tr>
<td>Pixel Size</td>
<td>5.6$\times$5.6$\mu$m</td>
<td>10$\mu$m$^2$</td>
<td>15$\times$15$\mu$m</td>
</tr>
<tr>
<td>Fill Factor</td>
<td>32$%$</td>
<td>18.5$%$</td>
<td>21$%$</td>
</tr>
<tr>
<td>Frame Rate</td>
<td>N/A</td>
<td>9.6fps</td>
<td>up to 21fps</td>
</tr>
<tr>
<td>Dynamic Range</td>
<td>68dB</td>
<td>53.7dB</td>
<td>&gt;84.9dB</td>
</tr>
<tr>
<td>FPN</td>
<td>0.52$%$</td>
<td>0.12$%$</td>
<td>18.42$%$</td>
</tr>
<tr>
<td>Power Consumption</td>
<td>3.12mW$^{(2,5)}$</td>
<td>0.42$\mu$W$^{(1)}$</td>
<td>15.8$\mu$W$^{(2,3)}$</td>
</tr>
<tr>
<td></td>
<td>55.2$\mu$W$^{(2)}$</td>
<td></td>
<td>8.83$\mu$W$^{(2,4)}$</td>
</tr>
<tr>
<td>Normalized Power</td>
<td>N/A</td>
<td>3.6$^{(1)}$</td>
<td>753$^{(2,3)}$</td>
</tr>
<tr>
<td>(pW/frame/pixel)</td>
<td></td>
<td>468$^{(2)}$</td>
<td>821$^{(2,4)}$</td>
</tr>
<tr>
<td>Power Generation (nW)</td>
<td>No</td>
<td>No</td>
<td>35.6 @ 29kLux</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>4.7M$\Omega$ load</td>
</tr>
</tbody>
</table>

(1) Array only (2) Whole chip (3) Full res. (4) Half res. (5) Estimated

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Conclusion

◆ **Smart water system** is a multi-disciplinary area: Requires collaboration from different disciplines.

◆ Electronic Engineers have a **key role to play particularly**: Sensors design and communications

◆ Smart Water Systems need to be equipped with **sensing, processing and wireless comm** and need to be low power/harvest energy.

◆ **Time-domain encoding** (in analogy with biological systems) presents a number of advantages:
  - **Immunity against noise**: as data are represented in digital domain.
  - **Reduced power**: as data can be represented in single transition.
  - **Simplified processing**

◆ “The difficulties posed by integrating: **sensing, processing and Communications** for smart water system applications will eventually lead to more opportunities for innovations”
Acknowledgments

- **My students** who have significantly contributed to this work
- **HK RGC** for providing funding for this research program.