Next Generation Cyber-Physical Water Distribution Systems

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Overview of Achievements

Data Reduction & Edge Processing
- Anomaly detection
- Lossless compression & Compressive sensing

Evaluation Platforms
- WaterBox: small scale testbed
- BendoBox: Low power wide area communication

Automatic Control
- Event-based Communication
**Achievements**
1. Implemented in C code which requires up to 10KB at runtime including lossless compression-miniLZO
2. Average compression rate **55%** and **32%** for pressure and vibration data respectively
3. Raw data size 5,526,864 values and compression rate 87,715 values => **98.42% computation reduction**
4. Content independent data analysis because compression rate is a normalized value [0,1)

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Water Pressure Data

Pipe vibration data
Adaptive Edge Analytics & Burst Localization

- Event-based communication
- Combination of edge decision making and server/cloud-side burst localization detection
- Achievements
  - ~98% computation reduction
  - ~99% communication reduction
  - 0.5m burst localization accuracy
  - Close to real time

<table>
<thead>
<tr>
<th>Node</th>
<th>Average Compression Rate</th>
<th>Anomaly Detection Accuracy</th>
<th>Communication Savings (Transmit Compressed Data)</th>
<th>Communication Savings (Transmit only Timestamps)</th>
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<tbody>
<tr>
<td>Node A</td>
<td>28.01%</td>
<td>90%</td>
<td>79.26%</td>
<td>99.88%</td>
</tr>
<tr>
<td>Node B</td>
<td>30.06%</td>
<td>91%</td>
<td>87.69%</td>
<td>99.93%</td>
</tr>
<tr>
<td>Node C</td>
<td>39.25%</td>
<td>100%</td>
<td>92.22%</td>
<td>99.95%</td>
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Simulate Bursts in Real Rig

- NEC Tokin Ultrahigh-Sensitivity Vibration Sensor
- Intel Edison Development Board

Event-based communication

Intel Edison Development Board

NEC Tokin Ultrahigh-Sensitivity Vibration Sensor

Average Compression Rate | Anomaly Detection Accuracy | Communication Savings (Transmit Compressed Data) | Communication Savings (Transmit only Timestamps) |
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±0.5m accuracy in localizing the burst
Lossless vs Lossy Compression

Adaptive Compressive Sensing (CS) in Smart Water Network

With lossess compression we achieved on average 55% compression rate (CR) while Compressive Sensing achieves 80% CR with 0.0009 error.

Flow Diagram

Original and reconstructed segments for sensor node 2 using the NESTA algorithm for (a) 2300 samples (~36 sec) and (b) 19 samples (~296 msec).

Average RMSRE as a function of the CS sampling rate.
Optimal Compression Rate Modelling

\[
\begin{align*}
\min f_1 &= \text{RMSRE}(\text{CR}(t_1)) \\
\max f_2 &= B(t_1)
\end{align*}
\]

with the constraints:

\[
\begin{align*}
g_1 &= \text{RMSRE}(\text{CR}(t_1)) - \text{RMSRE}(\text{CR}_{i}^0(t_1)) \leq 0, \\
&\forall i \in S, j \in \mathbb{N}^+ \\
g_2 &= -B_i(\text{CR}(t_1)) \leq 0, \\
&\forall i \in S, j \in \mathbb{N}^+ \\
g_3 &= B_i(\text{CR}(t_1)) - B_{\text{max}} \leq 0, \\
&\forall i \in S, j \in \mathbb{N}^+ \\
g_4 &= -\text{RMSRE}(t_1) \leq 0, j \in \mathbb{N}^+ \\
g_5 &= B_i(t_1) - B_i(t_{j-1}) - CR_i(t_j)E_i^i(t_j) - E_i^0(t_j) \leq 0, \\
&\forall i \in S, j \in \mathbb{N}^+ \\
CR_i(t_1) &\leq CR(t_1) \\
CR_i(t_1) &\leq C_{\text{max}} 
\end{align*}
\]

Multi-objective Genetic Algorithm Solution

1. \text{Objective: minimize } f_1, \text{ maximize } f_2
2. \text{Constraints: } g_1, g_2, g_3, g_4, g_5
3. \text{Initial population}\ x_0 = \{x_1, x_2, \ldots, x_n\}
4. \text{Evolve for } n \text{ generations} \\
5. \text{Select the best solution}\ x^* = \text{Select}(x_0) \\
6. \text{Output}\ x^* \\
7. \text{Evaluate } f_1(x^*), f_2(x^*)

Achievements
- Battery Life Extension \(\sim 46\%\)
- Communication Reduction \(\sim 66\%\)
- Reconstruction Error Minimization \(-2.80 \cdot 10^{-4}\) mmH2O (pressure)
BentoBox: A Battery-Driven Long-Range Hybrid Communication Sensor/Actuator Node

- Intel Edison
- Communication Modules
  - Lora (no standard)
  - Xbee868 (Zigbee)
  - Nwave (Weightless-N)
  - Wifi & Bluetooth (Embedded to Edison)
  - Two extra UART to support more modules (i.e. 4G)
- Power Consumption Sensors and Management modules
- SD Card Support
- Nwave Host PCB

Upgraded BentoBox Version for Fair Communication Technologies Comparison
Custom made alloy box supporting USB and three individual SMA antennas

NWave Host PCB
Examined Parameters under Different Environments:

1. Range
2. Power Consumption
3. Throughput & Data Rate
4. Delays
5. Success Rate
WaterBox: Monitoring & Control Water Network Testbed

Hardware and Software Upgrades
1. Local Wireless Network Infrastructure
2. Deployment of Water Temperature, Level Sensors, & Power Management System
3. Server-Side Application: Visualizing and Storing
Automatic Control: Event Based Communication

Combining **communication** and **control theory** to enable 4 event-based communication techniques.

**Control Scenario**

"Control water network valves and pumps to provide the appropriate amount of water to each DMA by:
(a) Covering QoS requirements (**pressure and flow lower bounds**),
(b) Ensuring robust water network operation without leakages and bursts (**pressure and flow upper bounds**) 
(c) Minimizing **pumping energy consumption** through an efficient scheduling by exploiting demand changes along the time."

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<thead>
<tr>
<th></th>
<th>Actuations</th>
<th>Aggr. Valve Movement</th>
<th>Comm. Rx</th>
<th>Comm. Tx</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>EBC A</strong></td>
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<td>18%</td>
<td>53%</td>
<td>1%</td>
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<tr>
<td><strong>EBC B</strong></td>
<td>11%</td>
<td>9%</td>
<td>15%</td>
<td>15%</td>
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<tr>
<td><strong>EBC C</strong></td>
<td>35%</td>
<td>25%</td>
<td>57%</td>
<td>64%</td>
</tr>
<tr>
<td><strong>EBC D</strong></td>
<td>15%</td>
<td>23%</td>
<td>50%</td>
<td>55%</td>
</tr>
</tbody>
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Savings Compare to Periodic Control (%)

Combining **communication** and **control theory** to enable 4 event-based communication techniques.