CSOnet: A Metropolitan Scale Wireless Sensor-Actuator Network

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WIDE kickoff - Siena Italy - Sept 26, 2008.
Outline

- Combined Sewer Overflow Problem
  - In-line Storage using CSOnet
- CSOnet System Hardware
- CSOnet Middleware
- Real-time Control Strategy
- Future Directions
CSOnet Project Background

- CSOnet concept: use of wireless sensor-actuator networks for distributed monitoring and control of combined sewer overflow (CSO) events.
- Concept originally created at Notre Dame (Lemmon/Talley)
  - Funded through the State of Indiana’s 21st Century Technology Fund
- Academic, private sector, and public sector partners

  150+ Sensor network monitoring 13,000 acres (summer 2008)
- Actuation component scheduled for completion in summer 2009
Combined Sewer Overflow Events

- **Combined sewer overflow (CSO) events** occur when a municipality dumps untreated water from combined storm and sanitary sewer flows into a river/stream.

- "Such ‘exceedances’ can pose risk to human health, threaten aquatic life and its habitat, and impair the use and enjoyment of the Nation’s waterways."


- EPA fines for CSO events
  - 1994 CSO Control Act
  - Fines are Significant

- Problem is Large-scale
  - Over 772 cities nationwide
Solution Strategies

Sewer Separation

Expansion of WWTP

Off-line Storage Tunnels
Chicago’s TARP project

These strategies all require significant investment in new infrastructure
In-line Storage

- Store excess water in unused parts of the system
- Reduces need for infrastructure enhancement
- Requires real-time monitoring and control of flows

Reduced inflow to Manhole B allows us to increase inflow through Manhole A
Centralized Model Predictive Control

- Pre-1974 combined sewer trunklines
- Interceptor Sewer to Wastewater Treatment Plant
- Monitoring and Control over SCADA network
Distributed In-line Storage

- Distributed Feedback Control of In-line Storage sets up interacting “control zones”
- Gateways connect to Internet to provide global monitoring of system
Ireland/Miami Network (Summer 2005)

Prototype system controls retention basin based on flow measurements at CSO 22 diversion structure

- 7 Relay Rnodes (radios)
- 3 Instrumentation Inodes (sensors)
- 1 Gateway Gnode connect to the internet
- Automated valve
- Network is fully deployed and operational

First month of service the system prevented 2 million gallon CSO discharge

Continuous operation since summer 2005.

Slide provided by courtesy of EmNet LLC
South Bend CSOnet

PHASE 1: (summer 2008)
- Monitor 36 outfalls, 27 interceptor locations, 42 trunkline locations, and 5 basins

PHASE 2: (summer 2009)
- Control at least 18 outfalls
- Control storage in retention basins
- Control remediation pumps wet weather discharges
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CSOnet Architecture

- Hierarchical network
  - Unicasts in low level subnets, Multicasts over higher level
  - 3 types of Nodes - Gnode, Rnode, Inode

Mesh Radio Subnet
sensor data flows to GNode which manages the actuator

GNodes broadcast their information to neighboring GNodes.
Actuators

Actuated Valve

Pneumatic Bladder

Slide provided by courtesy of EmNet LLC
Composite Manhole Cover

- Integration of processor, radio transceiver, and antenna into manhole cover
  - William Chappell - Purdue

- Manhole is extremely corrosive environment
- Initial prototypes “rusted” away with a few months
Intelligent Radio Antenna

- Municipal deployments must cope with fading effects due to multipath interference.
- Intelligent switching between multiple antennae
Chasqui Module

- Inode and Rnode are based on the Chasqui Module

- Based on UCB Mica2 Module
- MaxStream Radio (115 kbps/900 MHz)
- Rugged Sensor-Actuator I/F
- Precision Real-time Clock (2ppm drift)
- TinyOS Compatible
GNode

- Gateway Node consists of
  - Single Board Computer (SBC) xx86 - compact Linux
  - Chasqui Node (radio - actuator interface)
  - Cellular connectivity to Internet.

![Single Board Computer](image1)

![Chasqui Module](image2)
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Middleware for Mesh Radio Networks

- Middleware maintains an network abstraction that can be easily used by application software
  - Time-slotted publish-subscribe network abstraction

- Middleware services
  - Clock Synchronization
  - Networking Service
  - Routing Service
  - Power Management Service
  - Reprogramming Service

- Programmed using TinyOS
Networking Service

- Network service uses directed flooding to create a gradient table
Stateless Gradient-based Routing

- Broadcast to all upgradient nodes
Congestion Issues

- **CSOnet** has two types of subnets:
  - large diameter with few sensors
  - small diameter with many sensors

- Small diameter networks can have congestion problems unless the data received at the gateway is buffered

Subnet 23 Throughput Results

<table>
<thead>
<tr>
<th>Node</th>
<th>Throughput with buffering</th>
<th>Throughput no buffering</th>
</tr>
</thead>
<tbody>
<tr>
<td>G.23.1</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>I.23.1</td>
<td>46%</td>
<td>89%</td>
</tr>
<tr>
<td>I.23.2</td>
<td>56%</td>
<td>91%</td>
</tr>
<tr>
<td>I.23.3</td>
<td>77%</td>
<td>93%</td>
</tr>
<tr>
<td>I.23.4</td>
<td>91%</td>
<td>100%</td>
</tr>
<tr>
<td>I.23.5</td>
<td>75%</td>
<td>85%</td>
</tr>
</tbody>
</table>
Power Management

- Management of system duty cycle
  - 2 percent duty cycle - 5 minute period
  - During sleep cycle, microprocessor put into deep sleep mode. External timer is used to wake the system back up

- Requires tight “clock” synchronization
  - Chasqui uses Dallas DS3231 RTC with 2 ppm drift.
  - Resync network clocks every six hours

- Chasqui service lifetime
  - 2 years between service
  - 3.6 volt - 19 amp-hour lithium source
  - Currently more cost effective to replace batteries than to use renewable power systems such as solar.
Wireless Reprogramming

- “Stream” Reprogramming protocol developed by Dr Saurabh Bagchi (Purdue)
- Less overhead than Deluge
- Stream segments the program image into Stream-RS (Stream Reprogramming Support) and Stream-AS (Stream Application Support)

Stream-RS
  - Core reprogramming component
  - Preinstalled, before deployment, in all nodes

Stream-AS
  - A small subset of reprogramming component that is attached to the user application
  - Instead of wirelessly transferring through the network user application plus the entire reprogramming component, Stream transfers Stream-AS plus the user application
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Complete Dynamic Wave Model

- **Momentum Equation**

\[ 0 = gA \frac{\partial H}{\partial x} + \frac{\partial Q}{\partial t} - \sigma \frac{Q}{A} \left( 2 \frac{\partial A}{\partial t} + \frac{Q}{A} \frac{\partial A}{\partial x} \right) + gAS_f \]

- **Continuity Equation**

\[ \frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = 0 \]

- **Manning’s equation**

\[ S_f = \frac{(n/1.49)^2}{AR^{4/3}} Q|V| \]

where \( V = \frac{Q}{A} \) = flow velocity

\( R = \) pipe radius

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Simplified Wave Model

- Flow Resistance Equation (momentum equation)

\[ kQ^2 = H_u - H_d \]

where \( k = \frac{L(n/1.49)^2}{A^2 R^{4/3}} - \frac{\sigma}{gA^3} (A_d - A_u)R \)

- Simplified Continuity Equation

\[ a_i \frac{\partial H_i}{\partial t} = \sum Q_{\text{in}} - \sum Q_{\text{out}} + w_i \]

Where \( a_i = \) water surface area
Distributed Real-time Control

- Model Variables
  - \( w_i \) = storm inflow
  - \( O_i \) = overflow
  - \( u_i \) = diverted flow
  - \( H_i \) = water height (head)
  - \( Q_i \) = pipe flow rate

Optimal Control Problem

\[
\begin{align*}
\max_{u_i} & \quad \sum_{i=1}^{N} \int_{0}^{T} C_i u_i(t) \, dt \\
\text{subject to} & \quad \dot{H}_i = u_i + Q_{i-1} - Q_i \\
& \quad 0 = H_i - H_{i+1} k_i Q_i^2 \\
& \quad 0 \leq u_i \leq w_i \\
& \quad \overline{H}_i \geq H_i \\
& \quad \overline{Q} \geq \sum_{j} u_j \\
\end{align*}
\]

- Maximize “diverted flow”
- Subject to:
  - Conservation of Mass
  - Conservation of Momentum
  - Admissible control
  - No flooding
  - WWTP capacity limit

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Supervisory Control Strategy

Control Selection Algorithm

- Assume costs are ordered as $C_{i+1} < C_i$

- If node $i_j$ is flooded

  $$u_{i_j} = Q_{i_j} - Q_{i_j-1}$$

- If node $i_j$ is not flooded then

  $$u_{i_j}(\tau) = \begin{cases} 
  w_{i,j} & \tilde{Q} - W \geq w_{i,j} \\
  \tilde{Q} - W & 0 < \tilde{Q} - W < w_{i,j} \\
  0 & \tilde{Q} = W 
  \end{cases}$$
Supervisory Control Results

“Optimal” Supervisory Control Strategy

- Open valves until “flooding” constraint is active
- Then reduce diverted inflow to prevent violation of flooding constraint

<table>
<thead>
<tr>
<th>Storm</th>
<th>Existing System Overflow (ft³ x 10⁶)</th>
<th>Controlled System Overflow (ft³ x 10⁶)</th>
<th>Overflow Volume Decrease (ft³ x 10⁶)</th>
<th>Overflow Decrease (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Storm 1</td>
<td>1.50</td>
<td>1.10</td>
<td>0.40</td>
<td>27%</td>
</tr>
<tr>
<td>Storm 2</td>
<td>3.46</td>
<td>2.68</td>
<td>0.78</td>
<td>23%</td>
</tr>
<tr>
<td>Storm 3</td>
<td>13.6</td>
<td>9.45</td>
<td>4.15</td>
<td>31%</td>
</tr>
</tbody>
</table>

Table A. Scenario A—Moving Uniform Rainfall
Pressure-based Feedback

- Actual system only has “pressure” (head) measurements
- Decentralized Pressure-based Controller used to enforce flooding constraint.
- Model of Head Level Dynamics
- Limitation: the diverted flow must be positive
Input-Output Behavior of Node

- Testbed Experiments showed that “head” level dynamics had at least 3 state variables
  - Head level, downstream flow rate, water stored in upstream link

Ellipsoidal shape of response implies additional energy storage
Head Model Identification

- Drive interceptor line with a “persistently exciting” input signal
- Gather input/output data for a “design” set and a “test” set.
- Use “design” data set and Matlab’s SysID toolbox to identify a state-based model
- Test that model against the “test” data set.

\[
G_8(s) = \begin{bmatrix}
0.9899 & 0.002 & 0.012 & 0.114 & 0.002 \\
-0.048 & 1.004 & 0.046 & 0.453 & 0.385 \\
0.063 & -0.0001 & 0 & 0 & 0
\end{bmatrix}
\]
Pressure-based Controller Design

- Disturbance rejection problem
- Loopshaping Design
  - Often yields PID-type control
- State-based controller

\[ K_i(s) = \begin{bmatrix} \hat{A}_i & \hat{B}_i \\ \hat{C}_i & \hat{D}_i \end{bmatrix} \]

\[ K_i(s) = \begin{bmatrix} 1.97 & -0.10 & 4 \\ 1 & 0 & 0 \\ -2.38 & 2.39 & 400 \end{bmatrix} \]

Loopshaping Design Plot

\[ G(s) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \]

Controller design is shown in the diagram.
Flooding under Supervisory Control

- Supervisory strategy is only “necessary” for optimality
- This strategy can lead to localized flooding in a flooded node loses “control authority”

Upstream flow causes node 11 to flood, even though there is no storm water entering node 11.
Flood Prevention

- Flooding may occur if node loses “control authority”
- Flood Prevention Protocol
  - If node $i$ is about to flood and has no remaining control authority
    THEN request upstream node to “hold” at its current head level.

![Diagram of Flood Prevention](image)
Simulation Results - Head Levels

Flooding at node 11 prevented this time, by holding the upstream node's head level.
Simulation Results - Total Overflows ($\text{ft}^3$)

<table>
<thead>
<tr>
<th></th>
<th>Passive Threshold</th>
<th>Supervisory Control</th>
<th>Decentralized Control</th>
<th>Percent Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>STORM C</td>
<td>405980</td>
<td>123750</td>
<td>152490</td>
<td>60%</td>
</tr>
<tr>
<td>STORM D</td>
<td>1206900</td>
<td>770430</td>
<td>883560</td>
<td>26%</td>
</tr>
<tr>
<td>STORM E</td>
<td>2682800</td>
<td>2050200</td>
<td>2141200</td>
<td>20%</td>
</tr>
<tr>
<td>STORM G</td>
<td>9280600</td>
<td>8068800</td>
<td>8413400</td>
<td>9%</td>
</tr>
</tbody>
</table>

- 10-60 percent reduction in total overflow
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Moving toward Distributed Local Control

- CSOnet’s controller
  - High-level supervisor to enforce optimality
  - Low-level decentralized controllers to enforce safety (no flooding)
  - We could do better with “distributed” local controls

![Diagram of a storm water management system]

- Head level information from upstream and downstream nodes

Pressure Sensor (water height)

INODE

OverFlow

Valve

Storm Flow
Need for Real-time Middleware

- Distributed control requires hard/firm real-time message delivery
- It may be possible to develop real-time middleware services in isolation, but real-time guarantees are quickly lost as additional services are added.
- The lack of composable middleware services capable of providing end-to-end hard/firm real-time guarantees limits is an obstacle to the use of low-level distributed control.
- Future work is moving in this direction
- Additional CSOnet Developments
  - Deployment of Actuation in South Bend System (summer 2009)
  - Two additional Indiana cities are installing CSOnet
- Monitoring and Control of Civil Infrastructure
  - Bridge monitoring
  - Leak detection in water distribution networks
CSOnet Website

Overflow Event

Sensor Location
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