Towards the Building Integrated Operating System

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“Energy permits things to exist; information, to behave purposefully.”
W. Ware, 1997
Pervasive monitoring of a large complex load
To understand energy spend, reduce it, forecast
and optimize in concert with an intelligent grid
Towards an “Aware” Energy Infrastructure

Baseline + Dispatchable Tiers

Oblivious Loads

Generation → Transmission → Distribution → Demand

Non-Dispatchable Sources

Aware Interactive Loads

Communication
Where to Start?

• **Buildings**
  - 72% of electrical consumption (US),
  - 40-50% of total consumption,
  - 42% of GHG footprint
  - US commercial building consumption doubled 1980-2000, 1.5x more by 2025 [NREL]

• Where Coal is used

• Prime target of opportunity for renewable supplies
Load-following Supply

Cal ISO Daily Peak Loads
January 1, 2000 - December 31, 2000

Peak Day August 16 -
43.5 GW

Commercial AC
Residential AC
Growing proportion of renewables leads to higher price volatility. October 2008 to March 2010: >90 hours with negative prices; highest price reached: +€500/MWh, lowest -€500/MWh

Source: EEX spot prices.
Traditional Building Models

- Occupant Loads
- Process Loads
- Transport
- Light
- Electrical
- HVAC
- BMS

8/25/2010 LoCal Retreat 5-10
Integrated Energy View of Buildings
Stages of Energy Effectiveness

• Waste elimination
  – Do Nothing Well !!!

• Power Proportionality
  – Power : Performance (utilization)
  – Partial Load - from nothing to peak

• Sculpting
  – Identify the energy slack and utilize it

• Negotiated Grid / Load / Human Interaction
  – Plan, Forecast, Negotiate, Manage
Our Buildings

Do nothing poorly

- Wasteful
- <20 % Power Prop.
- Predictable
- Sculptable?
Our Buildings

Use

Design

Annual Consumption

Environmental

Operational

Soda Hall Power Consumption 494 KW

chart by amCharts.com

HVAC

Lighting

IT and Plug Load

PDUs, CRACs

Servers

Custom period: 2009-01-01 to 2009-12-31

8/25/2010 11
Building-Scale Monitoring Architecture

The 3 Views

Environments & Activity

Climate Plant

Load Tree

CT: mains power monitoring

panel level power monitoring

ACme: plug load energy monitor and controller

Building Environmental Manufacturing Infrastructure

Temperature

Humidity

Pressure

Vibration
Audit Methodology

• **Measure** the envelope
• **Map** the underlying load tree
• **Identify** major load points
• **Model, Instrument, Disaggregate**
  - specific instrument and analysis selection
• **Apply recursively**
Methodology Experience

• Guidance Criteria
  - Disambiguation goal isolates usage
  - Reconfiguration focuses on opportunities for mitigation
  - Sculptability focuses on shiftable loads

• Slices Alternative
  - instrument slice from supply to consumption

• Opportunism
  - Measure the best you can get ahold of
Waste Less

Building-Two Grid (B2G) Cory Hall Test Bed

Kick-Off

MBCx implementation

Cory Baseline

ML tool move

ML Fire

Winter Curtailment

Post-Instal Metering

Power Shutdown Meter Installation

8/15/09 9/15/09 10/15/09 11/15/09 12/15/09 1/15/10 2/15/10 3/15/10 4/15/10 5/15/10 6/15/10
State of the Art ...
# Buildings within a Building

## Floor Plan

<table>
<thead>
<tr>
<th>Floor</th>
<th>Area 1</th>
<th>Area 2</th>
<th>Area 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st</td>
<td>Graduate Student Offices</td>
<td>Staff Offices and Class Rooms</td>
<td>Research Laboratories</td>
</tr>
<tr>
<td>2nd</td>
<td>Office/Class</td>
<td>LABS</td>
<td></td>
</tr>
<tr>
<td>3rd</td>
<td>Electrical/General Mechanical Room</td>
<td>Data Center</td>
<td></td>
</tr>
</tbody>
</table>

## Equipment
- Chiller: 150 HP, 210 KVA
- Trans: 2 x 150 KVA
- Switch: 2 x 150 KVA
- Surge: 2 x 150 KVA
- Heat: 2 x 150 KVA
- Electric: 2 x 150 KVA
- Power: 2 x 150 KVA

## Highlights
- Power Meters
- Existing Environmental EDC System
- Obvious Campus Power Monitor

## Notes
- AH-1: Offices
- AH-2: Graduate Student Offices
- AC-4B: [2x4]
Layered Architecture

- **Presentation**
  - Portals
  - User Feedback
  - OADR
  - Forecast

- **Analysis**
  - Simulation
  - Recommissioning
  - Diagnosis

- **Logical**
  - Meta-Data
  - Model
  - Physical Information
  - Events
  - Networks
  - Repositories

- **Physical**
  - Building Systems
  - Sensors
  - Comms Links
Physical Tier

- 10 Dent Powerscout 18-channel (6x3) electrical meters
  - RS485 – Ethernet/IP – sMAP
- 2 Power Standards Labs meters
  - Ethernet
- 2 (existing) ION 6200 meters
- 70 ACME Receptacle meters
  - 802.15.4/LoWPAN/IP
- 4 rooftop Solar/TSR/PAR/Temp/Hum
- Condensate meter, Obvius Steam
- Vaisala Meteorological Station
- Existing SCADA integration
- Remote Programmable PCT => Action
- Interior usage, activity, environmental condition
Power Flows
Electric Tree Monitoring

- ION6200: mains power monitoring
- DENT PowerScout18: branch level
- VERIS E30: panel level
- AC Meter: plug level monitoring and control
Main Switch Block

12.5kV 3 Phase

ION 6200

480V 3 Phase

PSL PQUBE (2)

Dent PowerScout (10)

RS-485

Ethernet VLAN

eth0:pn-CEC

sMAP
• Connectivity: RS-485 – multi-drop serial protocol
• Data model: Modbus (“everything is a 16-bit register”)  
  – need register map to interpret
• Three-phase power measurements  
  – about 50 “channels” per three-phase circuit  
  – six circuits supported
• Registers updated at 2Hz
## Interconnect

<table>
<thead>
<tr>
<th>Protocol</th>
<th>Year</th>
<th>Network</th>
<th>Target Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modbus</td>
<td>1979</td>
<td>RS-485, TCP/IP</td>
<td>Industrial Control</td>
</tr>
<tr>
<td>Fieldbus/HART</td>
<td>1988</td>
<td>various</td>
<td>Industrial Control</td>
</tr>
<tr>
<td>BACnet</td>
<td>1995</td>
<td>AR CNET, Ethernet, IP, RS-232, etc.</td>
<td>Building Automation: HVAC, Lighting, Fire...</td>
</tr>
<tr>
<td>WirelessHART</td>
<td>2007</td>
<td>802.15.4e</td>
<td>Industrial control, wire replacement</td>
</tr>
<tr>
<td>SEP 2.0</td>
<td>2010</td>
<td>802.15.4</td>
<td>Home automation</td>
</tr>
</tbody>
</table>

- **HUGE installed/legacy base**
- **Multiple generations of hardware and software in the same building**
- **Typical integration: proprietary vertical BMS**
  - Data in at the bottom
  - Data products out at the top
# Real Data Feeds

<table>
<thead>
<tr>
<th>Type</th>
<th>Name</th>
<th>Connectivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electric</td>
<td>ION6200</td>
<td>XML/proprietary</td>
</tr>
<tr>
<td>Electric branch meter</td>
<td>Dent Powerscout 3/18</td>
<td>Modbus/RS-485</td>
</tr>
<tr>
<td>Electric branch meter</td>
<td>PSL PQube</td>
<td>HTML table</td>
</tr>
<tr>
<td>Electric panel meter</td>
<td>Veris E30</td>
<td>Modbus/RS-485</td>
</tr>
<tr>
<td>Electric home meter</td>
<td>GE</td>
<td>ANSI C12.19/IR</td>
</tr>
<tr>
<td>Chilled water</td>
<td></td>
<td>4-20mA current loop</td>
</tr>
<tr>
<td>Steam condensate</td>
<td></td>
<td>Modbus/TCP</td>
</tr>
<tr>
<td>Environmental</td>
<td>Sun Blackbox</td>
<td>XML/proprietary</td>
</tr>
<tr>
<td>PCT (programmable thermostat)</td>
<td>Basys QW Series</td>
<td>Zigbee</td>
</tr>
<tr>
<td>Climate</td>
<td>Hydrowatch node</td>
<td>6lowpan/IPv6</td>
</tr>
</tbody>
</table>
Key Enabler: Hardware Abstraction

Applications:
- Modeling
- Control
- Visualization
- Location
- Debugging
- Personal Feedback
- Continuous Commissioning
- Actuation
- Authentication

Physical Information:
- Water
- Electrical
- Geographical
- Occupancy
- Structural
- Weather
- Environmental
- Actuator

sMAP
IP Everywhere

sMAP Resources

- California ISO
- EBHTTP / IPv6 / 6LowPAN
- Wireless Mesh Network
- Edge Router
- Modbus
- AC plug meter
- Light switch
- Temperature/PAR/TSR
- Vibration / Humidity

Applications

- Google PowerMeter
- Cell phone
- Every Building
- Database
- SCADA

Internet

- Proxy Server
- EBHTTP Translation
- RS-485
- sMAP Gateway
sMAP restful web services

/ # list resource under URI root [GET]
data # list sense points under resource data [GET]
/sense_point # select a sense points [GET]
meter # meters provide this service [GET]
/channel # a particular channel [GET]
/reading # meter reading [GET]
/format # calibration and units [GET/POST]
/parameter # sampling parameter [GET/POST]
/profile # history of readings [GET]
/reporting # create and query periodic reports [GET/POST]

POST requests supply JSON objects as arguments:

POST: http://meter1.cs.berkeley.edu/reporting/create

{ "ReportResource" : "/data/325/meter/*/reading",
  "ReportDeliveryLocation" :
    "http://webs.cs.berkeley.edu/recv.php",
  "Period" : 0, "Minimum" : 50, "Maximum" : 100 }
Typical Interaction

• Discover sMAP Instance
• Read/Poll
  - GET /data/ABC/sensor/real_power/formatting
  - GET /data/**/**/reading
• Subscribe
  - Create reporting instance with HTTP URL for “callback”
  - Specify fixed rate or each new report
  - Persists until deleted, times out, or fails
  - Incremental update (part of a resource) sometimes necessary
Sense Point | Description | Channels
---|---|---
A, B, C | Single-phase | real, apparent, reactive power + energy. power factor. current. phase-neutral voltage
AB, BC, AC | Phase-to-phase | voltage
ABC | Whole-circuit | real, apparent, reactive power + energy. power factor. current. phase-neutral voltage. line frequency
Open Standards => Horizontal Integration
sMAP - homogeneous access to heterogeneous information

![sMAP Console](http://smap.cs.berkeley.edu/)

Model
- Type
- Make
- Status
- Uptime
- LocalTime
- Streams

![sMAP root](http://smap.cs.berkeley.edu/)
IS 4 Interface Overview

/      # root - status information [GET]
/is4   # a particular channel [GET]
     /info  # statistical system information [GET]
     /publish  # publishing resource [GET/PUT]
     /all  # list of all publishers [GET]
     /id  # sub-children [GET]
          /<id>  # id of publisher [GET/POST]
                   /name  # name alias for this id [GET]
                   /mysubs # list/add to pub subscriptions

[GET/PUT/DELETE]

POST requests supply JSON objects as arguments:

POST:
    http://is4server.com:8080/is4/Cory/lt/Main/devices/ion6200_5A7/A_sensor_currentDemand

DATA:
{
    "SummationDelivered": 6824953.0,
    "$schema": {"$ref":"http://webs.cs.berkeley.edu/schema/meter/reading"},
    "Version": 1,
    "ReadingTime": 1279859526,
    "SummationInterval": 30}
Web Applications

sMAP

Amazon Cloud EveryBuilding

Push

{ "ReportResource" : "/data/*//*/reading,  
  "ReportDeliveryLocation" : "http://...amazonaws.com/append/basement-1-elt-A"  
}

{ "ReportResource" : "/data/ABC/sensor/true_power/reading",  
}
Gateways for legacy devices, native implementations for new ones
Library of 8 different devices – currently represents XML/CSV feeds, Modbus, and embedded (mode-class)
Power Breakdown

sMAP Aggregate Plotting Engine

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Operational Efficiency and Fine-Grained monitoring

• Pump settings
• Elimination of simultaneous heating and cooling
• ...
The Data tells the story...

- Monitor Based Commissioning
  - Eliminate simultaneous heat/cool
  - AC91 on schedule
* Will continue decline on circuit 4PE as tools move.
AC 90 Scheduling HVAC on/off.
Extracting Deeper
Energy “Slack”

Thermostatically Controlled Load

Set Point

IPS

Graphs showing temperature, humidity, light, and power over time.
An Aware House
Supply-Following Loads
Supply-Following Loads

[Graphs and charts showing energy usage and power over time for different scenarios: Oblivious, Energy-aware, and Energy-aware 2.]
Towards Cyber/Physical Building

Cyber

Physical Building

BIM

Physical Models

Activity Models

External

Fault, Attack, Anomaly Detect & Management

Multi-Objective Model-Driven Control

Legacy Instrumentation & Control Interfaces

Pervasive Sensing

Activity/Usage Streams

Control Plan and Schedule

Human-Building Interface

Electrical

Light

Transport

Process Loads

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Occupant Demand
Demos

• **Time series**
  - http://smap.cs.berkeley.edu/db/plot/?stream=249&start=127070260&end=1278651060&sub=5

• **Time-series-difference scatter plot**
  - http://smap.cs.berkeley.edu/db/plot/vs.html

• **Aggregates**
  - http://smap.cs.berkeley.edu/db/plot/agg.html
Phone App

http://local.cs.berkeley.edu:8011/data/325/

http://local.cs.berkeley.edu:8011/data/325/sensor/real_power/profile
Basis for Grid-Responsive Bldgs

Portable Applications
- Modeling
- Continuous Commissioning
- Actuation and Control
- Debugging
- Personal Feedback
- Visualization

Core Services
- IS4 (storage)
- Location
- Authentication

sMAP Interface

IPv6 / 6LowPAN Wireless Mesh Network

sMAP

Proxy

RS-485

Modbus
Building Scale Monitoring Architecture