Massively Deployed Sensors
A report on a project done for the Power Systems Engineering Research Center (PSerc)

North American SynchroPhasor Initiative
Meeting
Scottsdale, AZ

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Core purpose
Empowering minds to engineer the future electric energy system

Important issues
• Pursuing, discovering and transferring knowledge
• Producing highly qualified and trained engineers
• Collaborating in all we do

• Arizona State University – Gerald Heydt
• University of California - Berkeley - Shmuel Oren
• Carnegie Mellon University – Marija Ilic
• Colorado School of Mines - P.K. Sen
• Cornell University – Tim Mount
• Georgia Institute of Technology - Sakis Meliopoulos
• Howard University - James Momoh
• University of Illinois at Urbana - Peter Sauer
• Iowa State University - Jim McCalley
• Texas A&M University - Mladen Kezunovic
• Washington State University - Anjan Bose
• University of Wisconsin-Madison - Chris DeMarco
• Wichita State University - Ward Jewell

PSerc
A collaboratory of 13 universities and ~40 sponsors with a core budget of 3.5M$/y plus about 2.0 M$ in university matching funds
Industry members

ABB
American Electric Power
American Transmission
AREVA T&D
Arizona Public Service
Baltimore Gas & Electric
British Columbia Trans. Co.
Bonneville Power Admin.
California ISO
CenterPoint Energy
Duke Energy
Entergy
EPRI
Exelon
GE Energy
FirstEnergy
Institut de recherche d’Hydro-Québec (IREQ)
ISO New England

ITC Holdings
MidAmerican Energy
Midwest ISO
National Grid USA
New York ISO
New York Power Authority
Pacific Gas and Electric
PJM Interconnection
PowerWorld
Quanta Technology
Salt River Project
Siemens
Southern California Edison
Southern Company
TVA
Tri-State G&T
TXU Electric Delivery
U.S. DOE
Western Area Power Administration
Researchers

• 40 researchers
• Multidisciplinary, specializing in:
  – power systems, applied mathematics, non-linear systems, power electronics, control theory, computing, operations research, T&D, power markets
  – economics, industrial organization and public policy

Students

• Strong synergy between research and education
  – About 60 graduate students working on PSerc research projects
  – Research improves quality of education experience
  – Research required of faculty
• Quality power programs (grad and undergrad)
• Employment search assistance

MORE INFORMATION AT WWW.PSerc.ORG
PSerc ‘Massively Deployed Sensors’ project participants

Faculty
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Jeffrey Selman
Jonathan Stahlhut

Web site: http://www.engr.wichita.edu/ces/sensors/
Main project elements

• Integration of existing sensory information from sensors (e.g. temperature and pressure, substation security perimeter status, substation battery voltage, neutral - ground voltage, liquid levels) into the EMS and alarm processing software tools.

• Investigation of unconventional sensors and sensory information (e.g., satellite graphic information, mechanical position and inclinometer-type sensors, static wire impedance, conduit and cable trough conductivity).

• Development of alarm processing techniques and algorithms that utilize a large number of sensory information sources including unconventional sensory information. The alarm processing techniques may use innovative mathematical techniques.

• The use of a very large number of signals for enhanced power system operation and operational decision making in order to capture new information and to enhance the accuracy, quality, and redundancy of the collected information. This includes, for example, analysis of data fusion, size and complexity of data, efficient power usage for sensors, optimal location of sensors with respect to chosen metrics, and availability of communication channels to transmit sensor data.
Forms of energy
Basis of sensory systems

- ELECTRIC
- MAGNETIC
- ATOMIC
- CHEMICAL
- POTENTIAL
- KINETIC
## Potential sensory signals

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Transmission Lines</th>
<th>Substations</th>
<th>Transformers</th>
<th>Circuit Breakers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acceleration</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vibration</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Stress / Strain</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tension</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shock</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pressure</td>
<td></td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Temperature</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Inclination / Tilt</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Position</td>
<td></td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Protective relay output</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>
### Bandwidth Requirements

<table>
<thead>
<tr>
<th>Bandwidth Requirements</th>
<th>BANDWIDTH</th>
<th>POWER TRANSFORMER</th>
<th>REVENUE PT</th>
<th>RELAYING PT</th>
<th>FIELD INSTRUMENTATION APPLICATIONS PT</th>
<th>LABORATORY GRADE PT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wide, greater than 10 kHz</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Moderate, 6 - 10 kHz</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Intermediate, 3 to 6 kHz</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Narrow, less than 3 kHz</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Very narrow, less than 100 Hz</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Assessment of the optimal number of sensors to improve an index of quality, $J$

![Diagram showing the relationship between the number of system states to be sensed and fed back and the optimal cost](#)

- **$J^*$**: Optimal cost
- **Range of effectiveness**: System order
- **Number of system states to be sensed and fed back**: $m$
- **Less effective states fed back**
- **Most effective states fed back**
Some innovative sensors
The Poynting vector

\[ \mathbf{S} = [\mathbf{E}] \times [\mathbf{H}] \]

It may be possible to assess losses in a post type insulator by measuring the Poynting vector, \( \mathbf{S} \), and integrating this across a surrounding surface. This is the lost active power in the insulator.
The Poynting vector

\[ S = [\mathbf{E}] \times [\mathbf{H}] \]
An application to the measurement of lost active power in a shunt reactor

Voltage and current are nearly 90 degrees out of phase – the low power factor is not zero due to losses
Value of a Poynting vector sensor

• Can be used to detect low level losses in systems with high levels of through power

• Can be used to detect low level losses in systems with very low power factor

• Can pinpoint location of losses – perhaps a discharge sensor
Absorption of alpha particles from an atomic source (as in a smoke alarm) can indicate the integrity of insulating oil.

**Alpha particle technology**

**Insulating oil integrity assessment using atomic particle absorption**
Potential applications of an alpha particle sensor

• Insulating oil integrity tests
• Nondestructive testing of insulating oils
• Transformer oil signature analysis and detection – for incipient failures
A giant magnetoresistive sensor (GMR)

The basic concept is a resistance measurement which is proportional to local magnetic field – and hence transmission line conductor current.

Requires sensitive resistance measurement – e.g., via a Kelvin bridge.

Double bridge balancing.

Wide bandwidth – basically limited by the speed of the electronic bridge balancing.
Potential applications of GMR technology

- Laboratory current measurements (even at high voltage)
- Local magnetic field measurements – e.g., a hand held $B$ field instrument
- A wideband CT
Satellite image technologies

- Tree trimming prioritization
- Physical security assessment

Stereo imaging
Satellite images

- The accuracy of the identification of ground objects depends on the ground sample distance (GSD) value.
- Satellite images are divided into pixels, where GSD is the pixel diameter in meters.
- GSD = 1 m is needed for the tree height determination, and GSD = 4 - 5 m are suitable for healthy vegetation identification.
- Multispectral stereo images can be obtained from a satellite:
  - IKONOS: GSD = 1 m, multispectral GSD = 4 m
  - QuickBird: GSD = 0.61 m
  - OrbView: GSD = 0.41 m, multispectral GSD = 1.64 m
Software development for tree trimming prioritization using satellite images

The procedure is divided into ten steps:
1. Load a pair of multispectral stereo satellite images
2. Load the data of transmission line towers
3. Calculate the pixel location of the lines and towers on the image
4. Load the coordinates of the danger zone
5. Display the danger zone
6. Select the threshold value for detecting vegetation
7. Detect the healthy trees and plants within the danger zone
8. Calculate stereo matching for each pixel within the danger zone
9. Generate three dimensional Digital Surface Model
10. Identify high trees and plants within the danger zone endangering the line
Software development: a GUI

The graphical user interface

- The **main panel** shows a satellite image and overlays results of analysis.
- A **sub-panel** displays the transmission tower as a small circle and the transmission line as a line.
- A **control-panel** gives index numbers which are used to interactively identify the land type such as bare land, trees, and buildings.
- An **info-panel** displays a table of the list of geographical coordinates of transmission towers.
Case study 1

- The figure illustrates the identification of areas with healthy vegetation

- QuickBird satellite image with a multispectral $GDS = 0.61$ m was used

- Location: Scottsdale, Arizona

- White areas identify trees or healthy bushes from multichromatic analysis
Case Study 2

• Location: San Diego, CA
• IKONOS satellite images, GSD = 1 m
• The transmission towers are located on the opposite sides of a freeway (I-8), and the overhead lines cross the freeway
• There is a vegetation area along the right of way – along the San Diego River (at Mission Bay Park)
• High trees are depicted in white, the white oval defines the study area
• A profile view appears at the bottom of the main panel
Results: case study 2
Case study 2

During the scanning each pixel is analyzed by calculating the normalized differenced vegetation index (NDVI) defined as,

\[ \text{NDVI} = \frac{\text{NIR} - R}{\text{NIR} + R} \]

\( \text{NIR} \) = near infrared, \( R \) = red. This minimizes the impact of variations in transmissivity from ground to satellite.

The effect of NDVI threshold on an IKONOS image illustrated here. The multispectral satellite image is, from top to bottom:

a) NDVI = 0.10
b) NDVI = 0.15
c) NDVI = 0.20
d) NDVI = 0.25
## Case study 2

<table>
<thead>
<tr>
<th>ID</th>
<th>Latitude (°N)</th>
<th>Longitude (°W)</th>
<th>Distance to lines (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>32.759251042034705</td>
<td>117.19985426770678</td>
<td>40.78245</td>
</tr>
<tr>
<td>1</td>
<td>32.75928400942072</td>
<td>117.1998345690552</td>
<td>42.64533</td>
</tr>
<tr>
<td>2</td>
<td>32.75953096171785</td>
<td>117.19973683669522</td>
<td>32.101067</td>
</tr>
<tr>
<td>3</td>
<td>32.75918758139942</td>
<td>117.19980425768894</td>
<td>38.711155</td>
</tr>
<tr>
<td>4</td>
<td>32.759336868606894</td>
<td>117.1997209176232</td>
<td>42.473488</td>
</tr>
<tr>
<td>5</td>
<td>32.759566403240605</td>
<td>117.19962773072264</td>
<td>31.185623</td>
</tr>
<tr>
<td>6</td>
<td>32.75927090915831</td>
<td>117.19960498847946</td>
<td>47.045143</td>
</tr>
<tr>
<td>7</td>
<td>32.75929827272182</td>
<td>117.19955346662981</td>
<td>48.571705</td>
</tr>
<tr>
<td>8</td>
<td>32.759388466048144</td>
<td>117.1994966434048</td>
<td>26.227222</td>
</tr>
<tr>
<td>9</td>
<td>32.759457505829374</td>
<td>117.19942315017384</td>
<td>32.37095</td>
</tr>
<tr>
<td>10</td>
<td>32.75943572141182</td>
<td>117.19935116877471</td>
<td>32.37095</td>
</tr>
<tr>
<td>11</td>
<td>32.75932871661798</td>
<td>117.19931252240548</td>
<td>24.45303</td>
</tr>
<tr>
<td>12</td>
<td>32.75923663067426</td>
<td>117.19920341145091</td>
<td>54.78344</td>
</tr>
</tbody>
</table>
Case study 2

Nearest distance from tree to line (m) 15 m
Case study 2

The five closest trees to transmission lines are extracted from the tree list and these are marked
# Contemplated risk and cost to benefit ratio of new sensors

<table>
<thead>
<tr>
<th>Need</th>
<th>Estimated risk</th>
<th>Estimated cost / benefit ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very low cost sensors*</td>
<td>Moderate</td>
<td>Very favorable</td>
</tr>
<tr>
<td>Direct measurement sensors</td>
<td>Moderate</td>
<td>Very favorable</td>
</tr>
<tr>
<td>Increase dynamic range of PTs and CTs</td>
<td>Low - moderate</td>
<td>Favorable</td>
</tr>
<tr>
<td>Development of semiconductor sensors</td>
<td>Moderate</td>
<td>Very favorable</td>
</tr>
<tr>
<td>Techniques using ‘non-sensors’</td>
<td>Low</td>
<td>Very favorable</td>
</tr>
<tr>
<td>Digital signal processing development for sensors</td>
<td>Low</td>
<td>Very favorable</td>
</tr>
<tr>
<td>Measurement of conductor sag</td>
<td>Low</td>
<td>Very favorable</td>
</tr>
<tr>
<td>Piezoelectric sensors</td>
<td>Moderate</td>
<td>Unknown</td>
</tr>
<tr>
<td>Very low current measurement</td>
<td>Low</td>
<td>Unknown</td>
</tr>
<tr>
<td>Transformer loss and temperature measurement</td>
<td>Low</td>
<td>Favorable</td>
</tr>
<tr>
<td>Video applications</td>
<td>Low</td>
<td>Favorable</td>
</tr>
<tr>
<td>Audio sensors</td>
<td>Low</td>
<td>Favorable</td>
</tr>
<tr>
<td>Double (Kelvin) bridge and other innovative bridge circuits</td>
<td>Low</td>
<td>Unknown</td>
</tr>
</tbody>
</table>
Latency – wide area measurement and control systems
Latency in delivering sensory signals

Remote signal → D/A → $T_b$ → $T_s$

Propag Delay → Routing Delay → ……

Propagation Delay → PSS input

$$T = T_s + T_b + T_p + T_r$$

$T_s$ is the serial delay, $T_b$ is the between packet delay, $T_p$ is the propagation delay, $T_r$ is the routing delay, $P_s$ is the size of the packet (bits/packet), $D_r$ is the data rate of the network, $\ell$ is the length of the communication medium, and $v$ is the velocity at which the data are sent though the communications medium (e.g., 0.6$c$ to $c$, where $c$ is the speed of light).
Latency in delivering sensory signals

It is possible to estimate the mean and variance of the latency

\[ E(T) = \begin{bmatrix} \frac{-P_s}{D_{ro}^2} & 1 & 1 \end{bmatrix} \begin{bmatrix} D_r \\ T_p \\ T_r \end{bmatrix} + T_b + \frac{2P_s}{D_{ro}^2} \]

\[ \sigma_T^2 = \begin{bmatrix} \frac{-P_s}{D_{ro}^2} & 1 & 1 \end{bmatrix} \begin{bmatrix} \sigma_{DrDr}^2 & \sigma_{DrTp}^2 & \sigma_{DrTr}^2 \\ \sigma_{TpDr}^2 & \sigma_{TpTp}^2 & \sigma_{TpTr}^2 \\ \sigma_{TrDr}^2 & \sigma_{TrTp}^2 & \sigma_{TrTr}^2 \end{bmatrix} \begin{bmatrix} \frac{-P_s}{D_{ro}^2} \\ 1 \\ 1 \end{bmatrix} \]
Calculation tools: the stochastic case

\[ E(T) = \left[ \frac{1}{D_r} \right] \left[ \begin{array}{c} E(P_s) \\ E(T_r) \end{array} \right] + T_b + T_p \]

\[ E((T - E(T))^2) = \left[ \frac{1}{D_r} \right] \left[ \begin{array}{cc} \sigma_{PsPs}^2 & \sigma_{PsTr}^2 \\ \sigma_{TrPs}^2 & \sigma_{TrTr}^2 \end{array} \right] \left[ \begin{array}{c} 1 \\ \frac{1}{D_r} \end{array} \right] = \sigma_T^2 \]

- These formulas are distribution free – they do not depend on type of stochastic variation
- Allows the estimate of the mean latency, and the variance (square of the SD)
The **WECC system** has nearly 30,000 buses above 69 kV. It is assumed that nearly one-fifth to one-quarter of these buses are, in fact, instrumented and ultimately result in measurements. For purposes of obtaining an illustrative example, the communication infrastructure of a WACS for the WECC is postulated.

The communications system specifications used in the WECC example are shown on the next slide. The table on the next slide shows the number of measurements for each zone and the maximum and minimum delay times for each of those zones (for a measurement in each of those zones to a central location $\ell$ km away).
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data rate of the network</td>
<td>50 Mbps</td>
</tr>
<tr>
<td>Between packet delay $T_b$</td>
<td>0</td>
</tr>
<tr>
<td>Packet size $P_s$</td>
<td>200 b</td>
</tr>
<tr>
<td>Length of the communication medium $\ell$</td>
<td>1000 km</td>
</tr>
<tr>
<td>Data velocity $V$</td>
<td>0.6c</td>
</tr>
<tr>
<td>Measurement rate $\Lambda$</td>
<td>50 (packets/s)</td>
</tr>
<tr>
<td>Router serving rate $\mathcal{M}$</td>
<td>50 Mbps</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Zone</th>
<th>Number of measurements</th>
<th>Minimum delay time (s)</th>
<th>Maximum delay time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zone 1</td>
<td>470</td>
<td>0.0206</td>
<td>0.0220</td>
</tr>
<tr>
<td>Zone 2</td>
<td>907</td>
<td>0.0206</td>
<td>0.0222</td>
</tr>
<tr>
<td>Zone 3</td>
<td>1310</td>
<td>0.0208</td>
<td>0.0222</td>
</tr>
<tr>
<td>Zone 4</td>
<td>840</td>
<td>0.0207</td>
<td>0.0222</td>
</tr>
<tr>
<td>Zone 5</td>
<td>504</td>
<td>0.0207</td>
<td>0.0220</td>
</tr>
<tr>
<td>Zone 6</td>
<td>638</td>
<td>0.0207</td>
<td>0.0222</td>
</tr>
<tr>
<td>Zone 7</td>
<td>1176</td>
<td>0.0219</td>
<td>0.0222</td>
</tr>
<tr>
<td>Zone 8</td>
<td>1008</td>
<td>0.0207</td>
<td>0.0220</td>
</tr>
</tbody>
</table>
Implications of latency – WECC example

In order to assess the impact of latency, the same WECC example is reconsidered with PSS measurements and controls implemented.

<table>
<thead>
<tr>
<th>Purpose</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gain for local input</td>
<td>5</td>
</tr>
<tr>
<td>Communication latency</td>
<td>Variable</td>
</tr>
<tr>
<td>Low-pass filter (lag)</td>
<td>$20/(1+s)$</td>
</tr>
<tr>
<td>Washout</td>
<td>$10/(1+10s)$</td>
</tr>
<tr>
<td>Phase compensation</td>
<td>$\frac{1 + 0.3s}{1 + 0.03s}$ $\frac{1 + 0.3s}{1 + 0.03s}$</td>
</tr>
<tr>
<td>Lower output limit</td>
<td>-0.1 p.u.</td>
</tr>
<tr>
<td>Upper output limit</td>
<td>+0.1 p.u.</td>
</tr>
</tbody>
</table>
Impact of 0.1 s delay

Generator electrical power output (pu on machine MVA base) at local bus

Simulation time (s)

Impact of 0.1 s delay

0.85 0.855 0.86 0.865 0.87 0.875 0.88 0.885 0.89 0.895

Remote input delayed by 0.1s
Remote input included without delay
Impact of 0.5 s delay

Simulation time (s)

Generator electrical power output (pu on machine MVA base) at local bus

- Remote input delayed by 0.5s
- Remote input included without delay
Impact of latency

- **Latency increases settling time** (graph at the right is the impact of delaying the remote bus frequency input from bus 35 to the PSS at bus 4 on interarea damping)
- There are cases in which latency in PSS signals result in **instability**
- Long latency times (e.g., > 0.25 s) show the greatest number of problematic cases
Impact of latency

• The latency issue is worse for cases of transmission circuit outages

• For example: the impact of delaying the remote bus frequency input from bus 35 to the PSS at bus 4 on interarea damping with a double circuit outage
Main conclusions from the latency study

• A straightforward calculation method and model of communication delays in power system WACS are shown for the case of dedicated sensory communication channels.

• Utilizing data representative of the WECC system, for a 50 Mbps network, an approximate interarea time delay of 20.6 ms is found.

• The standard deviation of the total interarea delay time may be calculated as well – and a typical value is about 4.6 ms.

• The latency calculations have been applied to a WACS test case. Introducing a remote input to a single PSS has been shown to enhance the stability of the test case by increasing the damping of the interarea mode under study. Latency has the effect of reducing the effectiveness of controls. However, WACS, with its attendant latency, appears to be more effective than local control in damping interarea oscillations.

• If additional processing delays were to exist, especially of the order of those introduced by satellite based communication, or data routing delays, conditions of underdamping (e.g., below those allowed operationally) will need to be checked carefully.
Some concluding remarks on the massive use of sensors in power systems
Advantages of deployment of sensors

1. **Advanced warning** of developing problems resulting in a fewer catastrophic failures.

2. **More efficient operations** of equipment and overall system resulting in lower losses, better conservation of resources and optimum operation.

3. **Improved emergency response** to problems; operators will have more information to diagnose and deal with problems for both normal and emergency operations.

4. **Increased security** of power grid, thereby, enhancing the homeland security.

5. Improved redundancy results in **improved reliability** of the measurements.
Examples of innovative sensory technology

• **Poynting vector** (an electromagnetic combination of electric and magnetic field) instrumentation may offer the capability of measurement of low electric and magnetic fields. The main issues to be addressed are the shielding of the sensor to reveal specific components of the Poynting vector. The instrumentation of the Poynting vector for electric power applications is a high risk venture.

• Measurement of **atomic particle absorption** (e.g., for detection of transformer oil contamination)

• Utilization of **satellite** electromagnetic (e.g. GPS) methods for sag identification of overhead transmission circuits, processing of satellite images for tree trimming prioritization

• Use of **time stamped remote measurements** for PSS signals
Questions – Comments – Remarks