Distributed fiber sensing systems for 3D combustion temperature field monitoring in coal-fired boilers using optically generated acoustic waves

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Department of Mechanical Engineering
University of Connecticut

Xinsheng Lou
Technology Manager
Alstom
Outline

1. The project team
2. Technical background of this project
3. Potential significance of the results
4. Relevancy to Fossil Energy
5. Statement of project objectives
6. Project milestones, schedule as related to SOPO tasks
7. Project risks and risk management plan
8. Project management plan
9. Project status
Project team (UMass Lowell)

People & Achievements

Dr. Xingwei Wang:
Optical bio/medical sensors; optical fiber sensors; MEMS

Postdoc: Dr. Nan Wu
Optical fiber sensing technology

Ph.D. student: Jingcheng Zhou
Sidewall fiber optic sensor

M.S. student: Poojitha Putchala
Fiber optic sensors, biosensors

Equipment & Facilities

General lab is used for the fiber optic device fabrication and testing.

Laser lab. All experiments using the nanosecond laser are performed in this room.
Project team (UConn and Alstom)

UConn

Dr. Chengyu Cao  
Dynamics and control;  
Adaptive and intelligent systems;

2 Ph.D. students

Tong Ma  
B.S. Harbin Institute of Technology, China 2013

Yuqian Liu  
B.S. Xi'an Jiaotong University, China 2013  
M.S. University of Connecticut, CT 2014

Alstom

Dr. Shizhong Yang  
Senior R&D Engineer at Alstom

Dr. Xinsheng Lou  
Technology Manager at Alstom
Reconstruct the 3D high temperature distribution within a boiler via a novel fiber optic distributed temperature sensing system using optically generated acoustic waves.
Technical background of this project

- Speed of acoustic waves depends on the temperature of gaseous medium.

- The TOF (time-of-flight) of an acoustic signal over a propagation path can be calculated as:

\[
TOF(l_j) = \int \frac{1}{C(x, y, z)} \,dl_j = \int \frac{1}{Z\sqrt{T(x, y, z)}} \,dl_j
\]

- \(C(x, y, z)\) the velocity of sound at position \((x, y, z)\)
- \(Z\) the heats ratio
- \(d(x, y, z)\) the reciprocal of velocity
- \(j\) the number of paths;
Potential significance of the results

- Distributed fiber sensors
- Survive high temperatures
The reconstructed 3D combustion temperature profile will provide critical input for the control mechanisms to optimize the fossil fuel combustion process. This will address the critical problem of achieving better operation safety, higher efficiency and fewer pollutant emissions in fossil energy power plants.
Establish a boiler furnace temperature distribution model and guide the design of the sensing system;

Develop the sensors with one active sensing element on each fiber as well as a temperature distribution reconstruction algorithm for proof-of-concept;

Develop the distributed sensing system to integrate multiple active sensing elements on a single optical fiber.
# Project Milestones

<table>
<thead>
<tr>
<th>No.</th>
<th>Title</th>
<th>Planned Date</th>
<th>Verification Method</th>
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<tbody>
<tr>
<td>M1</td>
<td>Develop Project Management Plan</td>
<td>July, 2014</td>
<td>Plan Submission to DOE</td>
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<tr>
<td>M2</td>
<td>Establish a Simulation Model for Furnace Temperature Profile</td>
<td>January, 2015</td>
<td>Simulation Program Files</td>
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<td>M3</td>
<td>Clarify Requirements for Distributed Sensing System Design</td>
<td>April, 2015</td>
<td>Requirements Report</td>
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<td>M4</td>
<td>Develop Active Sensing Element</td>
<td>October, 2015</td>
<td>Working Prototype</td>
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<td>M5</td>
<td>Characterize Distributed Sensing System I</td>
<td>April, 2016</td>
<td>Working Prototype</td>
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<tr>
<td>M6</td>
<td>Develop Reconstruction Algorithm</td>
<td>April, 2016</td>
<td>Algorithm Code</td>
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<td>M7</td>
<td>Field Test Distributed Sensing System I at Alstom</td>
<td>July, 2016</td>
<td>Test Report</td>
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<tr>
<td>M8</td>
<td>Develop Distributed Sensing System II</td>
<td>January, 2017</td>
<td>Working Prototype</td>
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<tr>
<td>M9</td>
<td>Field Test Distributed Sensing System II at Alstom</td>
<td>May, 2017</td>
<td>Test Report</td>
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<tr>
<td>M10</td>
<td>Develop Final Report</td>
<td>June, 2017</td>
<td>Deliver Final Report to DOE</td>
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# Project Schedule

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<thead>
<tr>
<th>Task</th>
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<th>End Date</th>
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<tr>
<td>Task 1.0</td>
<td>7/1/2014</td>
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<tr>
<td>Set Up Management Plan</td>
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<td>Task 2.0</td>
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<tr>
<td>Establish Simulation Model</td>
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<td>Task 3.0</td>
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<tr>
<td>Deliver Requirements for Distributed Sensing System Design</td>
<td>4/1/2015</td>
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<tr>
<td>Task 4.0 - Subtask 4.1</td>
<td>1/1/2015</td>
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<td>Design Active Sensing Elements</td>
<td></td>
<td>10/1/2015</td>
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<td>Task 4.0 - Subtask 4.2</td>
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<td>Develop Distributed Sensing System I</td>
<td>1/1/2016</td>
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<td>Task 4.0 - Subtask 4.3</td>
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<td>Characterize Distributed Sensing System I in Lab Environment</td>
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<td>Task 5.0</td>
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<td>Establish Reconstruction Algorithm</td>
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<td>Task 7.0 - Subtask 7.1</td>
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<td>Develop Distributed Sensing System II</td>
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<tr>
<td>Task 7.0 - Subtask 7.2</td>
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<td>Task 8.0</td>
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<td>Improve Reconstruction Algorithm</td>
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<td>Task 9.0</td>
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<tr>
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<td>5/30/2017</td>
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Orthogonal Code Based Signal Modulation

- **Orthogonal Code based coding:**
  - Enable parallel multiplexing mode
    - Satisfy the real time monitoring rate
  - Increase Signal to Noise Ratio (SNR)

**Method:**

Assign each emitters with a code, which is in a set of orthogonal pseudo-random sequences
SNR Effects

The signal captured by the receiver

\[ I(m, n, k) = S_0(m, n, k) + D(m, n, \alpha, \beta)P(k) \]

- \( D(m, n, \alpha, \beta)P(k) \) is the \( k_{th} \) acoustic signal coded as pseudorandom sequences
- \( S_0(m, n, k) \) is noise and other transmitters’ signal, which are all orthogonal to \( P(k) \)

Define the inner product

\[ R(m, n, k) = \frac{1}{N} \sum_{k-N}^{k} I(m, n, k)P(k) \]

The expectation of \( R^2(m, n, k) \) is,

\[ E[R(m, n, k)]^2 = \frac{1}{N} \left\{ E^2S_0(m, n, k) + E^2[D(m, n, \alpha, \beta)] \right\} \]

Higher SNR could be obtained,
- if we increase \( N \) or decrease the sampling rate
- if the length of pseudo-random sequence increases
The proposed Gaussian radial basis function (GRBF) based function approximation enables more precise field reconstruction given a set of paths.
Gaussian Radius Basis Function

- **G RBF:**
  \[ \phi_i(X) = e^{-\frac{||X-X_i||^2}{2\sigma_j^2}} \]
  - \(X_i\) and \(\sigma_j\) are the predefined center and variance, \(X\) is position with 3 dimensions \((x, y, z)\)
  - Nonlinear function approximated by basis functions with appropriate weights
  \[
  f(X) \approx \sum_{i=1}^{N} \omega_i \phi_i(X)
  \]

- **How to choose the optimum interpolation nodes?**
  - Divergence and fluctuation around the boundaries of the space
  - Increasing nodes lead to ill-conditioned interpolation matrix
  - A potential function can derive the optimum location of sample points.

  \[
  \int_{0}^{x} \mu(x) dx = \frac{j}{N}, \quad j = 0, \ldots, N.
  \quad \mu(t) \approx \sum_{k=0}^{N_{\mu}} a_k \frac{T_k(t)}{\sqrt{1-t^2}}
  \]

  \[
  \frac{\beta}{4} (x+1)^2 = \int_{0}^{L} \ln(|e^{\beta x} - e^{\beta t}|) \mu(t) dt + \text{constant}, \quad x \in [0, L].
  \]
Gaussian Radius Basis Function

- Weights can be obtained via the least square method
- Advantage of GRBF:
  - Better approximation capability for nonlinear functions
  - Superior in scalability
  - Low computation complexity
  - Ill-posed problems like the inversion of a stiff matrix
Then we can approximate the temperature field via GRBF:

\[ t_k = \int_{l_k} (z\sqrt{T(x, y, z)})^{-1} \, dl_k \]

\[ = \frac{1}{Z} \int_{l_k} \sum_{i=1}^{M} a_i g_i(x, y, z) \, dl_k \quad (1 \leq k \leq N) \]

\[ (\sqrt{T(x, y, z)})^{-1} = \sum_{i=1}^{M} a_i g_i(x, y, z) \]

\[ = \sum_{i=1}^{M} a_i \cdot \exp\{-[(x - X_i)^2 + (y - Y_i)^2 + (z - Z_i)^2] / 2\tau^2\} \]

\[ (1 \leq i \leq M) \]

- \( l_k \) is integral paths;
- \( N \) is the number of propagation paths which is decided by sensors;
- \( M \) is the number of Gauss functions.
Reconstruction of Temperature Field via GRBF

Solution to G RBF:

✓ Draw the vertical line from the center \((X_i, Y_i, Z_i)\) of Gauss function to the flight path \(l_k\)
✓ Calculation of \(t_k\) depends on whether the pedal is on the flight paths

- When the pedal is on the flight path:

\[
t_k = \frac{1}{z} \sum_{i=1}^{M} a_i \exp\left(-\frac{p_{ik}^2}{2\tau^2}\right) \times \left[\text{erf}(s_1^k) + \text{erf}(s_2^k)\right]
\]

- When the pedal is off the flight path:

\[
t_k = \frac{1}{z} \sum_{i=1}^{M} a_i \exp\left(-\frac{p_{ik}^2}{2\tau^2}\right) \times \left[\text{erf}(s_f^k) - \text{erf}(s_n^k)\right]
\]

✓ \(p_{ik}\) is the distance from center of the \(g_i(x, y, z)\) basis function to the \(k\) path
✓ \(s_1^k\) and \(s_2^k\) is the distance from the pedal to sensors on the ends
✓ \(s_f^k\) is the distance from the pedal to the farther sensor
✓ \(s_n^k\) is the distance from the pedal to the nearer sensor
1. PI Wang (UML) will be responsible for the physical aspect of the distributed sensing system including the fabrication and test of the sensing system at UMass Lowell and at Alstom.

2. PI Cao (UConn) will be responsible for the development of the CDMA based signal design and modulation/demodulation as well as the advanced 3D temperature field reconstruction algorithm.

3. Alstom’s Industrial Size Burner test Facility (ISBF) will be available for testing the new sensor system in 2015-2017 once the sensor system has been assembled and tested at university labs.
Project status

- Structure

- Remove fiber cladding
Project status

Coat gold nanocomposite on the tip of optical fibers [2].

Profile of ultrasound follows laser's. Ultrafast ultrasonic pulses [3].

Wide bandwidth (20 MHz) leads to high resolution.

Characterization of the fiber optic ultrasound generator.
In the simulation, 10 sensors are evenly distributed, 10 basis functions are used and 24 paths are chosen. The matching error is 1.95%.
Unimodal Deflection

\[ T(x, y) = 600 \exp\left(\frac{-(x - 4)^2}{\text{length}} - \frac{(y - 3)^2}{2 \cdot \text{height}}\right) + 1000 \]

In the simulation, 10 sensors are evenly distributed, 10 basis functions are used and 24 paths are chosen. The matching error is 0.8%.
References

1. Xiaotian Zou, Nan Wu, Ye Tian, and Xingwei Wang, ‘Polydimethylsiloxane thin film characterization using all-optical photoacoustic mechanism’

2. Ye Tian, Gang Shao, Xingwei Wang, and Linan An, ‘Fabrication of nano-scaled polymer-derived SiAlCN ceramic components using focused ion beam’

3. Ye Tian, Nan Wu, Xiaotian Zou, , Chengyu Cao, Xingwei Wang, ’Fiber-optic ultrasound generator using periodic gold nanopores fabricated by a focused ion beam’


