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

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University of Connecticut

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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

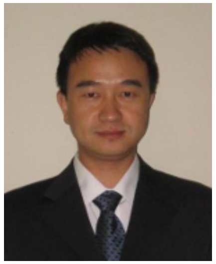
Equipment & Facilities

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)

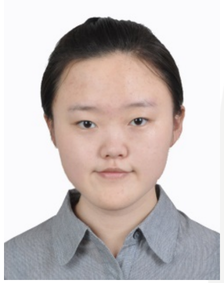
UConn



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

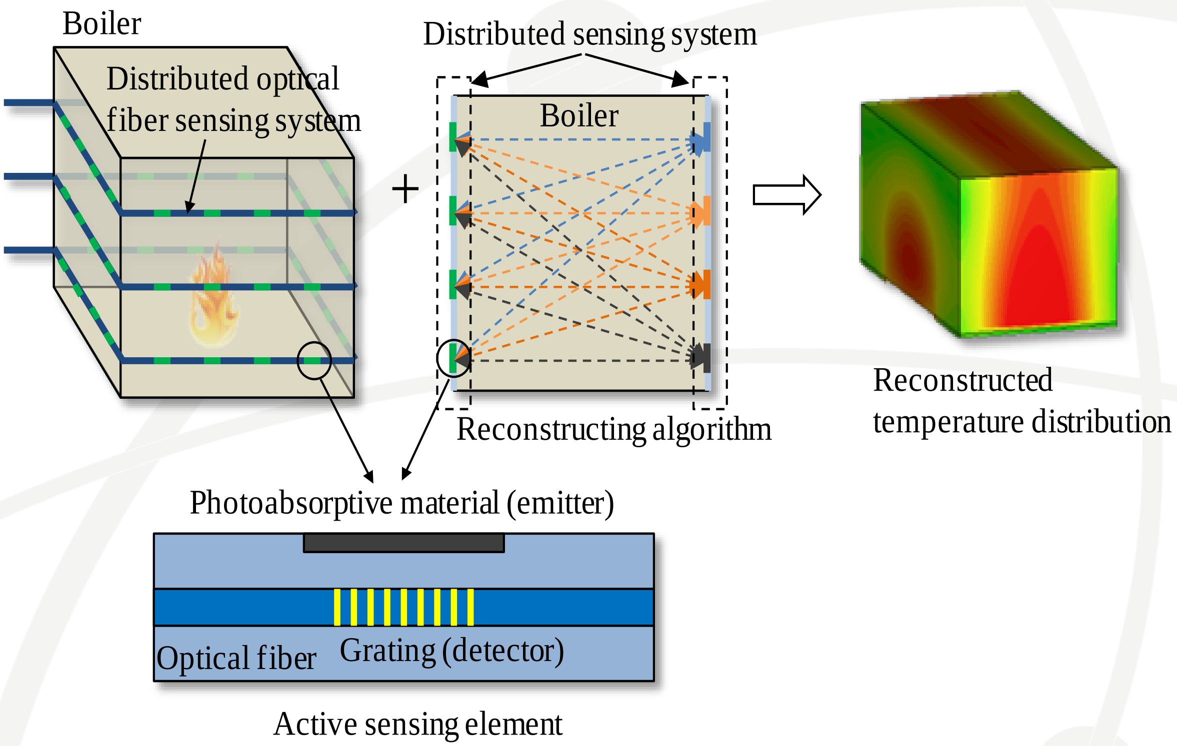
Dr. Shizhong Yang

Senior R&D Engineer at Alstom

Dr. Xinsheng Lou

Technology Manager at Alstom

Technical background of this project



Boiler

Distributed optical fiber sensing system

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Distributed sensing system

Boiler

Reconstructing algorithm

Reconstructed temperature distribution

Photoabsorptive material (emitter)

Optical fiber

Grating (detector)

Active sensing element

- 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

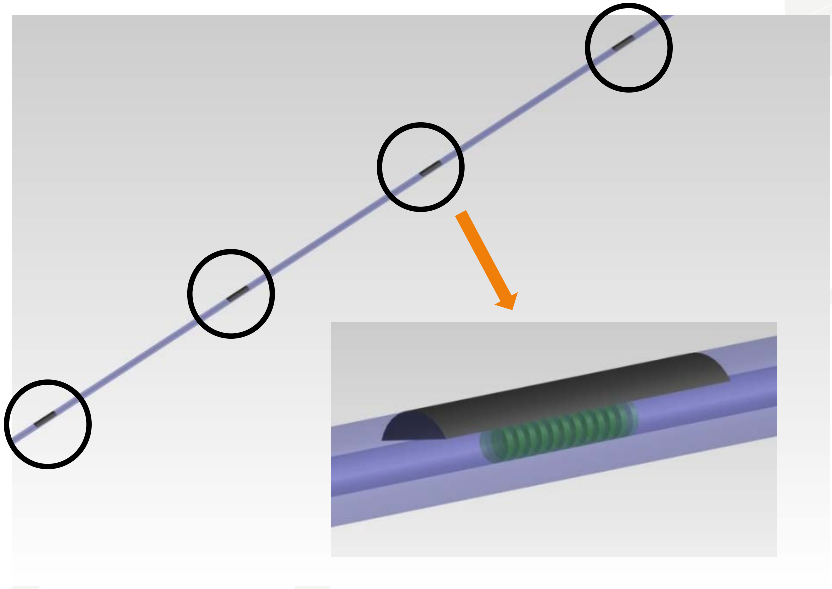
- ☐ Speed of acoustic waves depends on the temperature of gaseous medium.

- ☐ 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



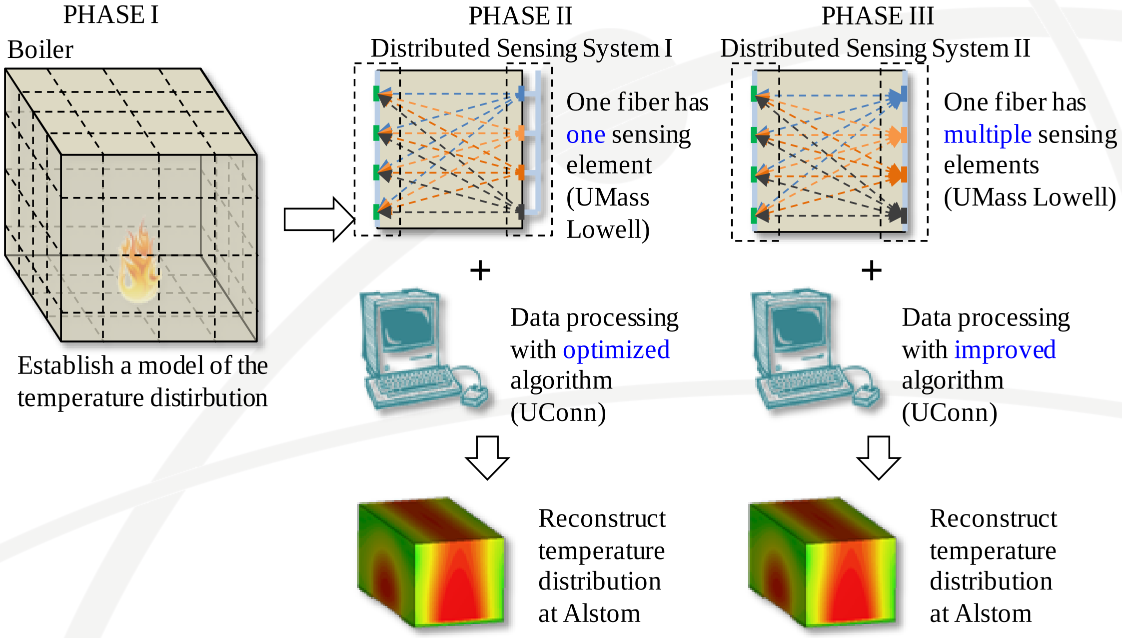
- Distributed fiber sensors

- Survive high temperatures

Relevancy to Fossil Energy

- 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 .

Statement of project objectives



PHASE I

Boiler

Establish a model of the temperature distribution

PHASE II

Distributed Sensing System I

One fiber has one sensing element (UMass Lowell)

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Data processing with optimized algorithm (UConn)

Reconstruct temperature distribution at Alstom

PHASE III

Distributed Sensing System II

One fiber has multiple sensing elements (UMass Lowell)

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Data processing with improved algorithm (UConn)

Reconstruct temperature distribution at Alstom

- 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

M1	Title:	Develop Project Management Plan
	Planned Date:	July, 2014
	Verification Method:	Plan Submission to DOE
M2	Title:	Establish a Simulation Model for Furnace Temperature Profile
	Planned Date:	January, 2015
	Verification Method:	Simulation Program Files
M3	Title:	Clarify Requirements for Distributed Sensing System Design
	Planned Date:	April, 2015
	Verification Method:	Requirements Report
M4	Title:	Develop Active Sensing Element
	Planned Date:	October, 2015
	Verification Method:	Working Prototype
M5	Title:	Characterize Distributed Sensing System I
	Planned Date:	April, 2016
	Verification Method:	Working Prototype
M6	Title:	Develop Reconstruction Algorithm
	Planned Date:	April, 2016
	Verification Method:	Algorithm Code
M7	Title:	Field Test Distributed Sensing System I at Alstom
	Planned Date:	July, 2016
	Verification Method:	Test Report
M8	Title:	Develop Distributed Sensing System II
	Planned Date:	January, 2017
	Verification Method:	Working Prototype
M9	Title:	Field Test Distributed Sensing System II at Alstom
	Planned Date:	May, 2017
	Verification Method:	Test Report
M10	Title:	Develop Final Report
	Planned Date:	June, 2017
	Verification Method:	Deliver Final Report to DOE

Project schedule

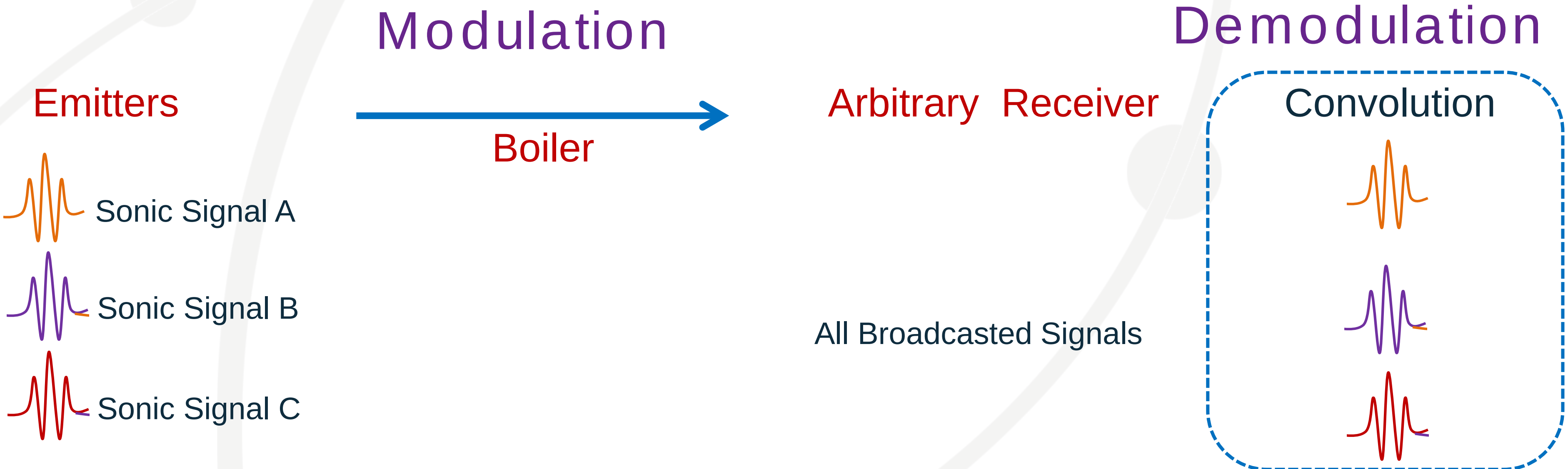
Task 1.0	Start Date:	7/1/2014
Set Up Management Plan	End Date:	7/31/2014
Task 2.0	Start Date:	7/1/2014
Establish Simulation Model	End Date:	1/1/2015
Task 3.0	Start Date:	1/1/2015
Deliver Requirements for Distributed Sensing System Design	End Date:	4/1/2015
Task 4.0 - Subtask 4.1	Start Date:	1/1/2015
Design Active Sensing Elements	End Date:	10/1/2015
Task 4.0 - Subtask 4.2	Start Date:	7/1/2015
Develop Distributed Sensing System I	End Date:	1/1/2016
Task 4.0 - Subtask 4.3	Start Date:	10/1/2015
Characterize Distributed Sensing System I in Lab Environment	End Date:	4/1/2016
Task 5.0	Start Date:	4/1/2015
Establish Reconstruction Algorithm	End Date:	4/1/2016
Task 6.0	Start Date:	4/1/2016
Field Test Distributed Sensing System I at Alstom	End Date:	7/1/2016
Task 7.0 - Subtask 7.1	Start Date:	10/1/2015
Develop Distributed Sensing System II	End Date:	10/1/2016
Task 7.0 - Subtask 7.2	Start Date:	7/1/2016
Characterize Distributed Sensing System II in Lab Environment	End Date:	1/1/2017
Task 8.0	Start Date:	7/1/2016
Improve Reconstruction Algorithm	End Date:	1/1/2017
Task 9.0	Start Date:	1/1/2017
Field Test Distributed Sensing System II at Alstom	End Date:	5/30/2017

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

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

$D(m,n,\alpha,\beta)P(k)$	k_{th} acoustic signal coded as pseudorandom sequences
$S_0(m,n,k)$	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,

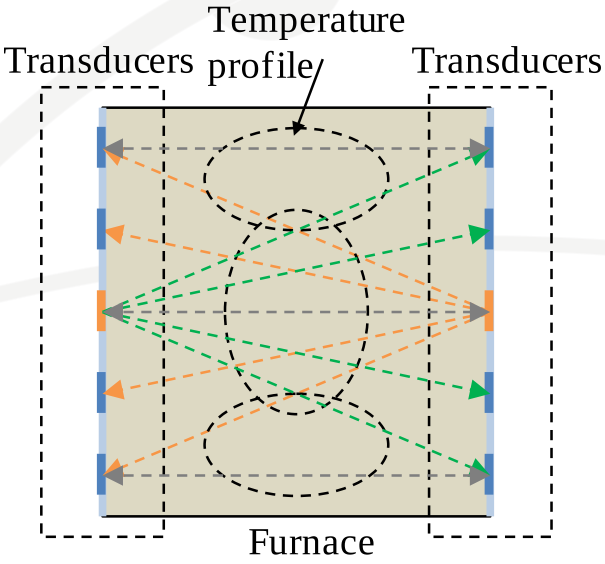
$$E[R(m,n,k)]^2=\frac{1}{N}\{E^2 S_0(m,n,k)+E^2[D(m,n,\alpha,\beta)]\}$$

Higher SNR could be obtained,

- if we increase N or decrease the sampling rate
- if the length of pseudo-random sequence increases

Project risks and risk management plan

- ❑ Accuracy of the reconstructed temperature field distribution



- ❑ The proposed Gaussian radial basis function (GRBF) based function approximation enables more precise field reconstruction given a set of paths.

Gaussian Radius Basis Function

❑ GRBF:

$$\phi_i(\mathrm{X}) = e^{-\frac{\|X-X_i\|^2}{2\sigma_j^2}}$$

- ✓ X_i and σ_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

$$f(\mathrm{X}) \approx \sum_{i=1}^{N} \omega_i \phi_i(\mathrm{X})$$

❑ 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.

$$\int_0^x \mu(x)dx = \frac{j}{N}, \qquad j = 0, \dots, N. \qquad\qquad \mu(t) \cong \sum_{k=0}^{N_\mu} a_k \frac{T_k(t)}{\sqrt{1-t^2}}$$

$$\frac{\beta}{4}(x+1)^2 = \int_0^L \ln(|e^{\beta x} - e^{\beta t}|)\mu(t)dt + constant, \qquad x \in [0, L].$$

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

Reconstruction of Temperature Field via GRBF

- Then we can approximate the temperature field via GRBF:

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

$$= \frac{1}{z}\int_{l_k}\sum_{i=1}^{M} a_i g_i(x,y,z)dl_k \qquad (1 \le k \le N)$$

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

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

$$(1 \le i \le M)$$

✓ 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 GRBF:
  - ✓ 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:

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

- ➢ When the pedal is off the flight path :

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

$$erf(x) = \int_0^x \exp(-\frac{t^2}{2\tau^2})dt \qquad (x > 0)$$

✓ p_{ik} is the distance from center of the $g_i(x, y, z)$ basis function to the *k* path

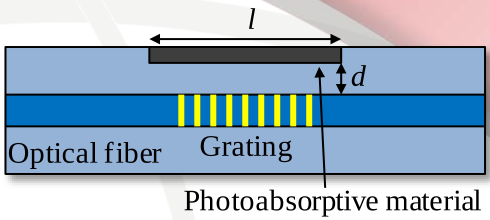
✓ s_1^k and s_2^k is the distance from the pedal to sensors on the ends

✓ s_f^k is the distance from the pedal to the farther sensor

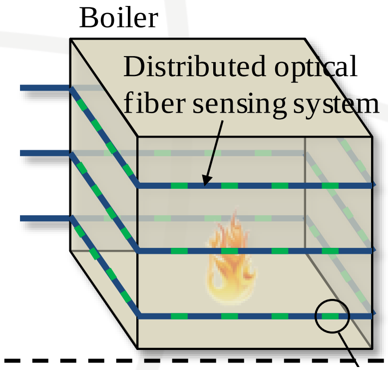
✓ s_n^k is the distance from the pedal to the nearer sensor

Project management plan

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.



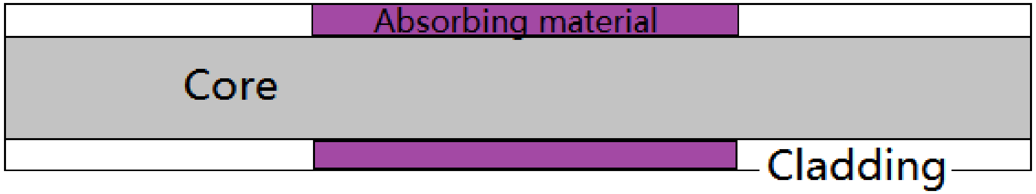
2. PI Cao (UConn) will be responsible for the development of the CDMA based signal design and modulation/demodulation as well as the advanced 3D temperature field reconstruction algorithm.



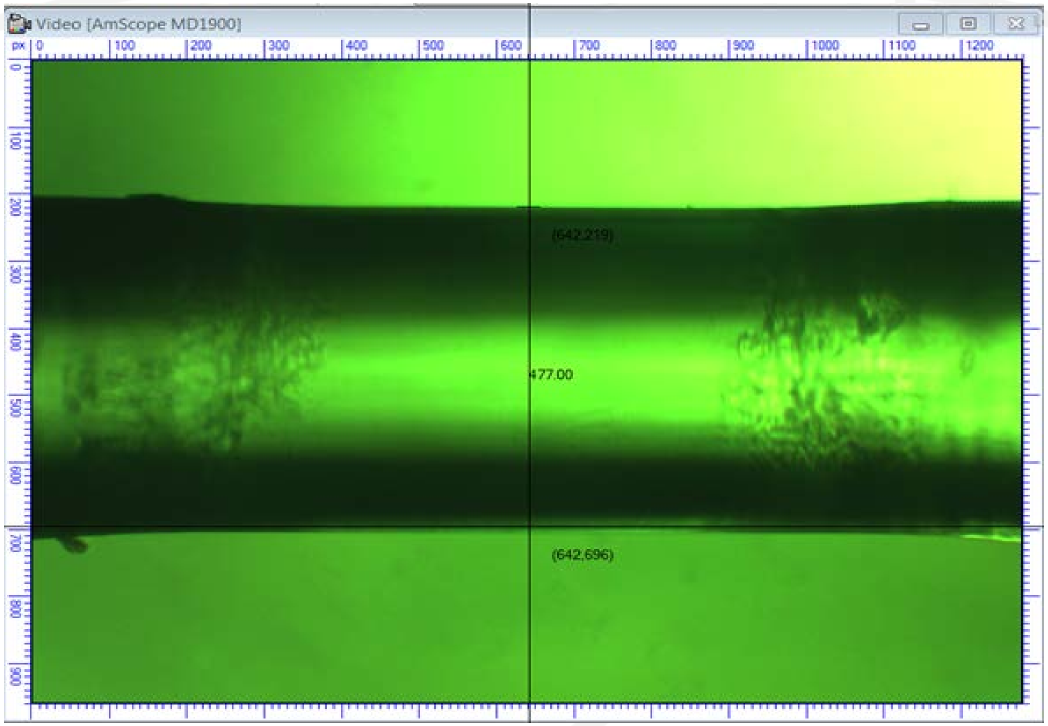
3. Alstom's Industrial Size Burner test Facility (ISBF) will be available for testing the new sensor system in 2015-2017 once the sensor system has been assembled and tested at university labs.

Project status

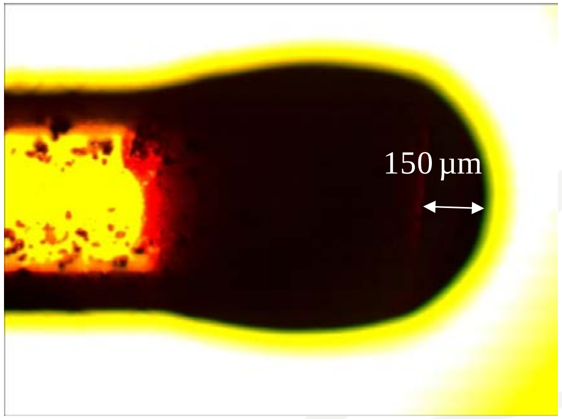
- ➢ Structure



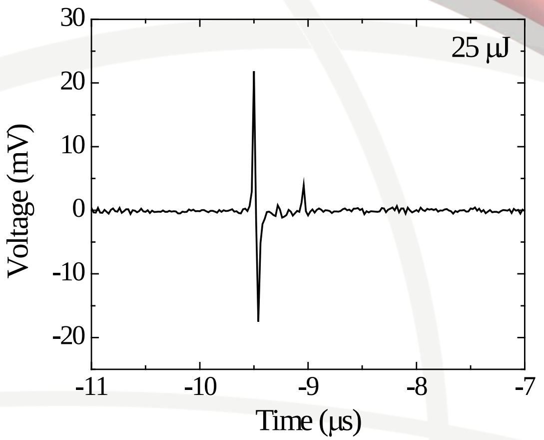
- ➢ Remove fiber cladding



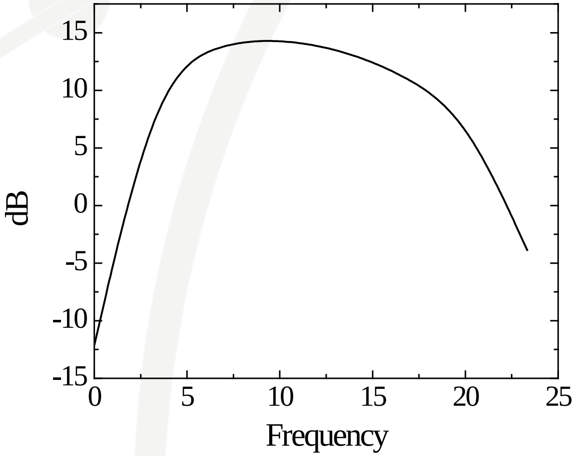
Project status



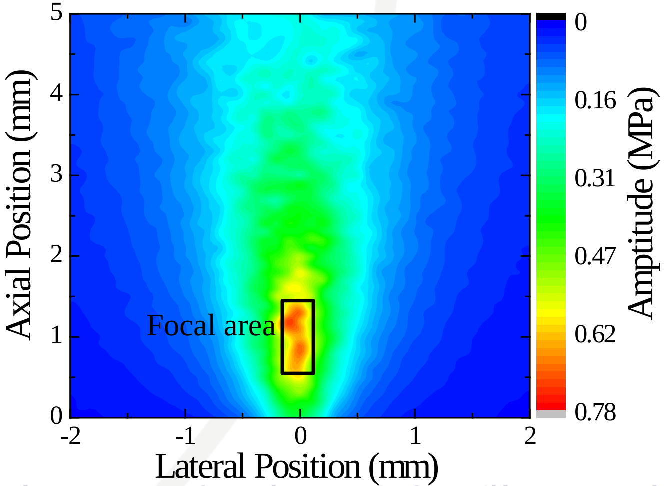
Coat gold nanocomposite on the tip of optical fibers [2].



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



Wide bandwidth (20 MHz) leads to high resolution.

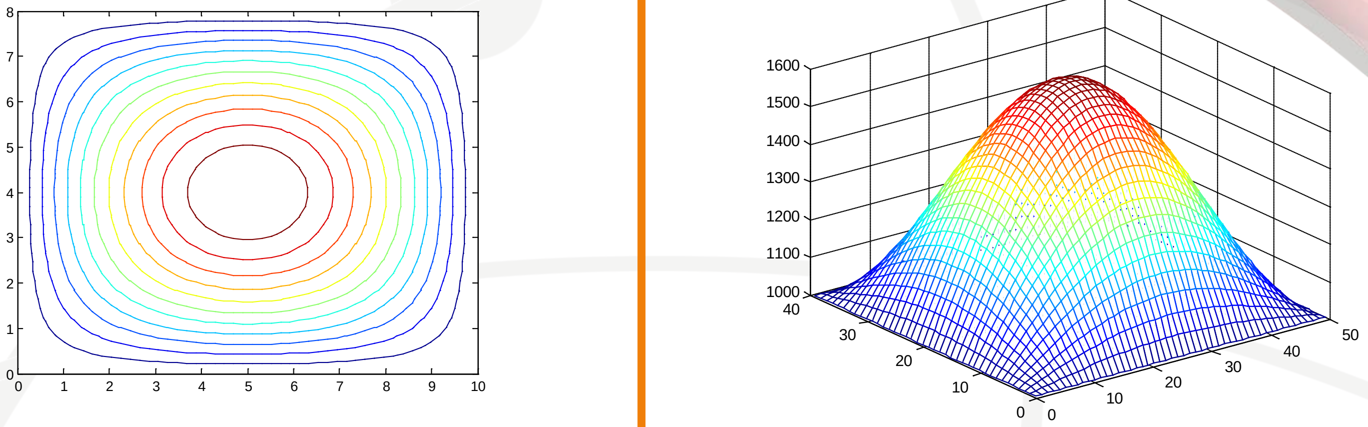


Characterization of the fiber optic ultrasound generator.

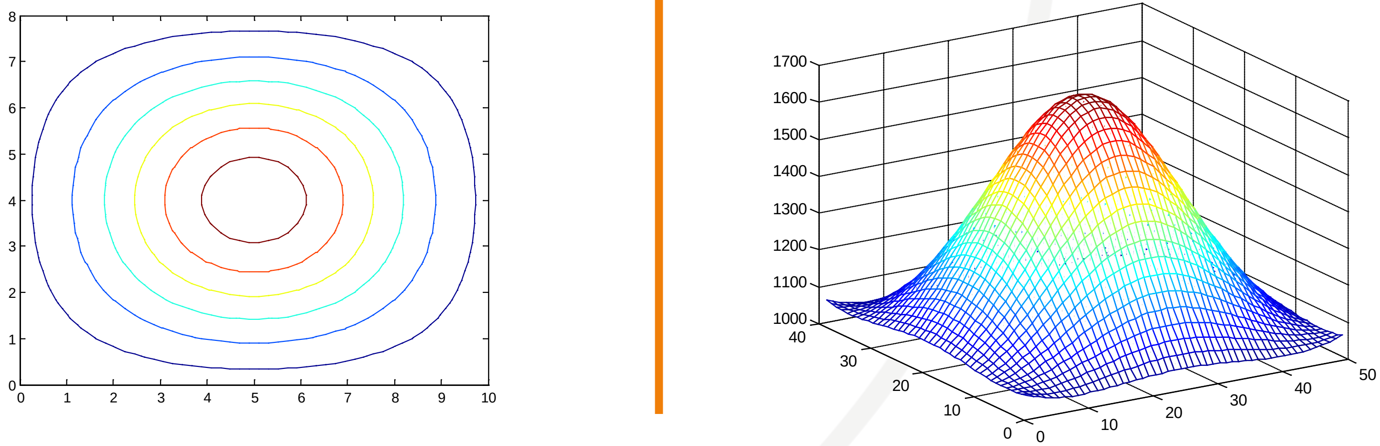
Project status

Unimodal Symmetric

$$T(x,y)=1000+600\sin(\pi x/length)\sin(\pi y/height)$$



Real temperature field



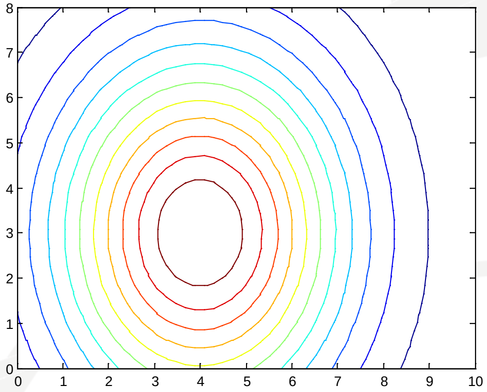
Reconstructed temperature field

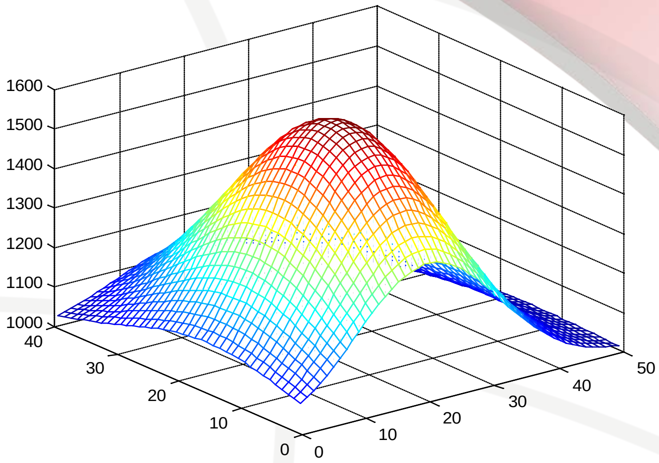
In the simulation, 10 sensors are evenly distributed, 10 basis functiones are used and 24 paths are chosen. The matching error is 1.95%.

Project status

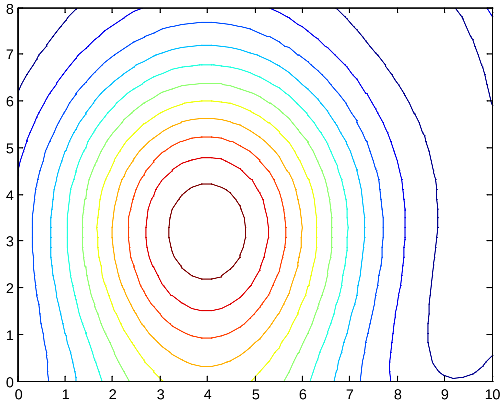
Unimodal Deflection $$T(x,y)=600\exp((-(x-4)^2)/length-((y-3)^2)/(2*height))+1000$$

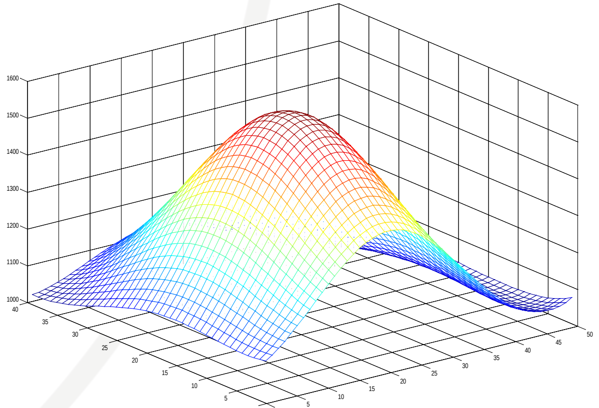
Real temperature field





Reconstructed temperature field





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’
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4. Minardo, A., et al. Fiber Bragg grating as ultrasonic wave sensors. in Second European Workshop on Optical Fiber Sensors. 2004: International Society for Optics and Photonics.
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