Developing Heterogeneous Fiber Optic Sensor Network for Online Monitoring of Combustors and Power Plants

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Abstract

Future advanced power plants will need to be more efficient and have far fewer emissions. This will require a significantly improved real-time monitoring, control, and analysis of the system. This paper focus on seeking improved performance of future power plants using online monitoring of a practical combustor under various operational conditions. A heterogeneous fiber optic monitoring system is proposed, which involves a diverse variety of sensors including novel micro-optical sensors for pressure, flow, and temperature measurements and nano-structured sensors for gas species measurements. It is expected that such a heterogeneous sensor system will provide more reliable view and higher confidence level on the operational status of the combustor as well as its implementation in future advanced power plants.

1. Introduction

New generation power plants are challenged to be significantly more efficient while reducing pollutants and eliminating carbon emissions. This requires new equipment design, new plant configurations, and new instrumentation. Future advanced power plants will require a large number of sensors that can provide detailed information on the various ongoing processes within the system. These sensors can be of the same type or different types located at different positions in the power plant. With too many sensors, one can obtain comprehensive information which then must be processed. By contrast, with one or few sensors, one will not be able to capture much of the detailed information in the system. Advances in photonics, micro/nano electronics, materials science, micro-electro-mechanical systems (MEMS) have led to dramatic improvements in the design of micro- and nano-scale sensors. A revolution in sensing and control is rapidly approaching. It is expected that in a decade time duration the sensors will be dramatically smaller, less expensive, capable of surviving harsher more challenging environments and smarter, similar to our past experiences in the case of personal computers. These micro-sensors will be able to provide comprehensive information on the various ongoing processes occurring in complex situations. In addition, a large number of sensors will provide an extensive amount of data for obtaining a detailed understanding of the process for technology enhancement, energy savings and pollution reduction.

There are many responses to this coming data flood. A first reaction to this revolution in sensing technology is that more data is good for detailed modeling and model development to evaluate the performance behavior of power plants. However, there are significant challenges in interacting with these micro-sensors and controlling a new generation power plant. Thus, the coming flood of data will challenge the current data handling and processing capabilities, and change how one uses sensors to control power plants. Based on the potential rewards and the significant challenges, it is important that one must consider research and development efforts for the design and selection of new types of sensors and develop algorithms and methodologies on how to use these future devices to come. Currently, very little is known on means to determine the number of sensors that must be used to provide adequate and effective information in a power plant, except that more may be better. Furthermore, it is not known what should be the critical locations for these sensors to provide representative information. Also, it is not known if special features (e.g., multiple functions for a single sensor, on board processing and decision-making tools) will substantially improve a plant's performance.

A starting place to resolve the above questions lies in linking sensors to physics based models that resolve data on the same length and time scales as the sensors. There are a couple of approaches to accomplish this. One approach could be to have the inputs from the sensors be directly compared with a physics based model running in real-time mimicking the plant behavior. There are several challenges to this approach. The current high fidelity models are slow and it is not clear how deviations among the data from the many sensors and the model predictions would be handled. Another approach is to have a hierarchical sensor network including leader sensor notes and micro-scale and nano-scale sensors as swarms or small groups rather than as individual sensors that work together to handle discrete tasks in the sensing and control network. This can be thought of as a holistic or cellular approach to sensors and control. Just as there are many cells in the body that perform important functions but are not individually directed by the brain, these sensors will need to perform their tasks without continuous direct intervention and reporting. To accomplish this, interactions for these sensors will need to be based on self-organization of complex adaptive systems with limited external direction.

In this paper we have focused our efforts on developing a new strategy for a high density fiber optic sensor network as well as on developing the potential methodologies that can be used so that the network can provide some detailed insights into the combustion and power plant operations for further technology advancement.

2. Sensor Consideration

The combustion behavior is very complex in almost all practical power plant systems. The combustor performance is dictated by many functions that a process must incorporate and also on the fate of many ongoing complex processes in the system. To effectively control its performance, the main problem lies in the determination of the actual conditions within the combustor. Sensors are critical elements for combustion control and combustion monitoring for achieving enhanced efficiency and robust performance of the combustion system.[1] Current sensors can hardly provide integral information of the entire combustor with adequate precision, high spatial resolution, and bandwidth. Since novel micro-scale and nano-scale sensors with improved performance are rapidly developing and they start to play more important roles in many applications, it is expected that they will also have a great impact on the combustion process monitoring since fuels and energy continue to be of greater importance than ever before.

Our envisioned high density sensor networks in power plants involve a diverse variety of heterogeneous sensors including novel micro-scale and nano-scale sensors for pressure, flow, and temperature, and various gas species concentration measurements. The heterogeneous sensor system can provide both complementary and competitive information about a combustion system. Complementary information refers to the measurements of different characteristics of the combustion process, while competitive information refers to the measurements of the same characteristic but from different sensor units. Such a heterogeneous sensor system can provide a more reliable view and a higher confidence level of the operational status of advanced combustion unit and power plant system.

To realize an effective, high density, heterogeneous sensor system, the following two fundamental questions need to be answered: i) what are the desired parameters to be measured and ii) what types of sensors need to be used. The first question has been addressed in the literature[2-6]. Some of these parameters include fuel concentration, fuel to air ratio, temperature, pressure, flow dynamics and residual gas concentration[2]. Due to the hostile conditions prevailing in combustors, the selected sensors should be able to withstand exposure to such an environment. In addition, the selection of the size of the sensor needs to be based on the spatial variations in the flow structure and the sensors needs to provide timely response to monitor relatively fast transient process. In the following we discuss some possible sensors to shed some light on the second question.

Fiber optic sensors have been proven to be successful for measurements in harsh environments[7], and these sensors possess the advantages of light weight, high sensitivity, not susceptible to electromagnetic interference (EMI), remote sensing capabilities, and multiplexible. Many of these sensors are made intrinsically within the optical fibers, and thus, the diameter sizes of these sensors are on the order of micro-scale. Fiber optic sensors have been demonstrated to provide measurement of temperature, pressure, gas concentration, and other key parameters to monitor details on the combustion process [8,9].

Among various kinds of fiber optic sensors, fiber Bragg grating (FBG) sensors are good candidates for combustion process monitoring. A fiber optic Bragg grating sensor consists of an optical fiber with a periodic perturbation of the refractive index at the core of the fiber. For a well-written fiber optic Bragg grating sensor, the reflection (and transmission) characteristics of the fiber include a reflection peak at the Bragg wavelength (and a transmission dip at the same wavelength). Due to the physical relationship between the optical properties of the fiber and an applied strain or temperature field, these sensors are appealing for strain and temperature sensing. The relationship describing the shift in the Bragg wavelength due to the applied temperature and strain fields can be expressed in terms of a linear equation. The coefficients in this equation may be obtained as Pockel constants. From the earliest stage of their development, fiber Bragg gratings have been considered as excellent sensor elements, suitable for measuring static and dynamic pressure fields. They also offer excellent multiplexing capabilities, which is definitely a good feature for a high density sensor network. However in hostile combustion environments, there are physical challenges associated with temperature that must be overcome so that they can be used over prolonged time duration.

Another type of fiber optical sensors that can be possibly used in a combusting environment is a Fabry-Perot sensor. These sensors provide a good solution for temperature and pressure sensing but at the expense of spatial resolution. These sensors are typically more sensitive than FBG sensors. For a highly noisy combustion process, these sensors are expected to provide better performance for chemical sensing.

3. Heterogeneous Fiber Optic Sensor Network

To develop high density sensor networks in hostile combustion environment encountered in power plants, the untapped potential of the fiber optic sensors needs to be further explored. Thus the first step must be to develop these micro-scale sensors and then apply to obtain information on pressure, flow, species, and temperature to achieve high performance conditions from a range of power plants. An example of a possible micro-optical sensor system configuration is shown in Figure 1. The uniqueness of this sensor system is derived from its heterogeneous nature, which include a low coherence Fabry-Perot sensor array for pressure, flow, and gas sensing and a Sapphire fiber Bragg grating (FBG) sensor array for temperature sensing. Wavelength division multiplexing (WDM) technique is used for the Bragg grating temperature sensor array that contains a number of FBGs with different Bragg wavelengths. For pressure, flow, and gas sensor arrays, spatial division multiplexing (SDM) technique is used. SDM enables distributed pressure, flow (from each of the two consequent pressure sensors), and gas sensing. Nano-structured zeolite based Fabry-Perot sensor can be used to measure various gas species in combustion process.

Owing to the remote sensing capabilities of fiber optic sensors, one can realize measurements in harsh environments by placing the optical system outside of the combustor. The sensors can be fabricated using sapphire fibers that will survive in temperature greater than 2000˚C. A cooling system can also be introduced in an inexpensive version of the sensor system by using a regular single mode fiber. In addition, due to the micro-scale nature, one can realize sensor arrays with micro-scale spatial resolutions.

4. Practical Sensor Networks in Power Plants

Sensor networks constitute the platform of a broad range of applications related to environment monitoring, inventory tracking, and health care. It is envisaged that in the near future, very large scale networks consisting of a large number of sensor nodes that have a wide range of capabilities will be deployed for various applications including combustors in advanced power plants. Although such sensor networks are expected to be a supporting technology for high performance and high efficiency power plants of the future, there are many challenges for deploying such sensor networks in power plants. First of all, one has to determine how one should develop an overall network architecture that can effectively accommodate the heterogeneity of a large number of sensors. Since it is important to have a global control of all the sensors in the network, it is anticipated that a number of subsystems will need to be formed and each subsystem able to handle self-organization of complex adaptive systems with limited external direction. The underlying question is how one should define these subsystems and how the sensors in each subsystem interact with each other. Moreover, a more difficult problem is related to sensor coverage and placement. Our goal here is to determine how many sensors are sufficient and where the sensors should be placed to ensure a defined degree of convergence and confidence.

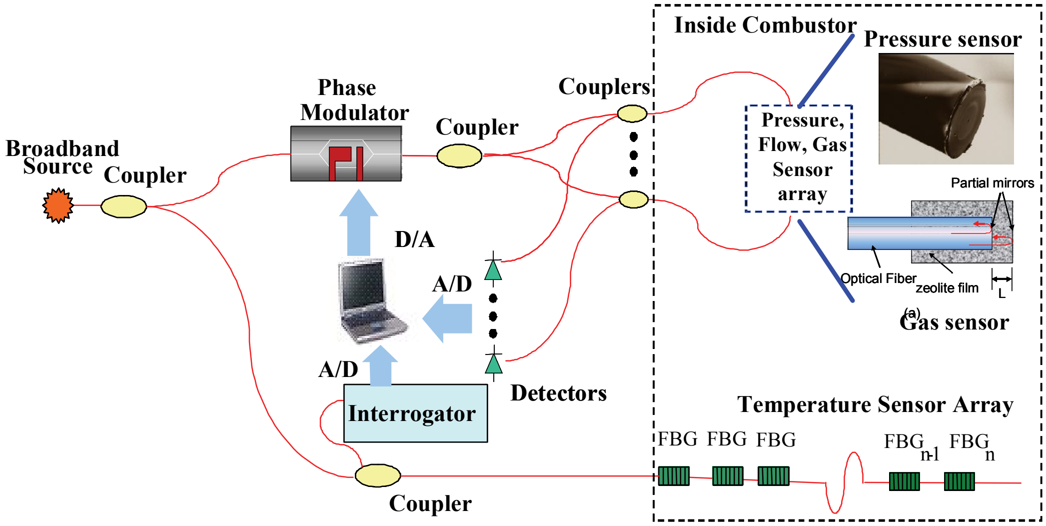

Figure 1. Schematic of a heterogeneous fiber optic sensor system for pressure, flow, gas species, and temperature measurements.

4.1 Hierarchical Network Structure

The sensors under consideration in this work are heterogeneous in terms of various aspects including sensing, computing, and communicating. An integrated hierarchical framework is proposed here to accommodate such heterogeneity and render principles for the design and deployment of sensor networks, which includes global control layer, sensor leader layer, and the underlying heterogeneous sensor notes. In this framework, as illustrated in Figure 2, sensor notes are logically organized into different cells (clusters) according to the model mimicking plant behavior. Each cell typically includes sensors that possess different capabilities. In fact, the first principle that is identified for deploying sensor networks is that all the cells in a power plant should in general collaborate. This is a usually a commonly agreed upon principle. Typically, a group of sensors residing at the same cell work together for some monitoring tasks and the data acquired from these sensors are delivered to the sensor leader in the cell.

After a set of sensors are selected as a cell, the second principle is identified as follows: the monitoring task should be tackled only by the sensors in the cell (to the maximum possible extent), and the solution should not assume dependency or seek outside help from sensors in the other cells. This *'independent'* rule matches practical applications well, and it greatly simplifies the design problem. Thus simply put one simply cannot design and deploy sensor networks by considering all the possible resources at all times.

Now given the set of (possibly heterogeneous) sensors, the next principle can be stated as follows: the problem should be solved by the sensors in a *distributed* manner; no centralized algorithm should be dependent on other external parameters. To enable distributed computation, communications (and therefore coordination) between sensors in a cell are needed. Distributed algorithms inherently possess better scalability and security properties, since it can provide efficient communication protocols and distributed algorithms that solve the incoming coverage determination and sensor placement problems. At the cell level, local sensing and control is organized by the sensor leader that is essentially a processor with computational and communication capabilities. In the case of fiber optic sensors, a cell itself can be an independent fiber optic system with multiplexed sensors and a central processor.

Upon finishing the self-organization, sensing, and control in each cell, the sensor leader can report the information to a global control station. The global control is optional but may be valuable to maintain the overall system integrity.

4.1 Sensor Coverage Problem

There has been a growing interest in studying numerous issues of sensor networks. One of the fundamental issues that arise in sensor networks is *coverage*. The sensor coverage problem has received increased attention recently, being considerably driven by recent advances in affordable and efficient integrated electronic devices. Due to the large variety of sensors and applications, coverage is subject to a wide range of interpretations. In general, coverage can be considered as the measure of *quality of service* (QoS) of a sensor network. Furthermore, coverage formulations can try to find weak points in a sensor field and suggest future deployment or reconfiguration schemes for improving the overall QoS.

The coverage problem of sensor networks can be posed in different ways. One way would be to determine the achievable coverage level in an area where sensors have already been deployed. This is the classical *coverage determination* problem. On the other hand, one may ask how the sensors should be organized in a given area so that some coverage level can be guaranteed. This formulation is the coverage-constrained *sensor placement* or *deployment* problem. Sensor placement directly influences resource management and the type of back-end processing and exploitation that must be carried out with sensed data in distributed sensor networks.

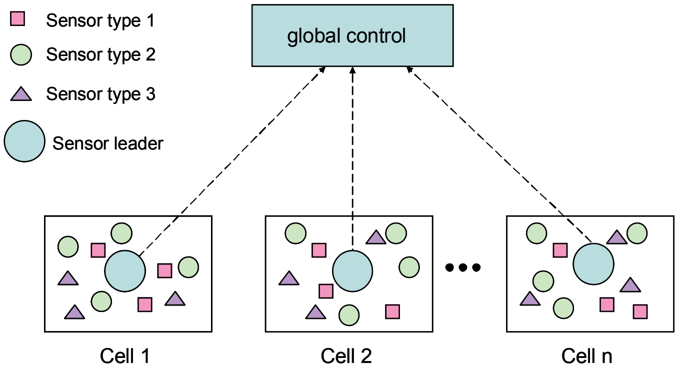

Figure 2. Schematic of the hierarchical network structure.

In this work, a general sensor coverage determination problem is considered. Given a set of sensors deployed in a target area (area of a cell), one needs to determine if the area is sufficiently *k-covered*, which represents that every point in the area is covered by at least k sensors (same types of sensors or heterogeneous sensors), where k is a predefined constant. Applications requiring $k > 1$ may occur in situations where stronger monitoring is necessary, such as, locations with large spatial or temporal gradient. It also happens when multiple sensors are required to detect an event. Enforcing $k \geq 2$ is also necessary for fault-tolerant purposes. A fundamental question is how many sensors are enough. This question should be addressed by using an available combustion model that can tell us the condition of each zone in the combustor. The principle here is that for certain critical locations, redundancy is necessary and thus $k > 1$ needs to be satisfied. Ideally, based on the combustion model prediction, the targeted coverage level of each cell in the combustor can be determined.

The second fundamental question to be addressed is how one can carry out effective sensor placement to realize the targeted coverage level. This is a somewhat more difficult problem. There are several attempts to solve this problem with graphic solution for some ideal geometry region. The coverage algorithms developed in [10] can be used here to determine whether a sensor network is *k*-covered. The solution can be easily translated to a distributed algorithm where each sensor only needs to collect local information to make its decision. Instead of determining the coverage of each location, the approach tries to look at how the perimeter of each sensor's sensing range is covered, thus leading to an efficient polynomial time algorithm. As long as the perimeters of sensors are sufficiently covered, the whole area is sufficiently covered. A difficult problem of sensor coverage and placement in a three-dimensional area of a combustor will be tackled.

5. Combustion Behavior

The combustion behavior is very complex in almost all practical power plant systems. The combustor performance is dictated by many functions that a process must incorporate and also on the fate of many ongoing complex processes in the system. In Figure 3, an experimental combustion test rig is used to examine the combustion instability that incorporates pressure waves to affect the combustor performance inside the combustion zone and past into the combustion tunnel. Clearly if one or two sensors were used in the combustion zone or the combustion tunnel, their numerical values will be erroneous since the local value of a given parameter will not be the actual representative behavior in the combustor. Thus, if one considers a practical combustion system, the challenges of local flow, pressure, chemical composition and thermal signatures are far more complex to impact their interaction and seek for optimum performance of the system.

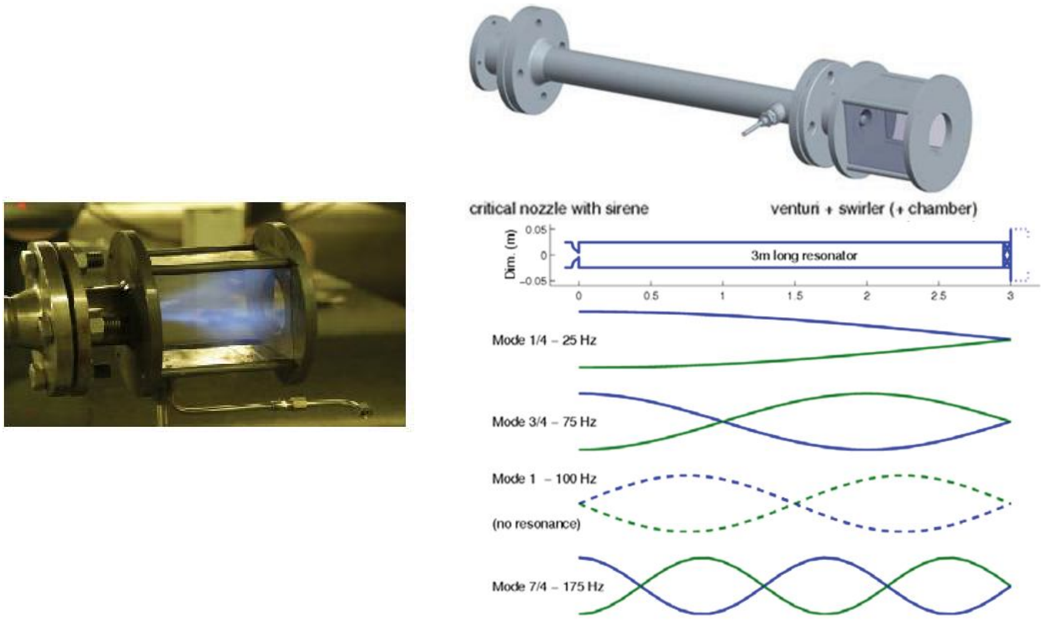

Figure 3. An experimental combustor with various modes of pressure waves inside the tube.

6. Test Rig for Seeking Initial Information from a Combustor

A photograph of the experimental test combustor that is planned to be used for detailed examination at the university of Maryland combustion laboratory is given in Figure 4. The combustor is of about 50 kW thermal loading and posses many of the key elements desired to be examined from a combustor that can provide pivotal information of significant practical importance in power plants. The combustor as well as the exit tube can be incorporated with a large number of different types of micro-sensors. These sensors are aimed at providing detailed local information on various parameters, such as, pressure, temperature, species concentration. Clearly one would like to obtain comprehensive information before combustion, during combustion and after combustion, both spatially and temporally. Our focus here is to start with selected types of sensor network at various locations upstream of the combustion zone, around the combustor and downstream of the combustor for seeking detailed information from the system.

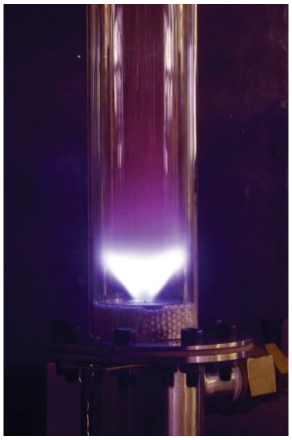

Figure 4. A photograph of the UMD test combustor.

7. Sensor Information Processing

7.1 Computational Sensor Calibration Model

The first step here will be to use a computational sensor calibration model to simultaneously calibrate all of the sensors used in the distributed sensor system. Usually, raw sensor output data are imperfect. Such calibrations will “remove” some errors embedded in the sensor output and provide more accurate measurements. The basic idea is to provide accurate estimate of “true” parameter values from the sensor outputs. Thus our initial goal will be to find a good mapping from raw reading of the sensors to determine their magnitude that will assist in control algorithm development procedure between the sensor inputs and output units. In order to achieve this, with a given known set of sensor input-output data points (a training sample), one can “train” a statistical multi-dimensional function that renders optimal estimates of sensor inputs according to some performance criteria, for example, maximum likelihood (ML) or minimum mean square error (MMSE). The trained model can then be applied to future output signals from the sensor and provide reliable estimated sensor input. As a result, the computational calibration model enables the sensors to endure some adverse effects in the face of uncertainties, nonlinearities, and cross-talk between sensors.

7.2 Data Aggregation

With readings from each group of the localized sensors in the distributed network sensor system, one first need to carry out preliminary data processing; for example, filtering and aggregating, to derive “information” from raw readings. Then, one would need to solve the problem of how can one determine the usefulness of each kind of the extracted information in order to achieve the desired parameters in combustion process control for each cell (sensor group). To solve this problem, in general, one needs to be equipped with some model that renders the dependence relationship between the desired parameters and the sensor readings. With such models, one can derive some information value of the metrics, from which different kind of information can be compared and the most needed information be subsequently transported. For example, Bayesian belief networks models[11] (which can be interpreted as generalizations of Hidden Markov models) capture well the dependency structure between various kinds of propositions, and notions from information theory, such as, information entropy and mutual information can be exploited to help determine information value. With such information, different kinds of sensor readings will play different roles and be treated differently for achieving the desired parameters.

7. Concluding Remarks

A sensor network framework for advanced combustion systems in future power plants is presented which is aimed at providing detailed database for further code developments and model validation. The past practices of one or two sensors from a power plant provide little to none or sometimes even misleading information on the ongoing combustion process in a system. The future plants will be more complex than they are today as our demands continue to elevate with optimal performance at all thermal loadings of the combustor with near zero emissions, high efficiency, alleviation of combustion instability and maximum energy conservation. This in turn requires detailed insights on the combustor behavior, both spatially and temporally. Thus, the future power plants will have more sensors; the exact number still requires close examination. A systematic development procedure is outlined here to determine the sensor type development with multi-function capability as well as their future means to process the large body of data. The specific focus is on spatial and temporal resolution on the various parameters at upstream region of the combustion zone, during combustion and post combustion zone. The sensor network includes a large number of heterogeneous nano-scale or micro-scale sensors. The roles of various sensors are discussed. The optical sensors, such as, fiber optic sensors can provide an important role for online monitoring of the detailed processes. The manner in which a hierarchical sensor network can be realized is also discussed.

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