CROSSCUTTING RESEARCH

SENSORS AND CONTROLS PROJECT PORTFOLIO

2020

U.S. DEPARTMENT OF ENERGY

NATIONAL ENERGY TECHNOLOGY LABORATORY

DISCLAIMER

CONTENTS

INTRODUCTION

NETL's Crosscutting Research Program matures novel technologies for commercialization that can enhance new and existing fossil-fired power plants. Six research and development (R&D) programs target enhanced fossil energy systems: High Performance Materials; Sensors, Controls, and Cybersecurity; Modeling, Simulation and Analysis; Water Management; Energy Storage; and University Training and Research.

The goals are to create transformational technologies that improve plant efficiency and security, reduce water consumption, and reduce costs, all under a single research umbrella. The research is leading to enhancements to the fleet such as improved plant efficiency, new ways to address the challenges of load following, better ways to counter cyber intrusions, and advancements in affordable, scalable technical solutions. Because of the broad scope of the Crosscutting Research Program's portfolio, its technologies often have applicability to other energy sectors such as oil and natural gas infrastructure and aviation (both commercial and military).

On behalf of the U.S. Department of Energy's Office of Fossil Energy, NETL pursues crosscutting R&D by collaborating with other government agencies, world-renowned national labs, entrepreneurs, industry, and academic institutions. Crosscutting Research efforts include sponsorship of two long-running university training programs that prepare the next generation of scientists and engineers to meet future energy challenges. These are the University Coal Research (UCR) program and the Historically Black Colleges and Universities and Other Minority Institutions (HBCU-OMI) program. By working with students on the university level, the efforts ensure that key technologies in areas including advanced manufacturing, cybersecurity, smart data analytics, and high-performance computing will be integrated into fossil plants of the future.

In combination, these investments in innovation, informed by private sector stakeholders, enable more comprehensive risk assessment and techno-economic analysis, increase the resiliency of the nation's fossil energy infrastructure, and enable the adoption of cutting-edge data technologies for plant owners and operators.

Sensors and Controls: The Sensors and Controls program improves fossil energy power generation with sensors, distributed intelligent control systems, and increased security. Advanced sensors and controls provide pivotal insights into optimization of plant performance and increasing plant reliability and availability. NETL tests and matures novel sensor and control systems that are operable in coal-fired power plants, capable of real-time measurements, improve overall plant efficiencies, and allow for more effective ramp rates. Given the crosscutting nature of sensors and controls, these technologies will also benefit natural gas power generation and other harsh-environment applications.

The Crosscutting Sensors and Controls program explores advances within and the integration of technologies across the following primary research areas: Harsh Environment Sensors, Robotic Inspection, Advanced Controls and Cyber Physical Systems, and Cyber Security.

High Performance Materials: High Performance Materials drives to characterize, produce, and certify cost-effective alloys and other high-performance materials suitable for the extreme environments found in fossil-based power-generation systems. NETL supports and catalyzes a robust domestic materials supply chain that prepares materials for advanced ultra-supercritical (AUSC) steam cycles and spinoff applications. The work also enables research in suitable materials for supercritical carbon dioxide (sCO_2) cycles that yield higher thermal efficiencies and supports the existing fossil fleet with materials solutions that enhance flexibility and reliability.

The Crosscutting Materials program works to accelerate the development of improved steels, superalloys, and other advanced alloys to address challenges of both the existing fleet and future power systems. Materials of interest are those that enable components and equipment to perform in the high-temperature, high-pressure, corrosive environments of an advanced energy system with specific emphasis on durability, availability, and cost both within and across each of four primary platforms: Advanced Manufacturing, Advanced Structural Materials, and Computational Materials Design.

Modeling, Simulation and Analysis: Modeling, Simulation and Analysis (MSA) focuses on developing and applying advanced computational tools at multiple scales: atomistic, device, process, grid, and market scales, to accelerate development and deployment of fossil fuel technologies.

Research in this area provides the basis for the simulation of engineered devices and systems to better predict and optimize the performance of fossil fuel power generating systems.

Computational design methods and concepts are required to significantly improve performance, reduce the costs of existing fossil energy power systems, and enable the development of new systems and capabilities such as advanced ultrasupercritical combustion and hydrogen turbines.

This effort combines theory, computational modeling, advanced optimization, experiments, and industrial input to simulate complex advanced energy processes, resulting in virtual prototyping. The research conducted in the MSA R&D develops accurate and timely computational models of complex reacting flows and components relevant to advanced power systems. Model development and refinement is achieved through in-house research and partnerships to utilize expertise throughout the country.

Water Management: Water Management addresses competing water needs and challenges through a series of dynamic and complex models and analyses that are essential in informing and deciding between priority technology choices. The program encompasses the need to minimize any potential impacts of power plant operations on water quality and availability. Analyzing and exploring plant efficiency opportunities can reduce the amount of water required for fossil energy operations.

New water treatment technologies that economically derive clean water from alternative sources will allow greater recycling of water within energy extraction and conversion as well as carbon storage processes. This helps reduce the amount of total water demand within fossil energy generation.

The program leads a critical national effort directed at removing barriers to sustainable, efficient water and energy use; developing technology solutions; and enhancing the understanding of the intimate relationship between energy and water resources. Water Management R&D focuses its research in three chief areas: increasing water efficiency and reuse, treatment of alternative sources of water, and energy-water analysis. These research areas encompass the need to minimize potential impacts on water quality and availability.

Energy Storage: FE's Advanced Energy Storage program aims to address the needs and challenges of fossil assets through the integration of energy storage technologies. As the penetration of variable renewable energy increases, energy storage at the generation site will be essential to a resilient and flexible electricity network. Energy storage also benefits the environment through optimization of fossil generation and by enabling additional renewables on the grid to reliably transmit their energy to end users. Program activities include plant- and system-level analyses, conceptual and detailed engineering designs, breakthrough R&D on innovative energy storage concepts, and targeted R&D on component and system-integrated energy storage technologies.

University Training and Research: University Training and Research supports two of the longest-running university training programs, the Historically Black Colleges and Universities (HBCU) and Other Minority Institutions (OMI) and the University Coal Research (UCR) programs, to support the education of students in the area of coal science is promoted through grants to U.S. colleges and universities that emphasize FE strategic goals. These training programs were designed to increase the competitiveness of universities in fossil energy research and discoveries. The student-led research programs advance energy technologies and allow for expansion of energy production while simultaneously facilitating energy sector job growth. The Outreach Initiative provides opportunities for qualified students and post-doctoral researchers to hone their research skills with NETL's in-house scientists.

SENSORS AND CONTROLS

The objective of the Sensors and Controls research area is to make available new classes of sensors and measurement tools that manage complexity, permit low cost, perform robust monitoring, and enable real-time optimization of fully integrated, highly efficient power generation systems. Research is focused on sensors capable of monitoring key parameters (e.g., temperature, pressure, and gas compositions) while operating in harsh environments, and analytical sensors capable of on-line, real-time evaluation and measurement. Controls development centers on self-organizing information networks and distributed intelligence for process control and decision making.

The Sensors and Controls project portfolio is categorized into the following research areas:

- Advanced Sensors
- Cybersecurity
- Distributed Intelligent Controls
- Robotics-Based Inspection
- Systems Engineering and Analysis

These new technologies are designed to improve the availability and efficiency of both existing and advanced power systems. As generational and transformational systems mature, sensors and controls will serve as essential and enabling technology to operate these systems under conditions in which optimal performance is balanced with reliability. In addition to sensing and control, users must be able to make and implement decisions and derived optimizations in real time. This capability will be attained via new computational tools that can match sensor data and analytical inputs to decision-making assistance and controls actuation, resulting in desired outcomes.

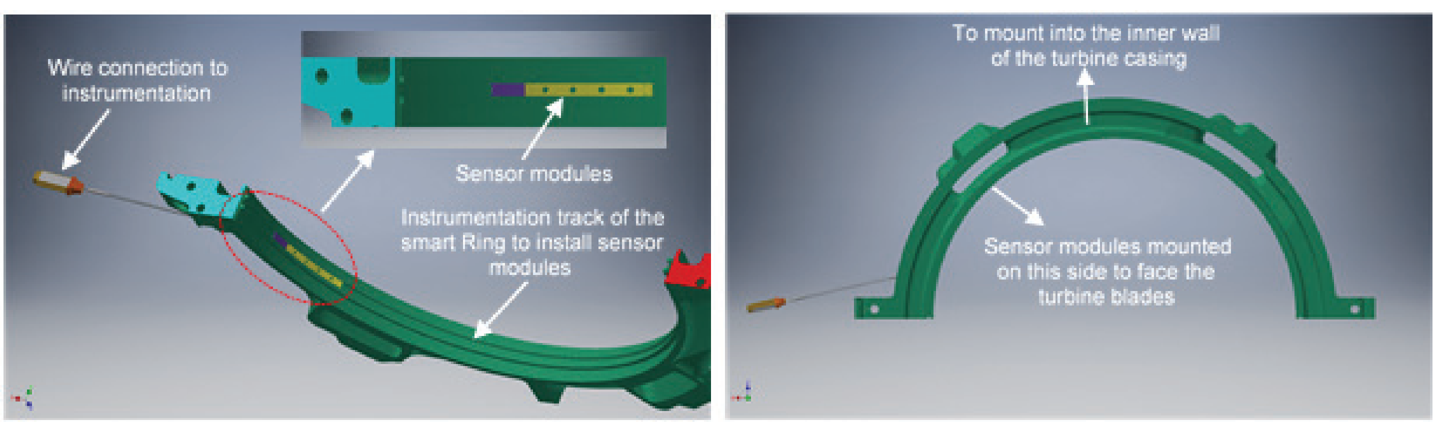
ADVANCED SENSORS

Additive Manufacturing of Circumferentially Embedded Optical Sensor Modules for In Situ Monitoring of Coal-Fueled Steam Turbines

Performer	**Clemson University**
Award Number	FE0031826
Project Duration	01/01/2020 – 12/31/2022
Total Project Value	$ 1,250,000
Collaborator	General Electric
Technology Area	Plant Optimization Technologies

The main objective of this project is to design, develop, additively manufacture, test, and validate three types (temperature, pressure, and blade tip timing/clearance) of optical sensor modules for in situ monitoring of the critical operation parameters in coal-fueled steam turbines. These sensor modules will be embedded into the Smart Ring (recently invented and patented by GE) and installed circumferentially and flush into the inner wall of the turbine casing for condition-based monitoring and control and maintenance scheduling. The optical sensor modules will be optimally designed based on simulations, and additively manufactured using the novel Integrated Additive and Subtractive Manufacturing (IASM) method developed at Clemson University. The sensor-embedded Smart Ring will be tested and validated under laboratory-simulated conditions as well as demonstrated in industrial-scale turbine testing rigs at GE's turbine testing facilities.

As power plant designs extend the limits of materials into higher temperature and pressure regimes in order to gain efficiency, turbine blade creep becomes a key issue. The sensors developed in this project will help to monitor blade creep and correlate it to operating conditions, thereby enabling condition-based control and maintenance scheduling and contributing to extended turbine lifetime.



Prototype of field measurement optical system design.

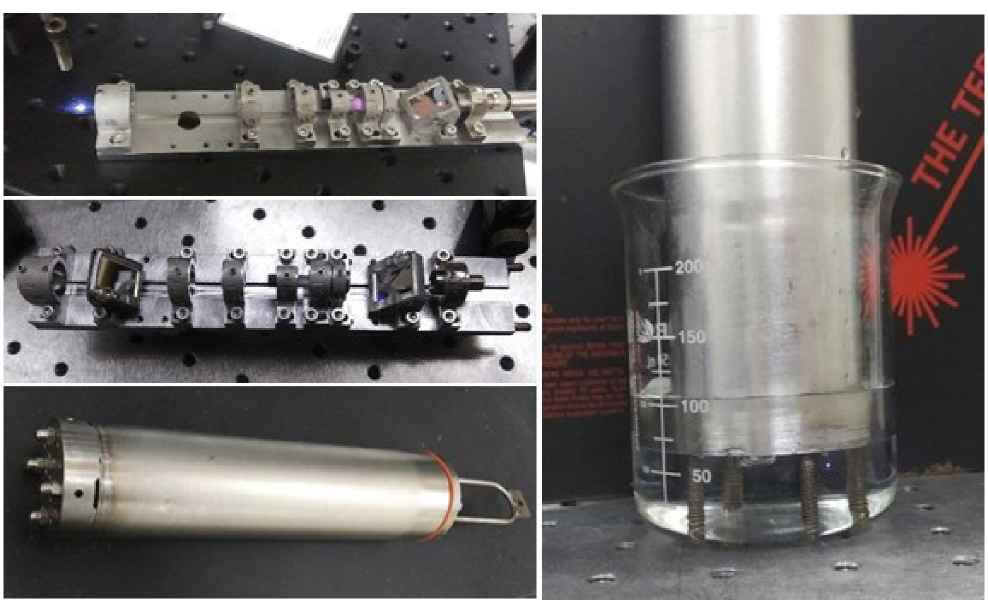
Development of LIBS for Specialized Fossil Energy Applications

Performer	**National Energy Technology Laboratory (NETL)**
Award Number	FWP-1022427 Advanced Sensors and Controls – Task 71
Project Duration	04/01/2020 – 03/31/2021
Total Project Value	$ 230,000
Technology Area	Plant Optimization Technologies

This research by NETL will provide data on the abilities and limitations of laser-induced breakdown spectroscopy (LIBS) at conditions of interest for fossil energy processes, and will adapt LIBS technology to optimize measurement capability in prototype field systems for use in the subterranean environment as well as power plant process environments. The technology development challenges are centered around the optimal application of LIBS to the fluids of interest, and their optical behavior at these conditions. Technical challenges include the selection and use of suitable optical materials and concomitant optical collection techniques that will be suitable to the application environment and provide enough signal in relation to noise for accurate measurement.

Experimentation with brines relevant to subterranean conditions has indicated that presence of sodium chloride enhances the spectral emission of other atomic constituents within pressurized brine, and the concentration of carbon dioxide affects the concentrations of minerals dissolved in the brine. A pressure vessel with optical accessibility capable of operations up to 6000 pounds per square inch and 150 degrees Celsius provides conditions relevant to subterranean carbon dioxide storage to study the spectroscopic behavior.

A miniaturized prototype downhole LIBS probe, fiber-coupled to the pump laser and spectrometer, has been constructed to begin field testing in 2020. This configuration is intended for use with the LIBS probe lowered into the well. It is likely to have application in other environments which would benefit from the split-system configuration. Field testing will provide data necessary for system improvement, validation, and technology transfer.



Prototype LIBS subsurface probe. The LIBS spark is visible in operational test in air (top left) and the smaller spark in water (right).

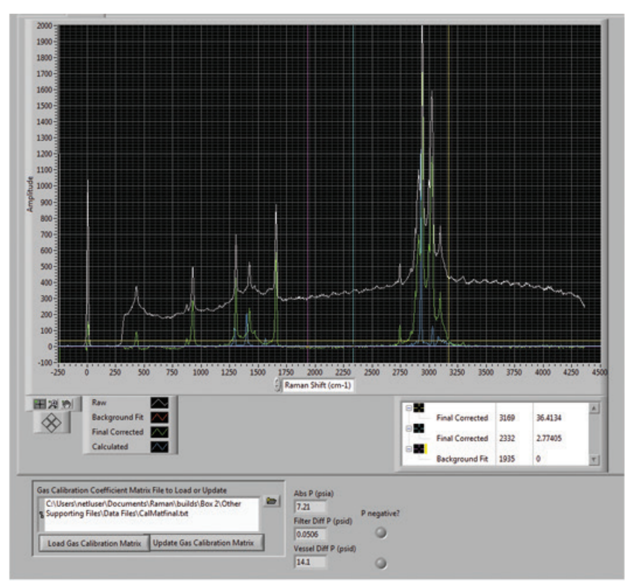
Field Testing of Raman Gas Analyzer

Performer	**National Energy Technology Laboratory (NETL)**
Award Number	FWP-1022427 Advanced Sensors and Controls -Task 41
Project Duration	04/01/2020 – 03/31/2021
Total Project Value	$ 133,000
Technology Area	Plant Optimization Technologies

Laser-based and other advanced laboratory diagnostics can be adapted to fossil energy research problems to provide non-contact sensing capabilities in harsh process environments, or to provide next-generation measurement capability for process control. Work on this project supports the field testing and improvement of the NETL-developed Raman gas analyzer (RGA), a next-generation technology for real-time composition analysis of fuel gases and other process gases. The RGA measures concentration of hydrogen, methane, ethane, and propane, as well as other common industrial gases (CO, CO_2, N_2, O_2, H_2O). It provides a new enabling technology for faster, smarter process control based on the chemical composition of the gases in the process, including improved fuel flexibility and efficiency for power generation systems.

The RGA applies Raman spectroscopy, a laboratory technique for non-destructive material analysis which has had great success previously with liquids and solids, to gases with an ingenious optical configuration which increases the signal more than 1000 times above that of the conventional approach. As a result, the composition of a gas mixture (such as natural gas or syngas) can be measured much faster than with conventional commercial technology; that is, fast enough to allow the method to be a powerful instrument to support process control. Field testing with commercial partners is the next step for technology readiness level advancement and market acceptance of the new technology. Test experience will also be used to improve the RGA to better meet the needs of end-use applications.

Raman gas analyzer field prototype.



Example of Raman spectra from gas in real-time analysis.

Optical Fiber Sensors for Harsh Fossil Energy Environments

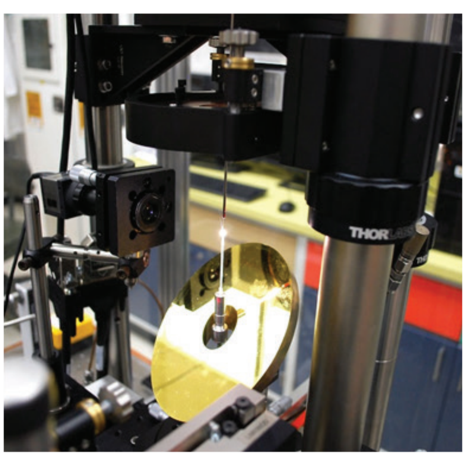
Performer	**National Energy Technology Laboratory (NETL)**
Award Number	FWP-1022427 - Advanced Sensors and Controls -Task 21-33
Project Duration	04/01/2020 – 03/31/2021
Total Project Value	$ 655,000
Technology Area	Plant Optimization Technologies

Fiber optic sensors have the potential to be applied at very high temperatures, particularly with the development of low-cost sapphire or other ultra-high-temperature optical fibers. Optical fibers may be used in multipoint sensors, allowing multiple measurement points along a single optical fiber with a single readout instrument. They have been embedded in ambient temperature applications such as structural monitoring of bridges and wind turbine blades, and could be embedded in structures of importance in fossil energy applications such as solid oxide fuel cell (SOFC) interconnects and boiler steam headers. Conventional silica optical fibers, however, have very limited durability in high-temperature process environments, particularly when exposed to hydrogen or water vapor.

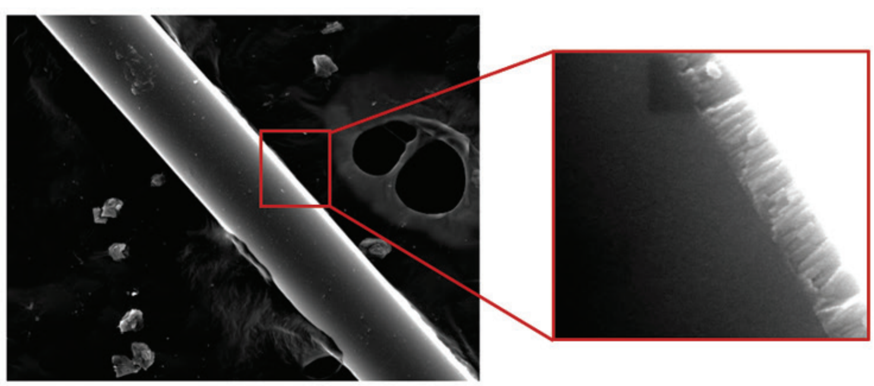
This project is pursuing technology solutions to several barriers to the widespread use of multipoint optical fiber sensors, for temperature, strain, and chemical measurements. NETL's laser-heated pedestal growth system is being utilized to refine the techniques needed to make high-temperature crystalline optical fibers (materials such as sapphire or garnet), and to develop a durable optical cladding. The optical cladding is needed to confine light within the optical fiber in many application environments.

Development of low cost and durable optical cladding and distributed interrogation for sapphire optical fibers will allow such fibers to be used for sensing in very high temperature locations beyond the capability of silica fiber, such as boiler or turbine exhaust.

Development of high-temperature functional materials for sensing of oxygen will support applications in sensing and controlling excess air levels in combustion, and support development of SOFC through measurement of oxygen levels in the cathode stream. Complementary to those efforts, methods for multipoint measurements along sapphire optical fibers are being investigated. Field testing of multipoint sensing in power plants will be performed to help mature new technology toward commercial use.



Laser heated pedestal growth system.



Functional thin films applied to optical fiber for gas sensing.

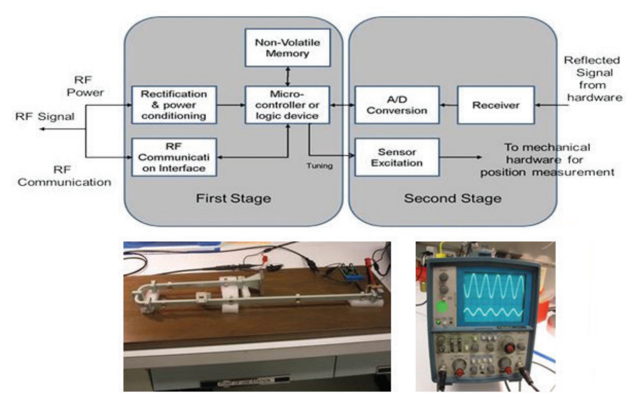
Embedded Sensors Integrated into Critical Components for In Situ Health Monitoring of Steam Turbines

Performer	Siemens Corporation
Award Number	FE0031832
Project Duration	10/15/2019 – 10/14/2021
Total Project Value	$ 1,249,898
Collaborator	United Technologies Research Center
Technology Area	Plant Optimization Technologies

Siemens, in partnership with United Technologies Corporation, proposes a holistic approach to develop embedded sensors to utilize radio frequency for not only coupling to sensors, but as the sensing modality. The goal of this project is to embed the novel sensing approach by using either additively manufactured or extruded waveguides that integrate the communications/sensing network on rotating blades for recording, evaluation, and monitoring of blade vibrations in low-pressure turbines, with applications extending to aeronautical engines.

This project (1) takes a holistic approach of integrating sensing, communication, and power into an otherwise electrically passive structural component without degrading either its functionality or lifetime and (2) renders a path for monitoring conditions inside a steam turbine with limited space, and attachment and routing constraints. The demonstration of sensor performance and acceptable materials interaction with sensor embedding (e.g., interfacing, adequate sensor lifetimes, thermal cycling durability, etc.) can show a tenfold or greater improvement in data bandwidth and communication and power transfer and a path to engine demonstration within two years. With the current intrusive blade monitoring approach involving the need to magnetize the blade and calculate the vibration amplitude and tip timing, the proposed system will transmit real-time, blade-specific data from the turbine blade, enabling a transition to lower-cost, condition-based maintenance to detect failures and precursors to failure that require maintenance.

A successful sensor could lead to cost reduction, reduced outage time, and increase availability of steam turbine equipment in existing coal-based plants. The primary cost savings comes from the potential to extend periods of operation between required maintenance downtime. In a combined cycle configuration, this extension of operations could be from 50,000 to 66,000 equivalent operating hours. In the longer term, this product may allow even longer operating times, but this ability will be determined after much stronger correlations from condition monitoring and inspection findings are established. This wireless transmission technology could potentially save power plants up to $1 million per turbine annually simply by eliminating unplanned downtime associated with the lead time on replacement parts. Another significant cost savings realized by this technology is the reduced validation costs of new engine designs. In order to validate new blade and engine designs, blade data are needed. With this new wireless multifunctional radio frequency sensing technology embedded on the blade, drilling of casings eventually can be avoided altogether. Also, severe consequences and monetary damages (in one example, up to $450 million in claim settlements occurred in an event involving a nuclear steam turbine) can be avoided by early indication of crack size that causes blades to separate.



New class of RF sensors: position, velocity, acceleration, pressure, vibration, temperature, etc.

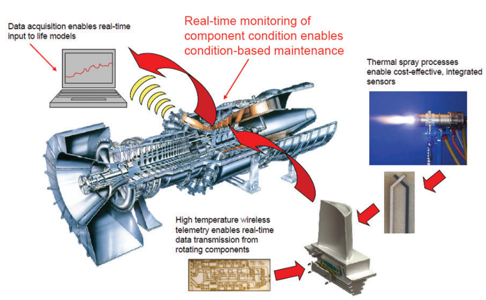
Novel Temperature Sensors and Wireless Telemetry for Active Condition Monitoring of Advanced Gas Turbines

Performer	Siemens Corporation
Award Number	FE0026348
Project Duration	09/16/2015 – 02/26/2021
Total Project Value	$ 4,687,500
Collaborator	Wolfspeed, University of Arkansas; Siemens Energy, Inc.
Technology Area	Plant Optimization Technologies

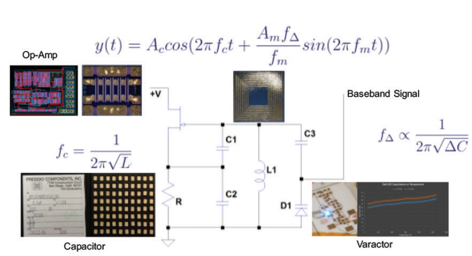
The objective of the program is to develop and engine-test hardware and software technologies that will enable active condition monitoring to be implemented on hot gas path turbine blades in large industrial gas turbines. The specific objectives are (1) to fabricate and install smart turbine blades with thermally sprayed sensors and high-temperature wireless telemetry systems in an H-class engine, and (2) to integrate the component engine test data with remaining useful life (RUL) models and develop an approach for networking the component RUL data with Siemens' Power Diagnostics® engine monitoring system.

Phase 1 has focused on down-selection of novel chemistries for ceramic thermocouples with capability to withstand 1400 degrees Celsius (°C) up to 4000 hours, development of wireless telemetry system components, and demonstration of an integrated sensor/wireless telemetry approach on a stationary lab test rig. Key successes from the Phase 1 effort include: (a) demonstration of ceramic thermocouples that showed ten-fold improvement in voltage output compared to metallic thermocouples (25 millivolts [mV] to 2.5 mV at 1200 °C), (b) development of a cutting-edge silicon carbide (SiC) integrated circuit operational amplifier-based system to perform analog signal conditioning of the sensor signal, which utilizes a closed-loop architecture to enable large, stable signal amplification across the range of operating temperatures, compared to previous open-loop architectures based around discrete SiC junction field effect transistors, which suffered from low gain that varied over temperature, (c) development of a new induced-power driver and receiver geometry capable of transferring 5 watts (W) of power over 17 millimeters, which constitutes an order-of-magnitude increase in power as compared to 0.5-1 W obtained from original designs, (d) improved wire-bond design capable of withstanding high centrifugal loading, and (e) successful lab test of the integrated sensor-wireless telemetry package on a gas turbine blade.

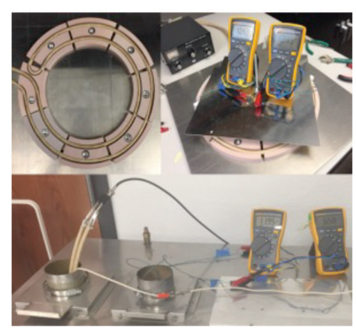
The advances in high-temperature wide-bandgap telemetry will be combined with the new geometry for an induced power driver and receiver to transmit digital data wirelessly. The current Phase 2 program will focus on validation testing of the sensor-wireless telemetry package in a spin rig and advanced operation-based assessment model utilizing artificial intelligence. Significant efforts will be expended on the application of the technology to components to be tested in an actual gas turbine engine for active condition monitoring using smart turbine blades.



Anatomy of a smart component.



High temperature wireless circuitry components



Power Transmission setup

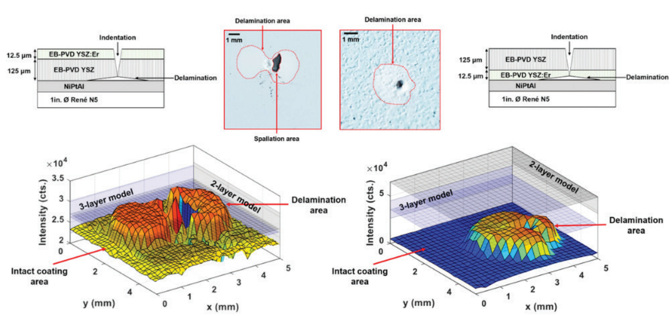
In-Situ Optical Monitoring of Operating Gas Turbine Blade Coatings Under Extreme Environments

Performer	**University of Central Florida**
Award Number	FE0031282
Project Duration	10/01/2017 – 09/30/2021
Total Project Value	$ 1,059,111
Collaborator	Siemens Energy
Technology Area	Plant Optimization Technologies

With engine temperatures exceeding the limits that metallic blades and vanes can endure, advanced monitoring techniques that ensure the integrity and durability of thermal barrier coatings are paramount to continuous and safe operation. The University of Central Florida has been using key properties of optical radiation—including temporal, spectral, and spectral intensity response modes, coupled with active sensing from coating properties—to gain diagnostic information on high-temperature thermal barrier coatings (TBCs). Materials design incorporating rare earth elements within TBCs to create the self-indicating property have been accompanied by research efforts to correlate optical measurements to TBC diagnostic parameters. This capability was demonstrated through the beneficial development of new coating delamination monitoring methods, materials and models and shown in Figure 1. The methods are being established in this project at the laboratory scale with the goal of future implementation in gas turbine conditions for improved engine efficiency and gas turbine blade lifetime.

UCF has focused on the development of an advanced phosphor thermometry instrumentation (Figure 2) that has shown higher precision and extended temperature range capabilities (the range of temperature that can be accurately measured using rare-earth doped YSZ configurations was extended up to gas turbine engine operating temperatures). This was achieved capturing simultaneously the decays and the intensity variations of a TBC system including two phosphors. The results open the way for the applicability of portable phosphor thermometry instrumentation to perform effective temperature monitoring on turbine engine materials and support the advancement of innovative sensing coatings.

This work provides a better understanding of temperature measurement locations in rare-earth doped TBCs. Using the project findings, doped TBC configurations represent a very attractive solution for precise in-situ temperature measurements and damage quantification. Current efforts in the project include the further characterization of thermomechanical properties of sensing coatings with the advanced instrumentation and benchmarked measurements.



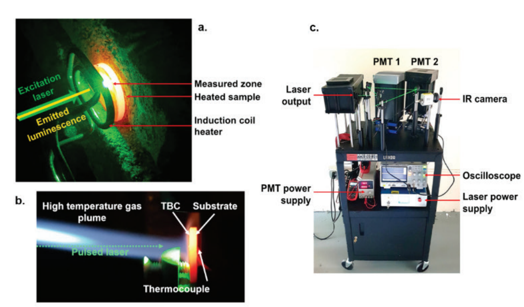


Figure 1 (left): Developed coating delamination monitoring methods, demonstrated using two sensing TBC configurations. [1]. Figure 2 (right): Lab-scale test setup configurations with a) induction system [3] and b) burner rig [5]. c) Laboratory-scale instrumentation developed for the demonstration of in-situ luminescence sensing under typical gas turbine engine temperatures [3].

High Temperature Integrated Gas and Temperature Wireless Microwave Acoustic Sensor System for Fossil Energy Applications

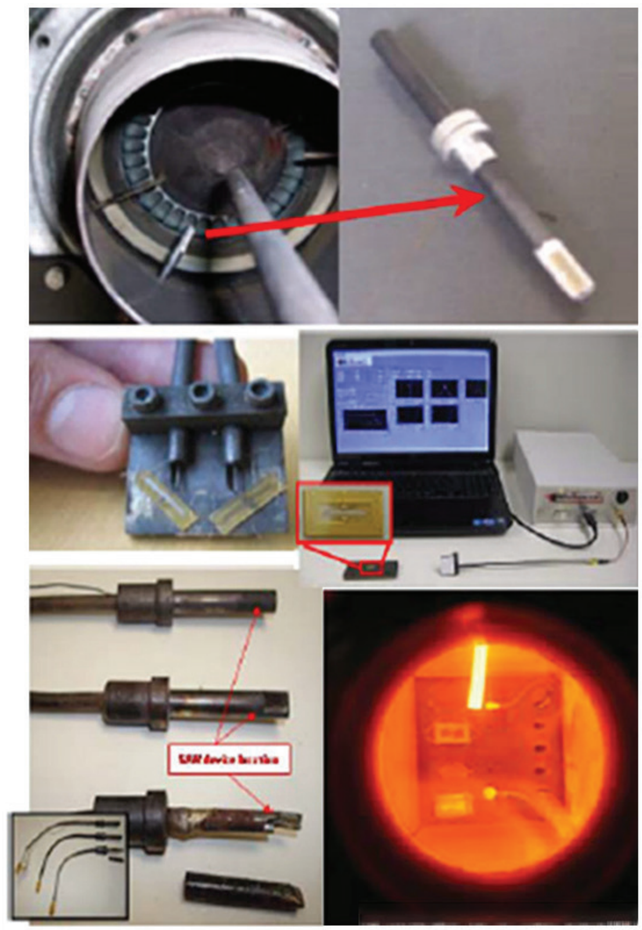
Performer	University of Maine System
Award Number	FE0026217
Project Duration	09/01/2015 – 12/31/2019
Total Project Value	$ 399,999
Technology Area	University Training and Research

The University of Maine System intends to develop a wireless integrated gas/temperature microwave acoustic sensor capable of passive operation (no batteries) from 350 to 1000 degrees Celsius (°C) in harsh environments relevant to fossil energy technologies, with specific applications to coal gasifiers, combustion turbines, solid oxide fuel cells, and advanced boiler systems.

The sensor system is based on a surface acoustic wave (SAW) sensor platform that could be used to detect hydrogen, oxygen, and nitrogen oxides and monitor gas temperatures in harsh environments. Fully packaged prototype sensors will be designed, fabricated, and tested under hydrogen (less than 5 percent), oxygen, and nitrogen oxide gas flows in laboratory furnaces, and the sensor response will be characterized for sensitivity, reproducibility, response time, and reversibility over a range of gas temperatures.

The SAW sensors have the advantage of being potentially readily scalable for rapid manufacturing using photolithography/metallization fabrication steps, followed by integrating each sensor into a stand-alone wireless harsh environment sensor package. The SAW gas sensor technology will be targeted for implementation and demonstration in a power plant environment.

Acquiring temperature and gas composition data from wireless sensors in diverse harsh environment locations in power plants will help increase fuel burning efficiency, reduce gaseous emissions, and reduce maintenance costs through condition-based monitoring.



Examples of harsh environment wireless langasite SAW sensors.

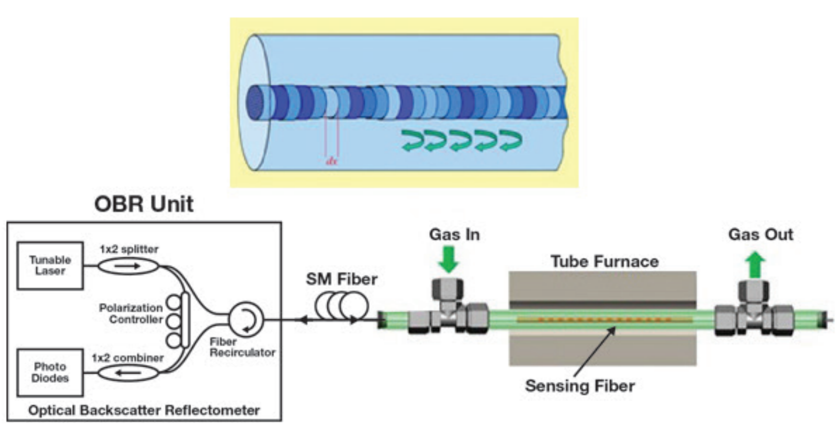
Engineering Metal Oxide Nanomaterials for Fiber Optical Sensor Platforms

Performer	**University of Pittsburgh**
Award Number	FE0028992
Project Duration	10/01/2016 – 12/31/2020
Total Project Value	$ 400,000
Technology Area	University Training and Research

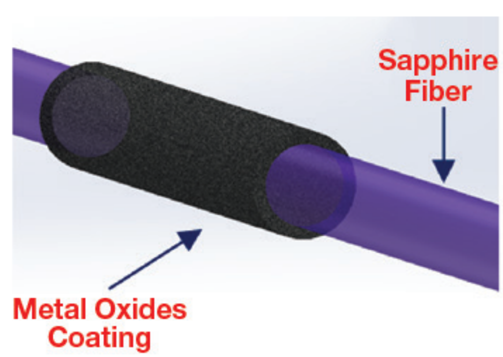
The University of Pittsburgh will explore nano-engineered metal oxides—a class of important sensor materials—for fiber optic chemical sensing for high-temperature energy applications using both silica and sapphire fibers as sensing platforms.

This project will develop an integrated sensor solution for performing direct and simultaneous measurements of chemical reactions and temperature in a solid oxide fuel cell (SOFC) with 5-millimeter (mm) spatial resolution. This project will measure the internal hydrogen consumption rate at very high temperatures (600 to 800 degrees Celsius [°C]), and test hydrogen sensors in an SOFC in the High-temperature Fuel Cell Testing Facility.

This project will develop a highly stable sensor for use in highly reactive gas streams for fossil-based power plant applications and will demonstrate real-time multi-species flue gas measurements at high temperatures (400 to 900 °C) using a single fiber.



Distributed Rayleigh scattering.



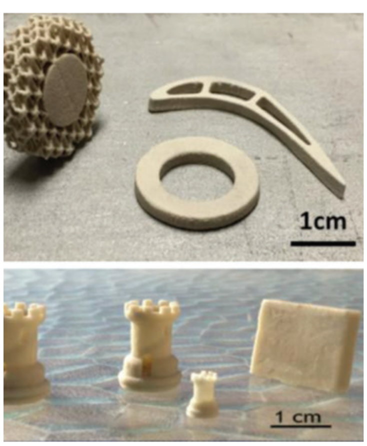
Sapphire fibers.

Additive Manufacturing of Energy Harvesting Material System for Active Wireless Microelectromechanical Systems (MEMS) Sensors

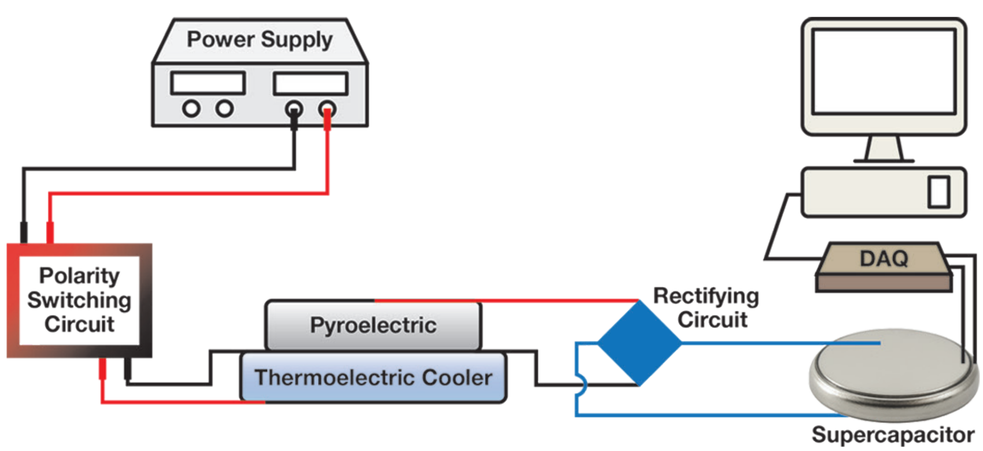
Performer	**University of Texas at El Paso**
Award Number	FE0027502
Project Duration	09/01/2016 – 08/31/2020
Total Project Value	$ 250,000
Technology Area	University Training and Research

University of Texas at El Paso is conducting R&D to design, fabricate, and evaluate an energy harvesting material system capable of working at up to 1200 degrees Celsius (°C) to harvest both vibrational and thermal energy for powering high-temperature wireless MEMS sensors. This project will establish theoretical models to predict the effective material property, fabricate ceramic-graphene composites using the binder jetting three-dimensional (3D) printing technique, and determine mechanical, thermal, and simultaneous energy harvesting properties at high temperatures.

This project will provide a full knowledge set of graphene/lithium niobate crystal modeling, 3D printing fabrication, characterization, and energy harvesting potential. Findings could lead to a new energy harvesting material design paradigm for powering wireless harsh-environment MEMS sensors.



Fabrication of complex shapes.



Thermal energy harvesting setup.

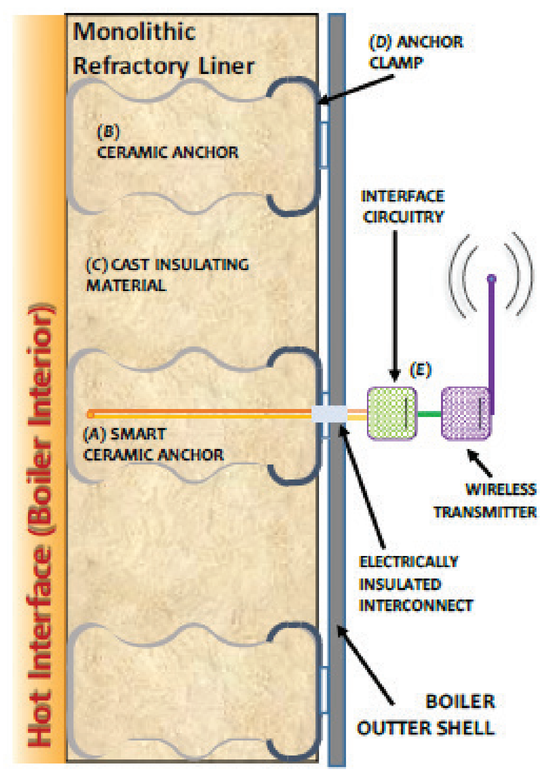
Advanced Manufacturing of Ceramic Anchors with Embedded Sensors for Process and Health Monitoring of Coal Boilers

Performer	**West Virginia University**
Award Number	FE0031825
Project Duration	01/01/2020 – 12/31/2022
Total Project Value	$ 1,254,719
Technology Area	Plant Optimization Technologies

West Virginia University Research Corporation will develop advanced manufacturing methods to fabricate and test ceramic anchors with an embedded sensor technology for monitoring the health and processing conditions within pulverized coal and fluidized-bed combustion boiler systems. The goal is to place ceramic anchors within the boiler system (such as within the primary furnace and ash hopper), where information on the temperature, strain, and local crack population can be continuously monitored. The project will include the development of advanced manufacturing technologies and processes for 3D printing electroceramic (conductive ceramic) sensor designs within the ceramic anchor microstructure during the manufacturing process.

Specifically, the project team will (1) define the chemical and microstructural stability, in addition to the electrical properties, of oxide and non-oxide ceramic composites to be embedded within the Al_2O_3-Cr_2O_3 ceramic anchor compositions that can operate at temperatures up to 1400 degrees Celsius, (2) develop and implement the 3D printing technology to pattern and control the microstructure of the ceramic anchor and embedded sensor circuits, (3) develop an interconnect technology which will permit easy installation of the ceramic anchors and signal collection at the boiler shell, (4) develop low-power analog electronics and wireless communication hardware to efficiently collect the sensor signal at each processing unit and transmit data to a central hub for data analysis, and (5) demonstrate the smart ceramic anchor system for temperature and liner fracture within a high-temperature processing unit, such as a boiler furnace or glass melting furnace floor/wall liner.

Data collected can be used to monitor the boiler refractory liner temperature and degradation, information that currently is not available to boiler operators because no sensors are currently placed within or near the boiler furnace floor, and inserting access ports within this monolithic (i.e., seamless) refractory liner is not feasible.



Schematic of boiler liner cross-section with smart anchors, metal interconnect clips/clamps, and low-power electronics.

Passive Wireless Sensors Fabricated by Direct-Writing for Temperature and Health Monitoring of Energy Systems in Harsh-Environments

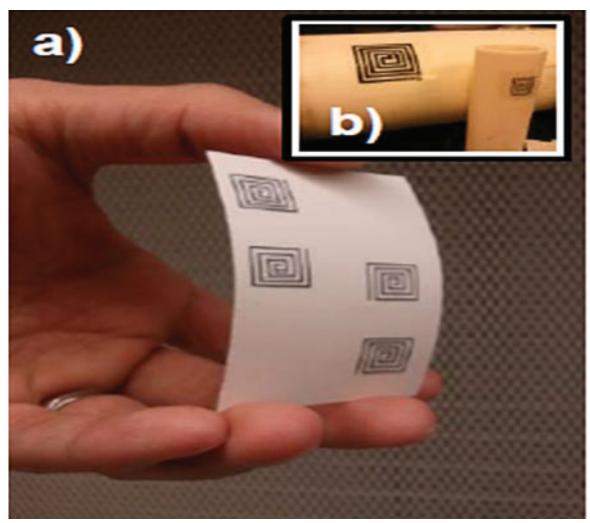
Performer	**West Virginia University**
Award Number	FE0026171
Project Duration	10/01/2015 – 09/30/2021
Total Project Value	$ 399,965
Collaborator	NexTech Materials, Ltd.
Technology Area	University Training and Research

West Virginia University will demonstrate a wireless high-temperature sensor system for monitoring the temperature and health of energy-system components. The active sensor and electronics for passive wireless communication will be composed entirely of electroceramic materials (conductive ceramics), which can withstand the harsh environments associated with advanced fossil-energy-based technologies.

The project will focus primarily on fabricating and testing thermocouples and thermistors (for temperature) and strain/ stress and crack propagation sensors (for health monitoring) that function at extreme temperatures (from 500 to 1700 degrees Celsius). To accompany the high-temperature sensor, a passive wireless communications circuit based on electromagnetic coupling that will enable transmission of the data to a nearby reader antenna will be developed, along with a peel-and-stick-like transfer process to deposit the entire sensor circuit onto various energy-system components.

The results of this research could reduce the need for interconnect wires near the active—and possibly rotating—energy-system component. The results may also permit economical and precise placement of the sensor circuit onto components of various shapes and locations, without altering the geometry and active features of the manufactured component or necessitating the removal (or decommissioning) of the component for installation.

The sensor system could be applied to solid oxide fuel cells, chemical reactors, furnaces, engines, boilers, and gas turbine systems for both energy and aerospace applications.



a) Picture of spiral inductor pattern ink-jet printed of ceramic ink onto fugitive carrier film, and b) Picture of two patterns transferred to alumina tubes by West Virginia University's "peel & stick" process.

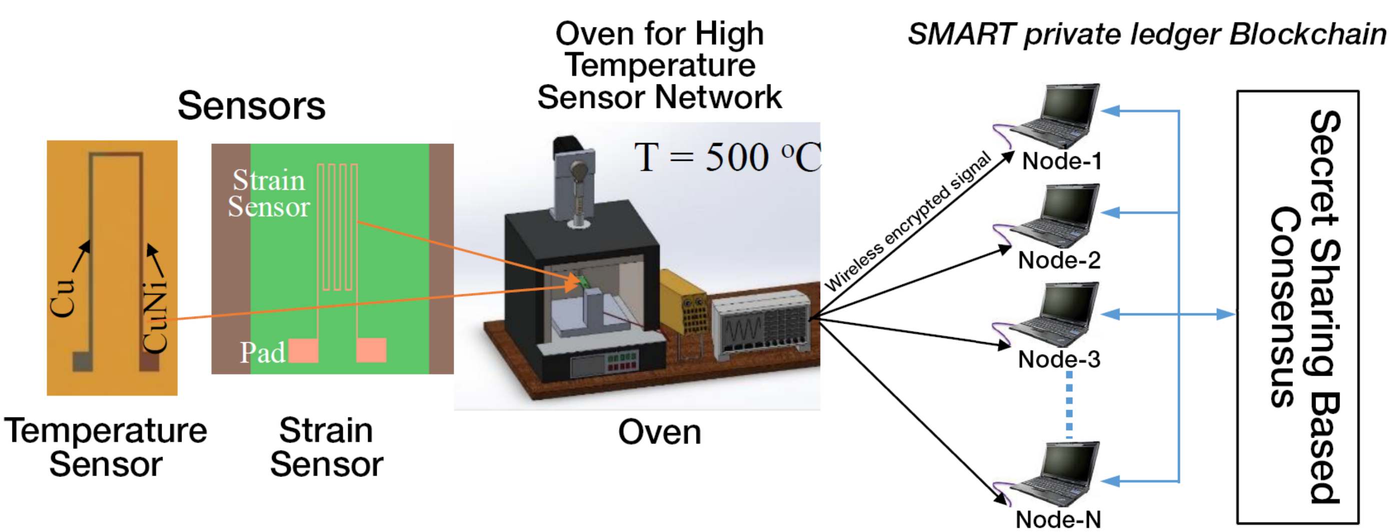
CYBERSECURITY

A Novel Access Control Blockchain Paradigm to Realize a Cybersecure Sensor Infrastructure in Fossil Power Generation Systems

Performer	**Carnegie Mellon University (CMU)**
Award Number	FE0031770
Project Duration	09/01/2019 – 08/31/2021
Total Project Value	$ 400,000
Technology Area	University Training and Research

The goal of this project is to demonstrate a secure private blockchain protocol designed for fossil power generation systems. The specific objectives include (i) design and implementation of a secure private blockchain architecture that can secure process signal data and other information flows within distributed sensor networks for fossil-based power generation systems, (ii) a simulated power plant environment that uses sensor data with cryptographic digital signatures and integration of the secure blockchain developed by the project team with this system, (iii) demonstration of the effectiveness of the developed blockchain technology by simulating a cyber-attack on the sensor infrastructure.

Benefits include a more secure system for data management for fossil power generation systems, and preparation of the next generation of researchers and engineers with highly interdisciplinary and complementary skills in these important areas for their own careers and maintenance of U.S. leadership in fossil energy sciences and technology.



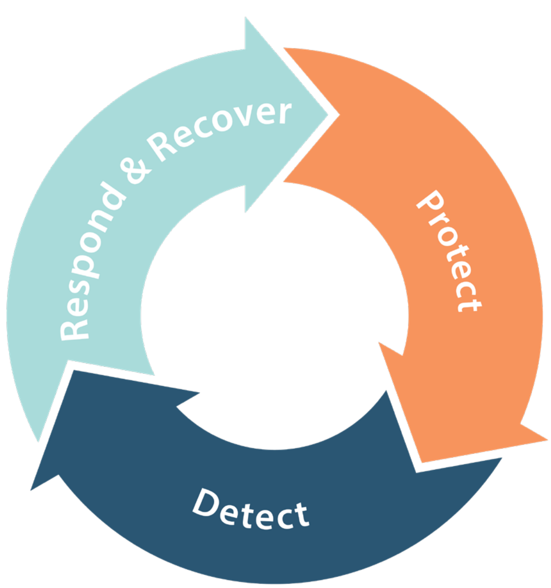
Integration in data acquisition system.

Cyber Security Risk Reduction Framework for Generation I&C Technology

Performer	**Electric Power Research Institute, Inc.**
Award Number	FE0031643
Project Duration	09/01/2018 – 08/31/2020
Total Project Value	$ 241,193
Technology Area	Plant Optimization Technologies

The objectives of the research are to develop a holistic risk reduction framework that (1) identifies the lifecycle of appropriate use cases of instrumentation and control (I&C) equipment in generating plants, (2) provides methodologies to protect power generation I&C equipment that reduces sensitivity to the changing threat landscape, (3) identifies technologies, programs, processes, integrations, and evolving approaches to detect and achieve threat-resilience against cyber-attacks, and (4) identifies processes for the design of systems to ensure that cyber security principles are incorporated from the outset. In addition, the objective of the framework development is to identify research area gaps and provide recommendations on future research items to advance cyber security for power generation I&C equipment. These objectives will be accomplished by incorporating past power generation-specific and cross-sector cyber security research as well as leveraging an advisory board of utility and vendor subject matter experts to capture operating experience and lessons learned.

The framework developed will enable utilities to: (1) identify the lifecycle use case in which their specific technology is staged, (2) use industry best-practice guidance, cyber security methods, technologies, and design to manage the changing threat landscape and remain compliant through changing regulatory requirements, (3) communicate with vendors and service providers on technology, features, functions, and capability requirements for designing cyber security into products and networks, and (4) identify internal programmatic, process, and integration areas of improvement to enhance overall cyber security.



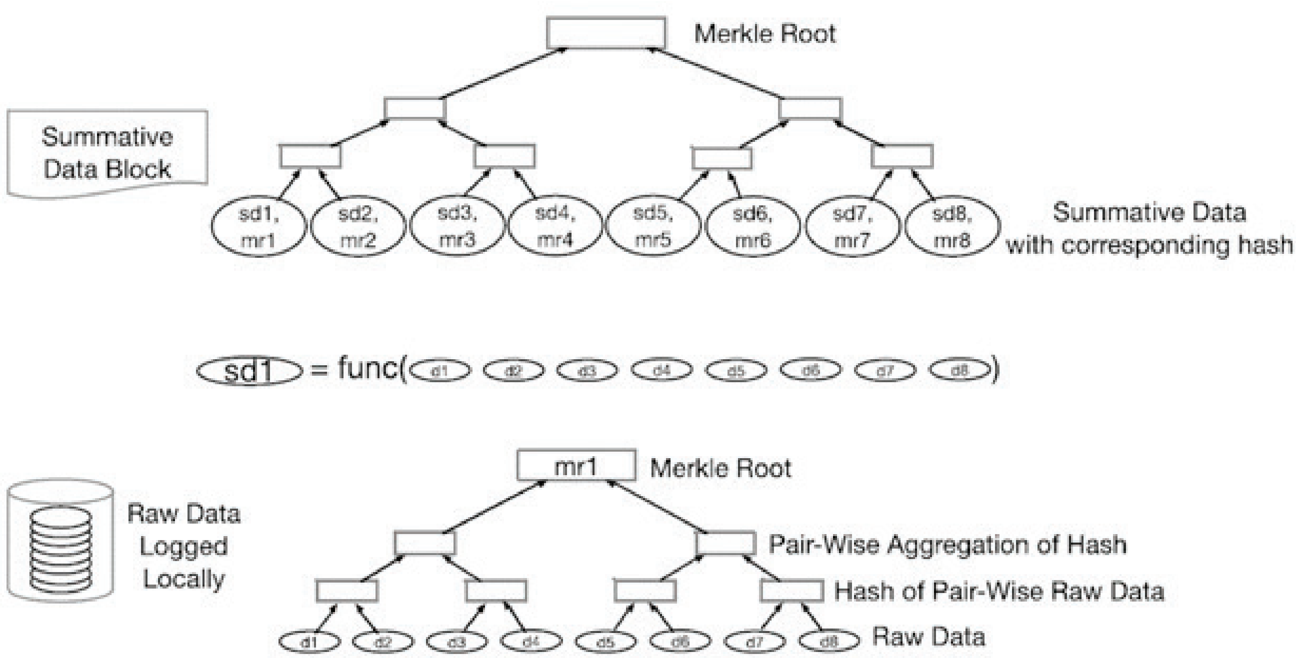
Electric Power Research Institute cyber security applied research focus areas.

Secure Data Logging and Processing with Blockchain and Machine Learning

Performer	**Florida International University**
Award Number	FE0031745
Project Duration	09/01/2019 – 08/31/2022
Total Project Value	$ 400,000
Collaborator	Cleveland State University
Technology Area	University Training and Research

The scope of work of this project includes (1) secure data logging for 'smart' sensors and wireless communications; (2) authentication and identity verification of sensor nodes, actuators, and other equipment within a network; and, (3) decentralized data storage. Florida International University will develop a novel platform that integrates two emerging technologies, namely blockchain and machine learning. This platform will incorporate a mechanism that ensures that only data sent by legitimate sensors are accepted and stored in the data repository, a suite of data aggregation methodologies using machine learning/deep learning algorithms to minimize noise and faulty data, and a two-level secure logging mechanism supported by an energy-aware blockchain solution.

If the project is successful, the fossil energy community will be able to develop a better understanding of how to securely store sensor data from various equipment in the power generating infrastructure. It will reduce data theft while increasing data logging efficiency.



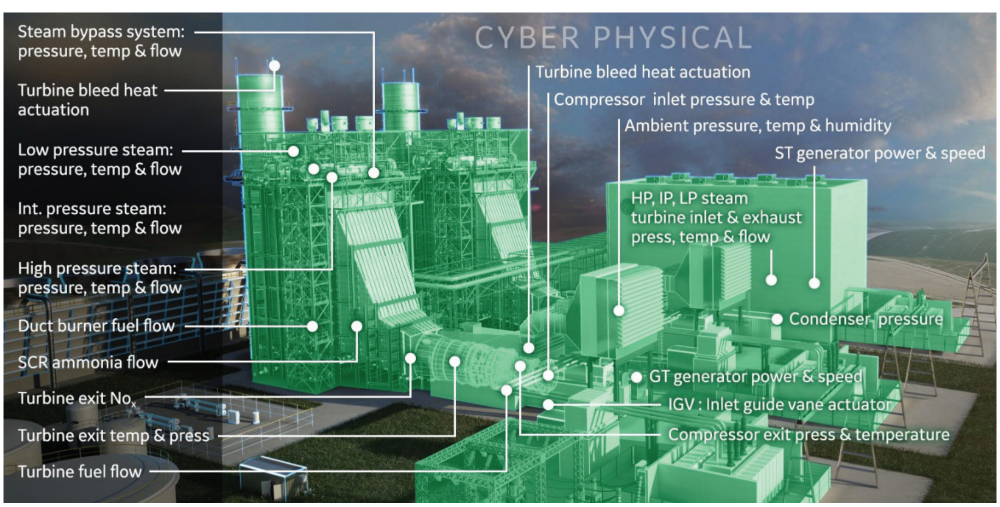
The two-level secure logging mechanism.

Physical Domain Approaches to Reduce Cybersecurity Risks Associated with Control Systems

Performer	**General Electric (GE) Company**
Award Number	FE0031641
Project Duration	10/01/2018 – 09/30/2020
Total Project Value	$ 312,076
Technology Area	Plant Optimization Technologies

General Electric Company (GE) will perform a comprehensive analysis of current state-of-the-art approaches that use distributed sensors and controls technology for securing fossil power plants from cyber-risks. The study will analyze physical domain approaches and fault-tolerant controls or similar technology extensible to cybersecurity needs (e.g., detection and neutralization of effects of cyber-attacks or faults). The team will use a generic reference solution example and assess the suitability to fossil power generation assets. The reference solution framework, being a physical defense layer, is unlike the conventional protections offered by information technology and operational technology employed in many industrial control systems. It uses a hybrid technical approach combining theoretical advances from multiple disciplines such as system physics, human physiology, machine learning, and control and estimation, with abilities to simultaneously process copious amounts of data from a heterogeneous sensing environment and learn from it. GE will also investigate further optimization and breakthroughs unique to fossil power plants. The paper study will report on (1) a survey of the cybersecurity landscape affecting control systems of fossil fuel power plants; (2) a list of high-risk threats and faults, identified vulnerabilities, risk factors, and their impacts; (3) capabilities of existing fault-tolerant control systems; (4) the applicability of current DOE-funded efforts; (5) the applicability of secure communications technologies; and (6) identified technical and non-technical gaps.

The key outcome of this study is a comprehensive analysis and methodology—vetted by industry experts to systematically identify gaps—that, when developed, reduces cybersecurity risks in control systems used for fossil powered generation systems such as gas and steam turbines, including those with environmental controls.



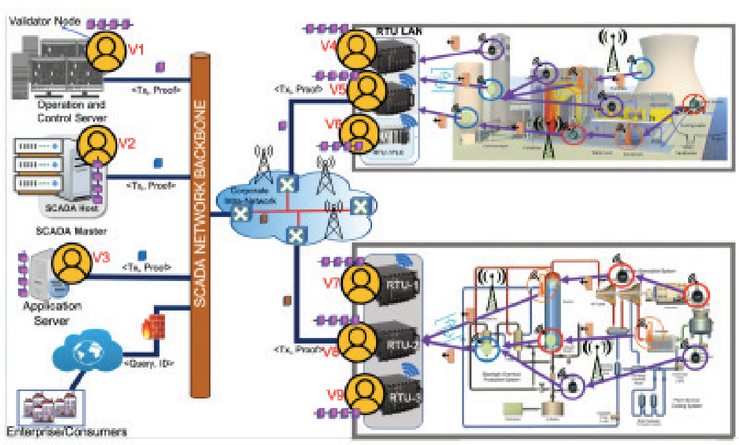
Study current state-of-the-art physical domain approaches applicable to reducing cybersecurity risks associated with the deployment of distributed sensors and advanced controls to fossil power generation assets.

Blockchain Empowered Provenance Framework for Sensor Identity Management and Data Flow Security in Fossil-Based Power Plants

Performer	Old Dominion University
Award Number	FE0031744
Project Duration	09/01/2019 – 08/31/2022
Total Project Value	$ 400,000
Collaborator	University of Texas at El Paso
Technology Area	University Training and Research

Old Dominion University will develop a blockchain-based provenance platform that would track data flow traffic from sensors deployed in fossil-based power plants and detect identity violations, unauthorized communication, and process integrity violation. The proposed platform will be scalable across a geographically distributed footprint. The blockchain-based platform would detect the presence of rogue or unauthorized sensors and unauthorized communication amongst the authorized sensors based on identity profiles derived from the analysis of network traffic. The proof-of-stake consensus protocol in the blockchain platform will be customized to ensure validation of transactions would take place on the order of milliseconds and achieve a balance between scalability and resilience based on the optimal number of validating nodes. Finally, the team will provide empirical evaluation of the proposed identity management, process integrity, and scalability by testing the system on both uncongested and congested networks.

The proposed framework will ensure high availability of a distributed ledger, which will be used to verify validity of process/signal data. A trusted framework with integrity assurance that is resilient against cyber-attacks will be developed. Analytics software can query the blockchain ledger and be assured that the process data integrity, which cannot be altered by a single malicious entity, is maintained. The provenance capability within the blockchain platform would provide the ability to audit equipment operations to ensure that they are operating according to terms and conditions of a service agreement. This capability would provide real-time validation of sensor data and detect incidental/accidental/malicious incidents that could cause the equipment to operate in violation of the service level agreement.



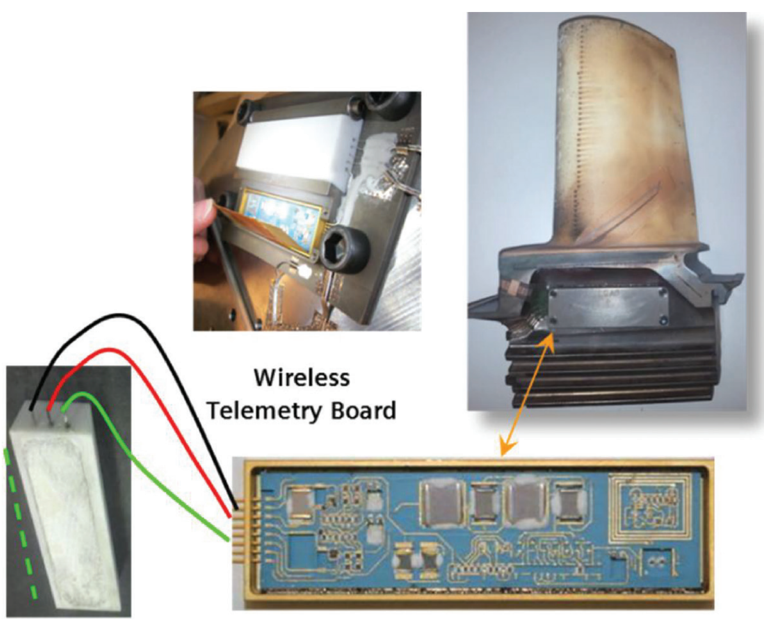
Blockchain architecture for fossil power plants.

Cyber Secure Sensor Network for Fossil Fuel Power Generation Assets Monitoring

Performer	Siemens Corporation
Award Number	FE0031666
Project Duration	08/31/2018 – 08/30/2020
Total Project Value	$ 312,500
Technology Area	Plant Optimization Technologies

The project objective is to develop a technology framework for integrating current cyber-physical security solutions with connected sensors that are deployed within fossil-fueled power generation plants. The proposed solutions will utilize Siemens-developed harsh environment wireless telemetry systems based on state-of-the-art wide bandgap (WBG) semiconductor devices, cutting-edge embedded passive components, and extreme-temperature packaging systems that can achieve harsh-environment capabilities such as wireless deployment of temperature sensing (greater than 1200 degrees Celsius) on rotating gas turbine components (high g-loads of approximately 16,000 g) in the hot gas path. Proposed security solutions aim to achieve a protection profile comprising (a) sensor component integrity (including at the integrated circuits level) protection; (b) detection of device firmware/software modification; and (c) detection of sensor parts quality degradation. The proposed cyber intrusion detection technology relies on secure control flow integrity of sensor applications based on side channel information monitoring such as device power consumption and electromagnetic emanations.

The proposed intrusion detection method is passive and "air-gapped", i.e., the setup of signal collection and signal processing platform does not rely on internet connection, so hackers will not be able to exploit the detection setup via a remote connection. Because addition of security functionalities requires no hardware modification or software purchase, the intrusion detection method proposed will provide a cost-saving solution.



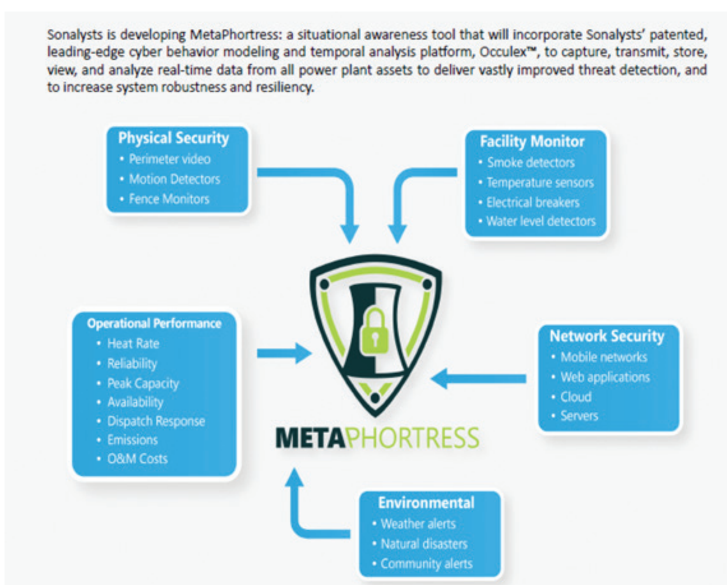
High-temperature wireless telemetry system integrates with turbine condition monitoring.

Metaphortress: A Situational Awareness Platform

Performer	**Sonalysts, Inc.**
Award Number	SC0018729
Project Duration	07/02/2018 – 08/18/2021
Total Project Value	$ 1,779,950
Technology Area	Plant Optimization Technologies

The team is creating an automated situational awareness tool that adapts its proven, patented cyber feature extraction and behavior analysis platform to provide comprehensive, simultaneous coverage of fossil power plant industrial control systems, information technology networks, and physics access control systems. The tool performs data fusion upon networked sensor outputs to characterize nominal operational modes, and then uses data analytics to detect deviations from those modes to determine which anomalous conditions correspond to malicious behavior and alert system operators to emerging cyber incidents. The enabling platform employs a temporal aggregation methodology that models dynamic, emergent threat behaviors and models the behaviors of known threats. The methodology is threat-centric: it categorizes the behavior of network entities instead of being a standard alert- or alarm-centric approach that classifies individual network incidents without associating them to entities. Aggregated behavior analysis makes the proposed situational awareness tool uniquely adept at discovering malicious entities that attempt multiple vectors across attack surfaces and attacks that unfold over varied timescales.

The automated tool will ultimately provide situational awareness for the full range of fossil fuel power generation infrastructure. In Phase II, the team will build upon the Phase I efforts by conducting a stakeholder forum, collaborating with industry subject matter experts, and developing a single-position prototype for delivery in Phase III. The Phase III effort will add distributed capabilities to the tool that will allow fossil fuel power plant owners and operators to coordinate their detection of area-wide anomalous conditions, obtain the information they need for mitigation, and ultimately share their detected threat behavior information with other facilities. The successful execution of this vision will greatly contribute to the resilience, safety, and reliability of the critical power generation infrastructure of the United States.

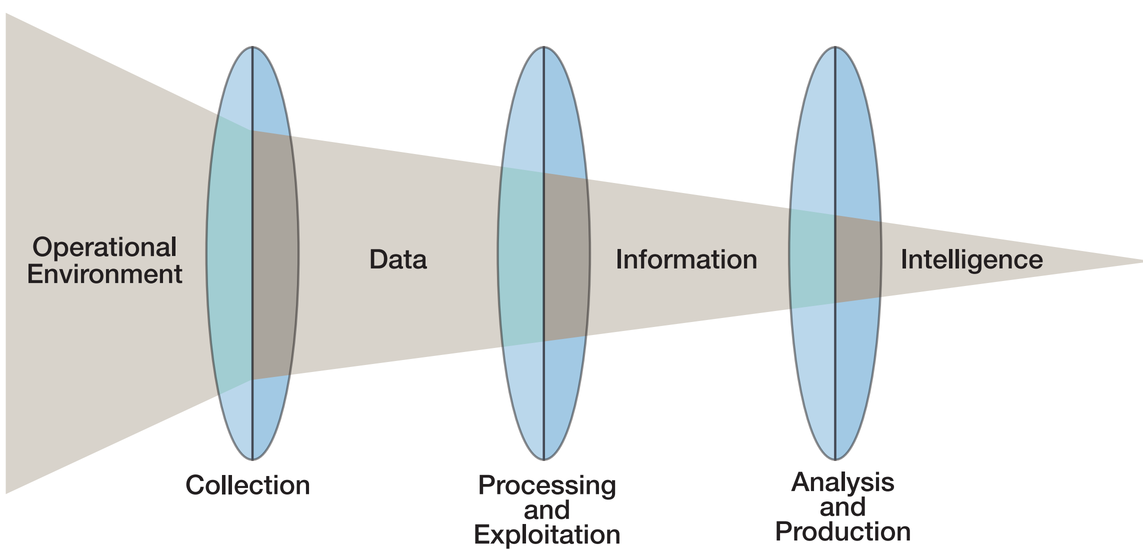


Operational Technology Behavioral Analytics

Performer	**Southern Company Services, Inc.**
Award Number	FE0031640
Project Duration	10/01/2018 – 09/30/2021
Total Project Value	$ 322,894
Technology Area	Plant Optimization Technologies

The objective of this project is to enable, improve, and protect power systems by melding traditional information technology (IT) cyber security, operational technology (OT) sensor and platform information, data analytics, and machine learning. This application of proven cyber security techniques with non-traditional data sources will enable real-time and predictive detection of anomalous power system behavior. The correlation of broad data sources will be used to detect pattern-like trends leading to the theory of operational technology behavioral analytics (OTBA). Models and associated analytics will be deployed for real-time monitoring and protection of operational networks.

The desired outcome is improved operational understanding, protection of power systems, and ability to respond to cyber threats through the creation of a data-centric predictive anomaly detection strategy for OT environments that is repeatable with minimal effort and cost while utilizing existing plant data.



Data analytics approach which leverages process information from operational environments at power plants for enhanced cybersecurity.

E-Blockchain: A Scalable Platform for Secure Energy Transactions and Control

Performer	**Taekion (formerly Grid7, LLC)**
Award Number	SC0017766
Project Duration	06/12/2017 – 08/26/2020
Total Project Value	$ 1,149,210
Technology Area	Plant Optimization Technologies

During its SBIR Phase I effort, Taekion built an innovative proof-of-concept software platform, E-Blockchain, which is built upon an enhanced blockchain layer to enable secure transaction and control applications within the SmartGrid or "Grid of Things" domain. The focus is on applications that involve the integration of centralized and decentralized powerplant control systems with industrial internet of things (IIoT) networks. The E-Blockchain software platform provides critical capabilities to (1) reduce the risk of cybersecurity threats for power system-based IIoT networks, (2) increase SmartGrid reliability, (3) reduce power plant emissions, and (4) increase plant efficiencies. The E-Blockchain platform is designed to be scalable, resilient, secure, and resistant to quantum computer attacks, which is well suited for power-system-based IIoT networks. In Phase II, E-Blockchain will be beta tested for commercial operation.

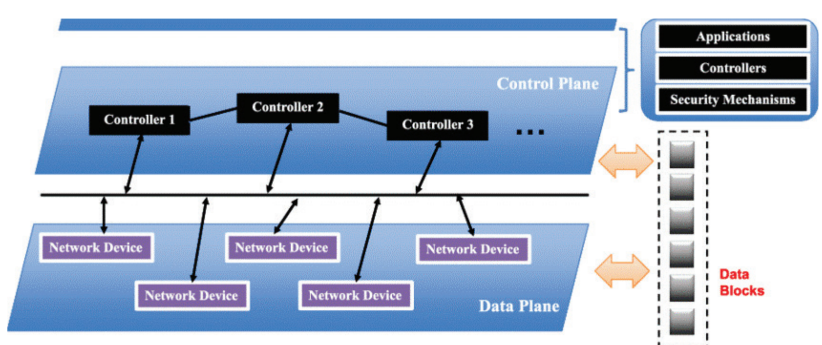
Project overview.

Incorporating Blockchain/P2P Technology into an SDN-Enabled Cybersecurity System to Safeguard Fossil Fuel Power Generation Systems

Performer	**University of North Dakota Energy and Environmental Research Center (UNDEERC)**
Award Number	FE0031742
Project Duration	09/01/2019 – 08/31/2022
Total Project Value	$ 400,000
Technology Area	University Training and Research

This project will investigate the functionality and performance of a blockchain/peer-to-peer (P2P)-enhanced, software-defined networking (SDN)-enabled cybersecurity protection system. This cybersecurity system will operate on a group of controllers which form the control plane of an SDN system. The group of SDN controllers determine how traffic flows are handled passing through switches in the SDN forwarding plane. The forwarding switches relay the communications traffic flows among the cyber-capable devices (e.g., monitors and actuators) deployed in the industrial control system (ICS) for managing and controlling the power plant, transformer yard and power bus functions, transmission system, and distribution substations. The actions of handling traffic flows reflect the desire of an ICS for allowing legitimate flows and blocking suspicious traffic flows pertaining to possible network intrusions or denial-of-service attacks. The actions are expressed in the form of rules which can be programmed into the forwarding switches by the SDN controllers. Cybersecurity protection based on the present SDN technology is susceptible to attacks targeting the control plane or targeting the communications between the forwarding and the control planes. However, the PIs believe that blockchain/P2P technology can be incorporated into an SDN-based cybersecurity protection system to mitigate the security risks. The prototype of a blockchain/P2P-enhanced cybersecurity protection system can be used to demonstrate a cost-effective reinforcement of the security protection safeguarding the operations of fossil fuel power generation systems. A testbed needs to be developed to examine the technical feasibility of incorporating blockchain/P2P technology into an SDN-enabled cybersecurity protection system, from both inter-operability and performance perspectives.

This project will also create a synergy between the University of North Dakota and its project partner, Minnkota Power Cooperative, for addressing the practical need of cybersecurity protection over fossil fuel power generation systems. In the long term, the project is expected to facilitate the sustained efforts in advancing ongoing research in adopting emerging technologies to enhance cybersecurity protection in a broader range of applications.



The generic framework of blockchain-based SDN.

DATA ANALYTICS

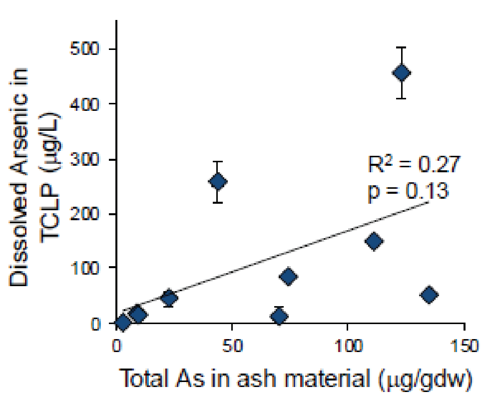
Characterization of Arsenic and Selenium in Coal Fly Ash to Improve Evaluations for Disposal and Reuse Potential

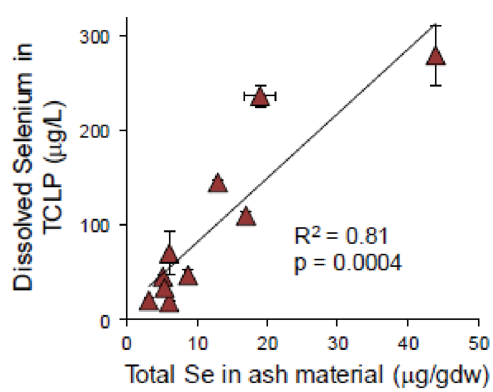
Performer	**Duke University**
Award Number	FE0031748
Project Duration	09/01/2019 – 08/31/2022
Total Project Value	$ 400,000
Technology Area	University Training and Research

This project aims to establish high throughput characterization methods for arsenic (As) and selenium (Se) species in coal fly ash and understand how coal combustion parameters might influence leachable As and Se contents from fly ash. Specifically, the project will (1) compare methods for determining As and Se concentration, chemical speciation, and mass distribution in fly ash and establish the efficacy of these methods taking into account data quality and operator accessibility, (2) evaluate As, Se, and fly ash characteristics and measurement methods that can improve indications of leachability and mobilization potential from fly ash, and (3) perform a survey of As and Se characterization for fly ashes representing a variety of coal feedstocks, combustion conditions, and emissions controls. Duke University will study methods to quantify the chemical forms of As and Se by comparing a series of state-of-the-art quantitative methods (e.g. synchrotron-based X-ray spectroscopy and microsocopy) with alternative 'benchtop' spectroscopy methods that are commonly employed in the materials and geological sciences.

The evaluation will consider benefits and trade-offs of each method, including quantitative versus qualitative determination, throughput capacity, and ease of sample processing. These characterization techniques will be compared to As and Se mobilization potential from fly ash as indicated by waste leaching protocols established by waste disposal regulations. These evaluations of As and Se concentration, speciation, mass distribution, and mobilization potential will be applied to a large variety of coal fly ashes that represent a range of coal sources, boiler type, ash collection systems, emissions controls, and combustion conditions.

Results obtained from this work will enable practitioners to understand data generated from qualitative methods that may be more accessible than state-of-the-art synchrotron techniques. A comprehensive database of As and Se speciation in a variety of coal fly ashes and other residuals will be generated. The study will outline advantages and tradeoffs for each method and establish correlations to leaching potential.





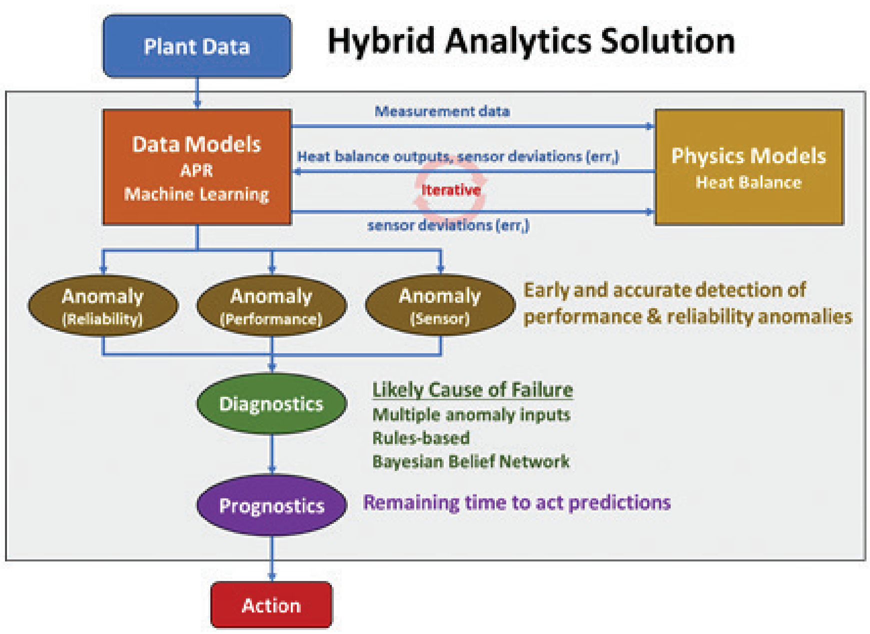
Leachable As and Se from 10 coal ash samples subjected to the toxicity characteristic leaching procedure. Data from Schwartz et al. 2018

Hybrid Analytics Solution to Improve Coal Power Plant Operations

Performer	**Expert Microsystems, Inc.**
Award Number	FE0031753
Project Duration	10/01/2019 – 09/30/2021
Total Project Value	$ 989,616
Collaborator	MapEx Software, Inc.; XMPLR Energy LLC
Technology Area	Coal Utilization Science

The goal of this project is to develop, demonstrate, and commercialize a new real-time monitoring approach (the Hybrid Analytics Solution) to improve coal plant operations. This hybrid analytics software tool will provide real-time information on the relationship between plant operational data (such as measured temperatures, pressures, and flow rates) and plant performance and reliability. The hybrid analytics solution will integrate machine-learning-based data analytics with thermal analysis in a manner that enables increased accuracy and scope of the thermal analysis, resulting in improved ability of the data analytics to monitor changes affecting plant operations.

The anticipated outcome of this project will be a plant monitoring and modeling system that will be able to recognize patterns of operation involving the fuel composition, excess oxygen, measured gas temperatures, air leakages, tube bank metal temperatures and heat transfer rates, steam/water temperatures, and boiler efficiency. With the hybrid analytics solution, operators will be able to understand these patterns to find "sweet spots" where plant performance is optimized and to optimize control strategies for flexible plant operation.



The data analytics and heat balance analysis exchange information as part of the data-driven advanced pattern recognition analysis.

Deep Analysis Net with Causal Embedding for Coal Fired Power Plant Fault Detection and Diagnosis

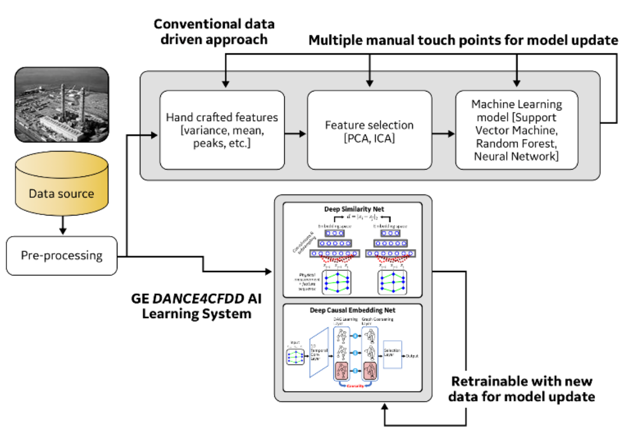
Performer	**General Electric (GE) Company**
Award Number	FE0031763
Project Duration	09/01/2019 – 08/31/2021
Total Project Value	$ 2,499,796
Collaborator	Electric Power Research Institute, Inc.; Southern Company Services, Inc.
Technology Area	Plant Optimization Technologies

GE Research, in collaboration with Electric Power Research Institute (EPRI) and Southern Company Services Inc., is developing a novel end-to-end trainable artificial intelligence (AI)-based multivariate time series learning system for flexible and scalable coal power plant fault detection and root cause analysis (i.e., diagnosis) known as Deep Analysis Net with Causal Embedding for Coal-fired power plant Fault Detection and Diagnosis (DANCE4CFDD).

The objective of the proposed program is to develop DANCE4CFDD AI learning system and bring the technology maturity from TRL 2 to TRL 5, with final validation performed based on data from a coal-fired power plant. DANCE4CFDD aims to address a range of challenges faced by today's asset health management system for coal-fired power plants: (1) high-dimensional nonlinear interaction among multiple time series measurements; (2) high measurement variance induced by operational conditions/modes; (3) variation among asset types and plant configurations; and (4) a small number of faulty events to learn from. DANCE4CFDD aims to address these real-world challenges with a combination of two novel components: a deep similarity net and a deep causal embedding net.

At the end of this program, the validated DANCE4CFDD AI learning system is expected to produce the following benefits:

- State-of-the-art accuracy.
- Applicability to a broad range of asset types and plant configurations for improving coal-fired power plant reliability.
- Learnability with even a small number of faulty events from plant data, addressing a major real-world challenge.
- High scalability—reduce development time by 50 percent by eliminating the need for manual and time-consuming domain expert feature engineering.
- A foundation for sustainable AI model life-cycle updating due to its end-to-end trainability.



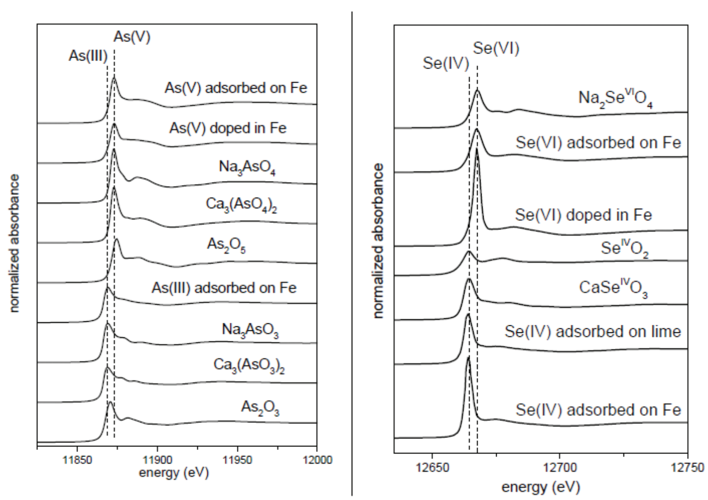
DANCE4CFDD AI learning system approach compared to conventional approach.

Elucidating Arsenic and Selenium Speciation in Coal Fly Ashes

Performer	**Georgia Tech Research Corporation**
Award Number	FE0031739
Project Duration	07/01/2019 – 06/30/2022
Total Project Value	$ 399,706
Collaborator	Electric Power Research Institute
Technology Area	University Training and Research

This research will systematically characterize arsenic (As) and selenium (Se) speciation within a representative matrix of coal fly ashes using state-of-the-art synchrotron X-ray spectroscopic and microscopic techniques in order to develop a comprehensive correlation and searchable database for coal source/type, generation condition, As/Se speciation, and As/Se mobility. The project will be implemented in three phases. Phase I will establish a detailed survey documenting the current state of knowledge on fossil power generating units as a function of coal type/source, operating conditions, environmental control systems, additive use, and fly ash handling methods, as well as common existing techniques for analyzing As and Se concentration. Based on this survey, a matrix of fly ash samples representing a range of conditions will be chosen, collected, and used for Phase I studies. Phase II is composed of three main tasks: (1) traditional characterization techniques will be conducted to provide bulk characteristics of the fly ash samples, such as elemental composition, microstructure, chemical and mineralogical composition, surface area, and particle size distribution, (2) state-of-the-art synchrotron X-ray microscopy and spectroscopy techniques will be applied to reveal the molecular scale speciation information of As and Se, such as oxidation state, association with other elements/minerals, embedded mineral phase, and complexation states, and (3) the mobility of As and Se in the fly ash samples will be evaluated using different leaching methods. Phase III will incorporate the information obtained from phases I and II and establish a searchable database, detailing the correlations among coal type/source, utility operating conditions, As/Se speciation, and As/Se mobility.

When successfully completed, this technology will allow plant operators to quickly asses the amount and valence state of heavy metals in their coal fly ash.



As K-edge XANES spectra of selected reference compounds (left),
Se K-edge XANES spectra of selected reference compounds (right)

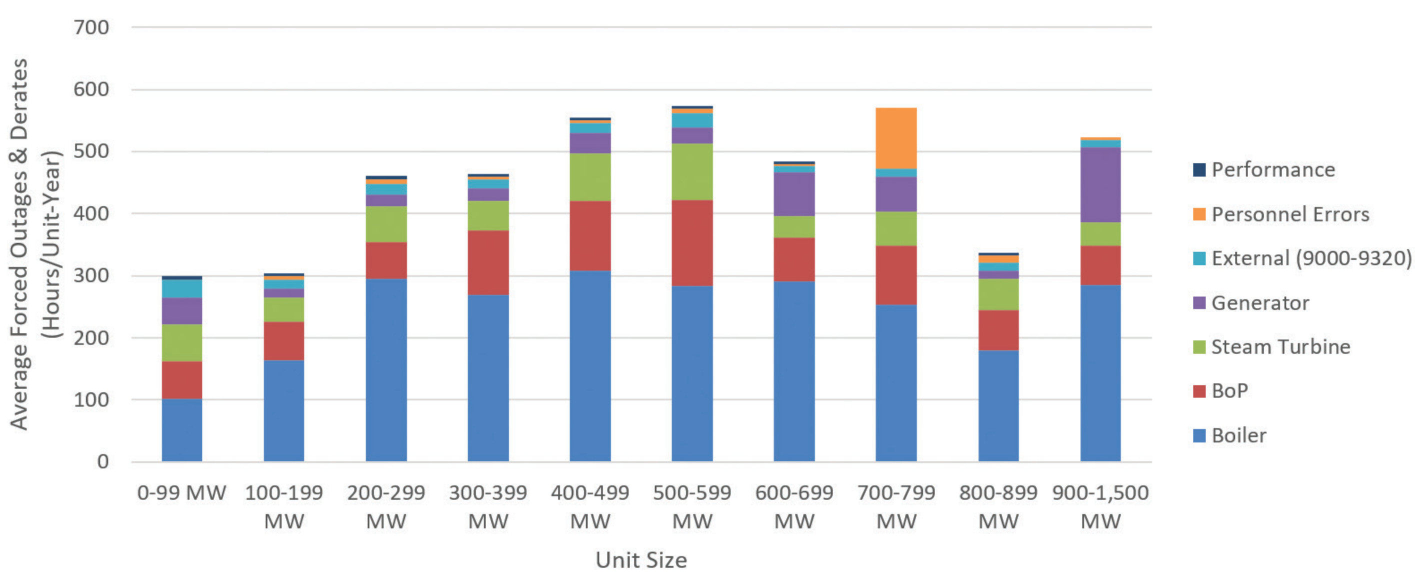
Market and Benefits Analysis

Performer	National Energy Technology Laboratory (NETL)
Award Number	FWP-1022427 Advanced Sensors and Controls – Task 64
Project Duration	04/01/2020 – 03/31/2021
Total Project Value	$ 100,000
Technology Area	Plant Optimization Technologies

The research and development projects managed by NETL aim to develop advanced sensors and controls necessary to optimize both operation and performance to achieve seamless, integrated, flexible, and intelligent power systems. These projects span harsh environment sensors, advanced controls, inspection technologies including robotics, data analytics and artificial intelligence, and cybersecurity. While most of the R&D is at an early technology readiness level, it is still important to perform system analysis studies to show the benefits and potential market penetration of this research.

Historically, the primary economic benefit of advanced sensors and controls was expected to accrue through improvements to plant efficiency (heat rate). Recent changes to the dispatch and operation of coal-fired power plants, however, have changed the economic management of their operation. Frequent operational cycling is causing increased maintenance costs, and part load performance is of much greater importance. The techno-economic analysis of the benefits of advanced sensors and controls needs thoughtful revision to capture the potential benefits including better information for management of component degradation and greater flexibility of operation.

This project will map commercial sensor technology and ongoing research and their relation to early detection of boiler failure mechanisms, which will provide insight into technology gaps.



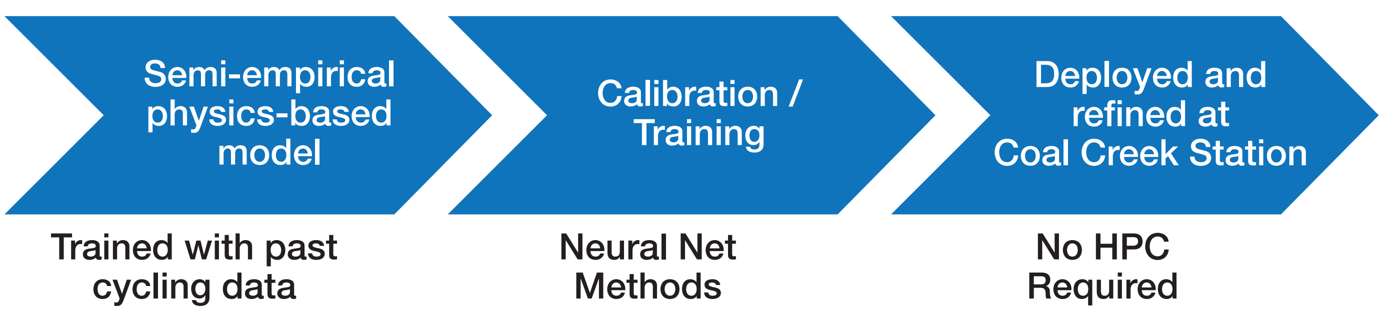
Average annual forced outage hours for coal-fired units (2013–2017), from analysis of NERC GADS data.

Generation Plant Cost of Operations and Cycling Optimization Model

Performer	**National Rural Electric Cooperative Association (NRECA)**
Award Number	FE0031751
Project Duration	10/01/2019 – 03/31/2022
Total Project Value	$ 2,010,400
Collaborator	Great River Energy; Pacific Northwest National Laboratory; Purdue University
Technology Area	Coal Utilization Science

The National Rural Electric Cooperative Association (NRECA) in collaboration with Great River Energy, Purdue University, and Pacific Northwest National Laboratory has undertaken a project to develop resources and tools that will allow utilities to determine the costs of operating their large coal boilers at reduced capacity. The resource will allow large coal boilers to cycle safely to provide enhanced resiliency and reliability while utility systems accommodate increased penetration of renewable resources such as wind, solar photovoltaics, or other small generators.

The project team will develop a model to accurately estimate the costs of cycling boilers in large coal plants so that coal generators can be fairly considered and efficiently operated as part of a comprehensive strategy for dispatch and generation planning. The Generation Plant Cost of Operations and Cycle Optimization Model (Coco) will be refined and integrated with one or more dispatch and generation planning models through an application programming interface. NRECA will employ its extensive publishing, education, training, and event management capabilities to publicize and socialize Coco—first to NRECA's 60-plus utilities with coal generating facilities, then to the broader utility community at large.



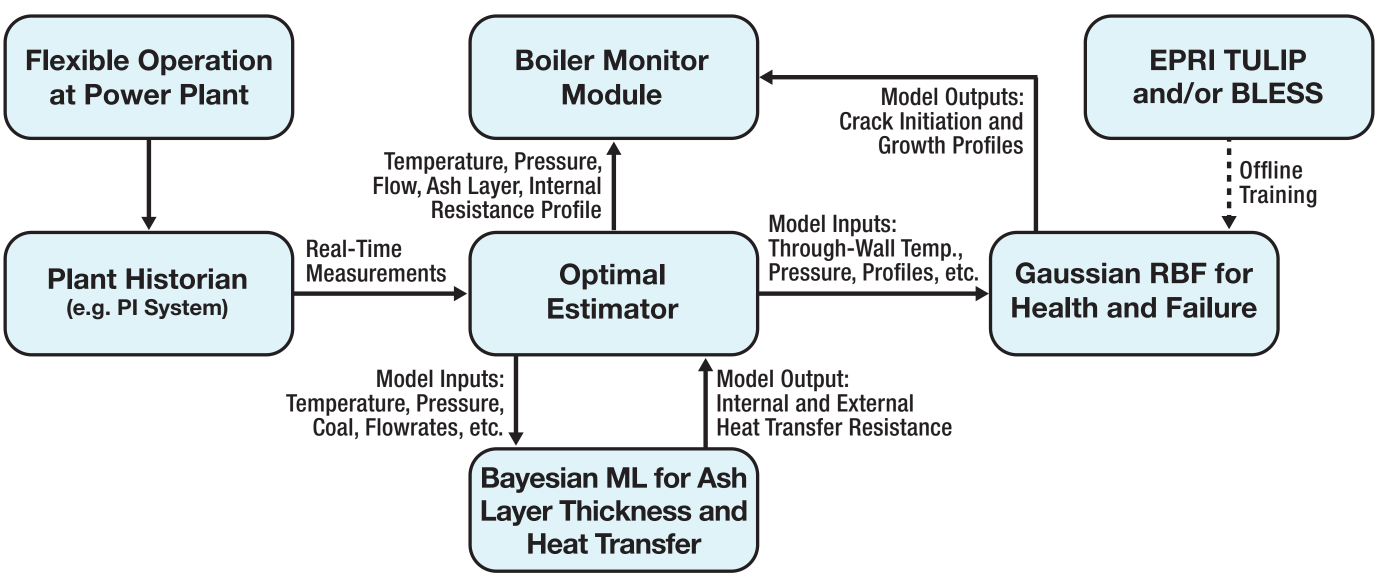
Boiler Health Monitoring using a Hybrid First Principles-Artificial Intelligence Model

Performer	**West Virginia University Research Corporation**
Award Number	FE0031768
Project Duration	09/01/2019 – 08/31/2022
Total Project Value	$ 2,509,016
Collaborator	Electric Power Research Institute, Inc.; Southern Company Services, Inc.
Technology Area	Coal Utilization Science

This project seeks to develop methodologies and algorithms to accomplish (i) a hybrid first principles-AI model of the PC boiler, (ii) a physics-based approach to material damage informed by ex-service component evaluation, (iii) a transformative, online health-monitoring framework that synergistically leverages the hybrid model and plant measurements to provide the spatial and temporal profile of key transport variables and characteristic measures for plant health, and (iv) a field implementation and demonstration at Southern Company's Plant Barry in Bucks, Alabama.

The methodologies and algorithms developed in this project will be calibrated and validated using data from Southern Company's Plant Barry. The framework will also be deployed at Plant Barry and evaluated for online monitoring of boiler health.

The Electric Power Research Institute, a sub-awardee, will provide real-world operation and material damage inputs to the hybrid creep and thermo-mechanical fatigue damage models.



Hybrid model based boiler health monitoring framework.

DISTRIBUTED INTELLIGENT CONTROLS

Advanced Tool for Cyber Physical Systems and Digital Twins

Performer	Ames National Laboratory
Award Number	FWP-AL-18-450-015
Project Duration	10/01/2018 – 09/30/2020
Total Project Value	$ 610,000
Technology Area	Plant Optimization Technologies

This project will build the tools needed to integrate the concept of cyber-physical systems and digital twins into the current energy system development process of research and development, design, and deployment. The goal is to create a “discovery-application feedback loop” in which the first four steps of the current technology development process can be merged. This will enable newly conceived ideas to be rapidly tested and sorted, and various challenges overcome more effectively, reducing the time needed to deploy new energy technologies from decades to years. Specifically, this work is focused on combining real time experimental analysis with simulation modelling studies to create a cyber-physical energy system development platform.

Ames Laboratory (Ames) is working to further develop and integrate digital twins and cyber-physical systems as tools that address specific sensor and controls issues for hybrid systems using the Hybrid Performance (Hyper)/merged environment for simulation and analysis (MESA) system. As a part of this project, machine learning tools were integrated into the cyber-physical/digital twin working environment to improve the accuracy of real time analysis. Using system dynamics and controls, the application focus of this research ensures that Ames research will be readily extensible to solving practical problems in the existing fleet of power plants and to aiding energy system research and development processes.

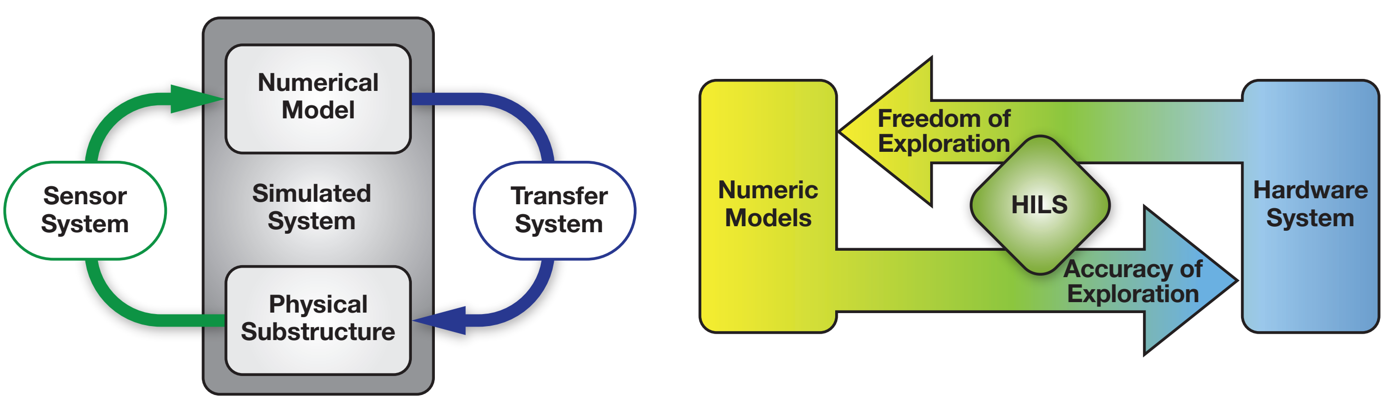
MESA enables seamless transitions from physical to virtual.

Expedited Real Time Processing for the NETL Hyper Cyber-Physical System

Performer	Georgia Tech Research Corporation
Award Number	FE0030600
Project Duration	08/01/2017 – 07/31/2020
Total Project Value	$ 504,130
Technology Area	Plant Optimization Technologies

The primary objective of this project is to provide the National Energy Technology Laboratory's Hybrid Performance Facility (Hyper) with needed numerical methods algorithms, software development, and implementation support to enact real-time cyber-physical systems that simulate process dynamics on the order of five milliseconds or smaller. The proposed paths forward comprise three distinct approaches to faster transient simulations. They fall under the numerical methods categories of (1) optimizing key parameters within the facility's present real-time processing scheme; (2) introducing an "informed" processing approach wherein a priori computations expedite real-time attempts; and (3) implementing alternatives to the presently employed explicit-implicit blended finite difference (spatio-temporal) approach. Although each of these three classes will be attempted independently as options for improvement, in some cases one may complement another.

The three approaches provide individual paths that will expedite critical computational steps. They are also anticipated to have points of compatibility to synergistically speed processing. Achieving the five-millisecond time-step threshold for the pioneering Hyper cyber-physical system would afford dynamic operability studies that capture higher-time-resolution phenomena (e.g., electrochemical-fluidic dynamics) at the full response capability of the Hyper system.



Cyber-physical simulation.

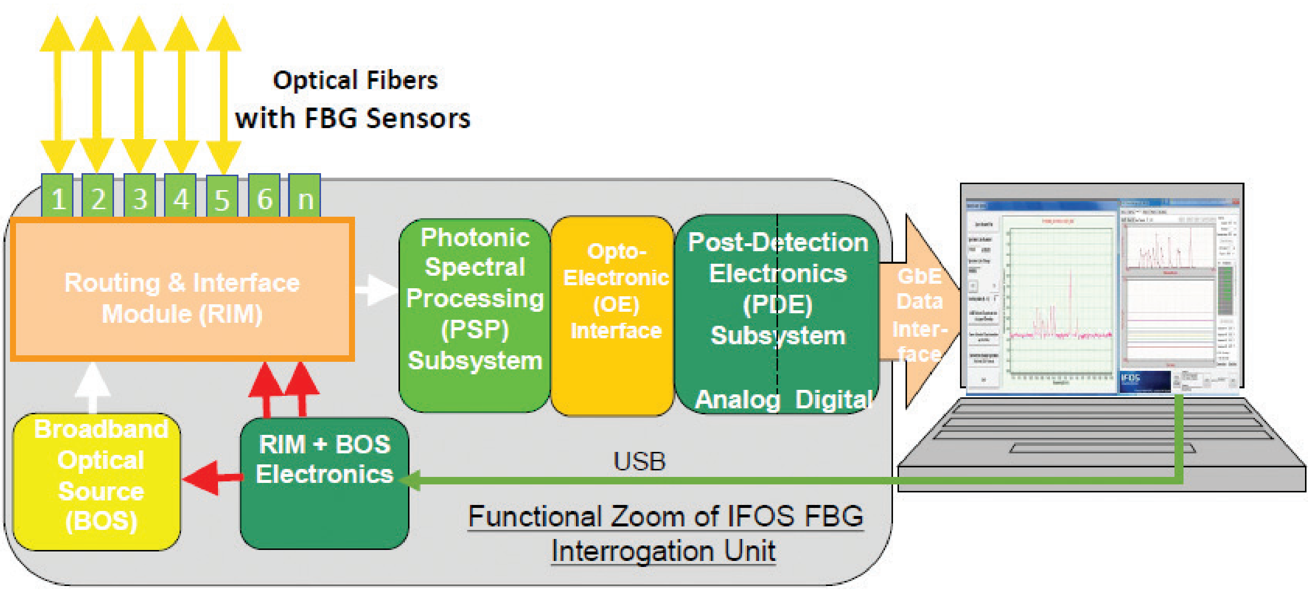
Embedded Multiplexed Fiber-Optic Sensing for Turbine Control and PHM

Performer	**Intelligent Fiber Optic Systems Corporation**
Award Number	SC0018576
Project Duration	04/09/2018 – 05/27/2021
Total Project Value	$ 1,149,885
Technology Area	Plant Optimization Technologies

Intelligent Fiber Optic Systems Corporation (IFOS) will develop an innovative, embedded-sensor-enabled control approach for industrial gas turbines. The IFOS concept leverages advanced existing fiber-optic sensing technology including ultra-thin, sub-50 mm diameter fibers. IFOS's approach will enable measurement of turbine blade temperature and stress parameters that are closer to the harshest of turbine environments, and use this information to augment existing control schemes to decrease margins and thereby increase system efficiency. Conventional electronic sensors are relatively bulky and require multiple lead wires.

Few sensors have been able to be deployed on production turbines. In IFOS's approach, however, there are no 'active' components on the turbine blade or shaft—all optical signal processing and post-detection electronics are situated on stationary components in a relatively benign environment, removing the need for ultra-high-temperature electronics.

Fiber optic sensors can provide multipoint measurements of temperature, heat flux, dynamic strain, pressure, and recession, and are immune from electromagnetic interference. Silica fibers allow sensing to approximately 1000 °C, and sapphire fibers to over 1800 °C.



IFOS I*Sense Interrogation System.

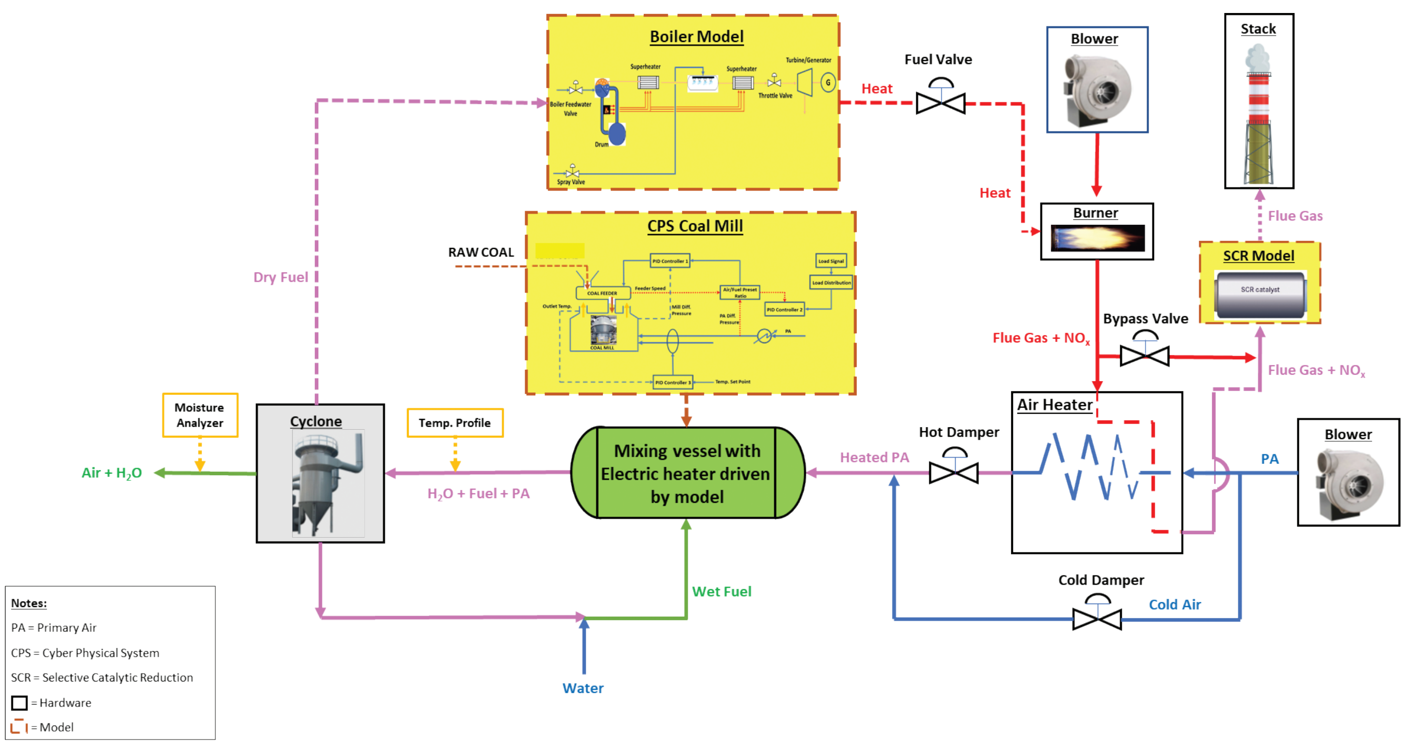
Agent-based Controls for Power Systems

Performer	**National Energy Technology Laboratory (NETL)**
Award Number	FWP-1022427 - Advanced Sensors and Controls - Task 51
Project Duration	04/01/2020 – 03/31/2021
Total Project Value	$ 175,000
Technology Area	Plant Optimization Technologies

Development of next-generation power systems such as fuel cell turbine hybrids encounters technical barriers which include the difficulty of dynamic control of coupled nonlinear systems. Start-up, shut-down, and rapid ramping capabilities are needed in these power systems to make them practical for broad implementation. Traditional PID (proportional–integral–derivative) control has struggled to address the dynamic operations problems, so NETL is investigating non-traditional control approaches such as agent-based control as a potential solution.

In this project, a multi-agent controls approach with agent coordination, previously shown feasible on Hyper, will continue to be investigated for use in fossil energy power systems. Temperature control of a coal pulverizer, with the power plant responding to load changes, has been identified as an application which is likely to benefit from an agent-based control approach. This project will work with an industry partner to model the control problem, and use either a plant simulator or cyber-physical system to develop and test the agent-based control approach. Transition to a field test with the industrial partner is expected following the initial simulation work.

Work on this task also will develop a formalization of the design method and use of cyber -physical systems for research, an area which has been investigated for several years in partnership with Ames Laboratory.



Planned cyber-physical system for coal pulverizer temperature control development and testing.

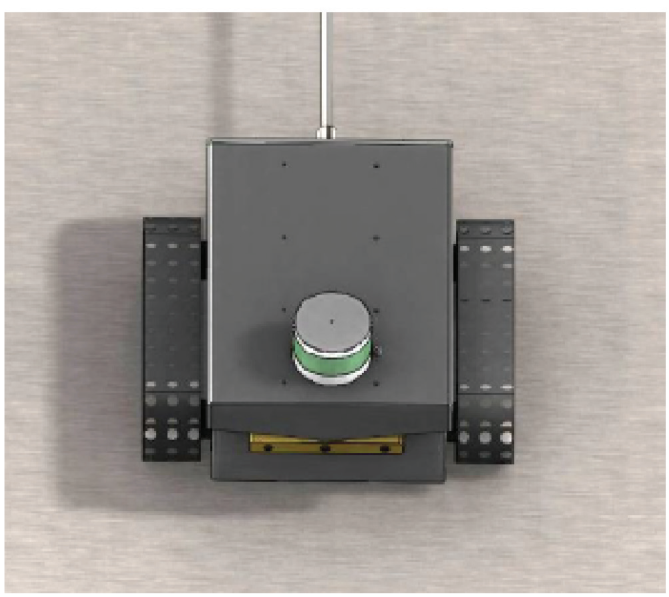
ROBOTICS-BASED INSPECTION

AI Enabled Robots for Automated Nondestructive Evaluation and Repair of Power Plant Boilers

Performer	**Colorado School of Mines**
Award Number	FE0031650
Project Duration	09/01/2018 – 08/31/2021
Total Project Value	$ 473,972
Collaborator	EnergynTech Inc.; Michigan State University; Xcel Energy
Technology Area	University Training and Research

Colorado School of Mines researchers are collaborating with partners from Michigan State University to develop an integrated autonomous robotic platform that (1) is equipped with advanced sensors to perform live inspection, (2) operates innovative onboard devices to perform live repair, and (3) uses artificial intelligence (AI) for intelligent information fusion and live predictive analysis for smart automated spatiotemporal inspection, analysis, and repair of furnace walls in coal-fired boilers. The autonomous robotic platform will be capable of attaching to and navigating on vertical boiler furnace walls using magnetic drive tracks. Live non-destructive evaluation (NDE) sensors and repair devices will be developed and integrated in the robot. In addition, the robot will be empowered with AI to automate data gathering (e.g., mapping and damage localization), and live predictive analysis will incorporate end-user feedback to continuously improve performance and achieve smart autonomy. Performance will be verified on vertical steel test structures in the principal investigators' laboratories and at facilities provided as in-kind support by Xcel Energy and EnergynTech.

Successful robotic inspection will limit or eliminate the need to send inspectors to assess difficult-to-access or hazardous areas, enable automated live inspection, reduce risk to human operators during maintenance or unplanned outage, and enable smart collection of comprehensive and well-organized data. The impact is increased boiler reliability, usability, and efficiency.



Concept image of the tracked robot platform without the NDE or repair equipment attached traversing a steel plate.

Development of a Pipe Crawler Inspection Tool for Fossil Energy Power Plants

Performer	**Florida International University**
Award Number	FE0031651
Project Duration	09/01/2018 – 08/31/2021
Total Project Value	$ 398,333
Technology Area	University Training and Research

Florida International University researchers are developing a robotic inspection tool to evaluate the structural integrity of key components in fossil fuel power plants. The tool will consist of multiple modular crawlers that can navigate through the 2-inch-diameter superheater tubes typically found within power plant boilers—which are often subject to corrosion and micro cracks—and provide information regarding the health of the pipes. Design modifications to reduce the tether load and maximize the pull force will be made. Multiple systems will then be synchronized to increase the length of pipe that can be inspected. The base system will house a camera for video feedback and contain a module that utilizes thumbnail- size ultrasonic sensors for measuring pipe thickness, and a LiDAR (light detection and ranging) sensor to detect any pipe buildup, damage, and/or misalignment. In addition, the module will provide a means to prepare the surface prior to measuring. The team will develop and conduct bench-scale tests to optimize the design of the crawler and its modules and conduct engineering-scale tests to validate the system.

The proposed robotic system will improve the state of the art for inspection tools in pipes that are subject to extreme conditions and for which structural integrity assessments are difficult to obtain. The technology will lead to better understanding of the health of critical components, and plant downtime will be reduced, efficiency increased, and cost savings realized.

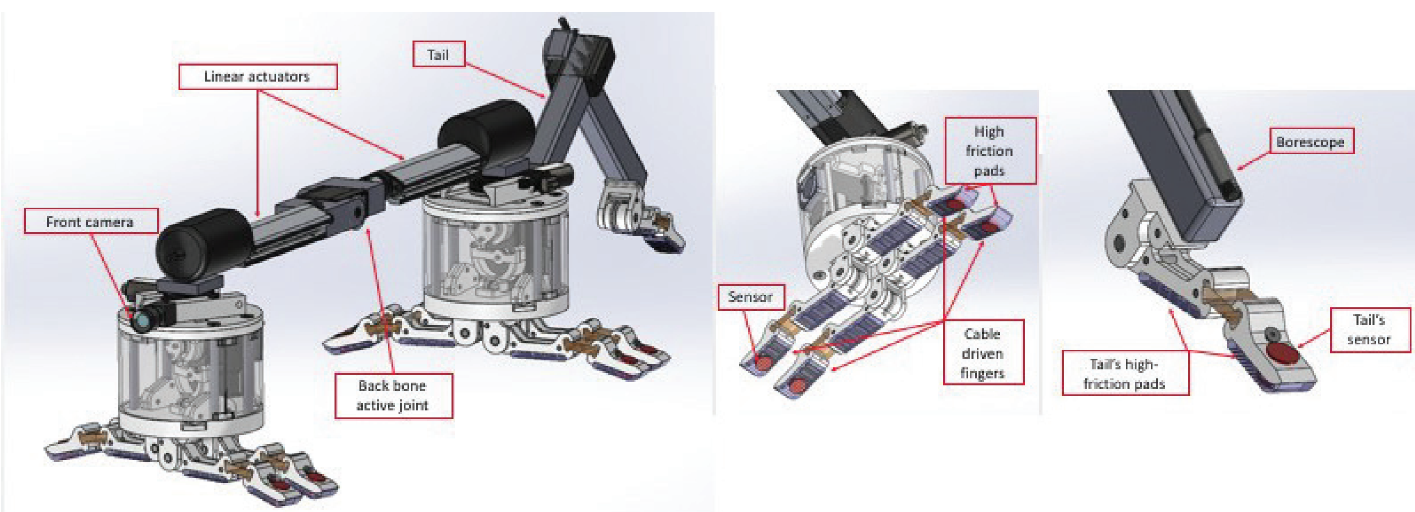
3- and 4-inch pneumatic pipe crawler developed at Florida International University.

A Lizard-Inspired Tube Inspector (LTI) Robot

Performer	**New Mexico State University**
Award Number	FE0031649
Project Duration	09/01/2018 – 08/31/2021
Total Project Value	$ 400,000
Collaborator	Arizona State University
Technology Area	Plant Optimization Technologies

New Mexico State University researchers are developing a versatile lizard-inspired tube inspector (LTI) robot with embedded inspection sensing components that will eliminate the need for point-by-point scanning of tube surfaces for detecting and evaluating cracks and erosion. Inspired by lizards which have evolved to live within tight spaces with complex geometries and rough surfaces, the robot will integrate couplant-free ultrasound sensing and transmission, advanced Lamb wave-based ultrasound imaging, and a friction-based mechanical mobility component to eliminate the need for smooth surfaces and simple geometries for mobility and scanning. This project will replace the wheel-based approach to tube inspection with friction and/or adhesion-based mobility to significantly increase the flexibility and maneuverability of the LTI robot, providing easy access to a power plant unit such as a boiler to inspect components of interest (e.g., curved and flat surfaces, non-ferromagnetic or ferromagnetic materials, and tubes with rough surfaces and complex geometries). In addition, advanced imaging will enable the robot to image the entire area between and around the robot's multi-functional mobility system (grippers) using Multi Helical Ultrasound Imaging and a Lamb wave-based Total Focusing Method recently developed by the principal investigator.

The results of the current project may revolutionize robotic inspection technology used to inspect power plant components. The advanced imaging and mobility of the LTI robot makes it a unique tool that can be adopted for inspection of other power plants' hard-to-reach components such as steam turbines, heat recovery steam generators, gas turbines, and electrical generators without a need for overhaul.



Conceptual design of the LTI robot.

A Robotics Enabled Eddy Current Testing System for Autonomous Inspection of Heat Exchanger Tubes

Performer	**University of Missouri**
Award Number	FE0031645
Project Duration	09/01/2018 – 08/31/2021
Total Project Value	$ 410,864
Technology Area	University Training and Research

University of Missouri researchers will develop a robotics-enabled eddy current testing (ECT) system for autonomous inspection of heat exchanger tubes. The proposed system will be capable of precisely controlling the location and speed of the ECT probe into or out of tubes of various sizes and geometries. An imaging system and adaptive control algorithm will be employed to quickly identify the outer geometry of the tubes and their positions relative to the probe, enabling precise movement of the ECT probe to the inlet of each tube. Insertion and extraction speeds will be controlled for fast and more consistent scanning during testing. A convolutional neural network or other machine learning algorithms will enable autonomous inspection via a feedback loop, which will be employed to learn from historical data categorized by the signatures of the various failure modes (e.g., cracking and corrosion; abrasive and erosive wear). If measured data from suspicious regions of the tubes match these signatures, the controller will make a real-time decision on insertion and extraction speeds and probe location for more detailed scanning, thus increasing measurement accuracy while enhancing testing efficiency.

The developed robotic platform will enable automated eddy-current testing, thus reducing labor time and cost. Well-controlled testing speeds will reduce human inconsistencies in data gathering and analysis. The artificial intelligence algorithm will enable deep mining of historical data for in-situ analysis and real-time decision making.

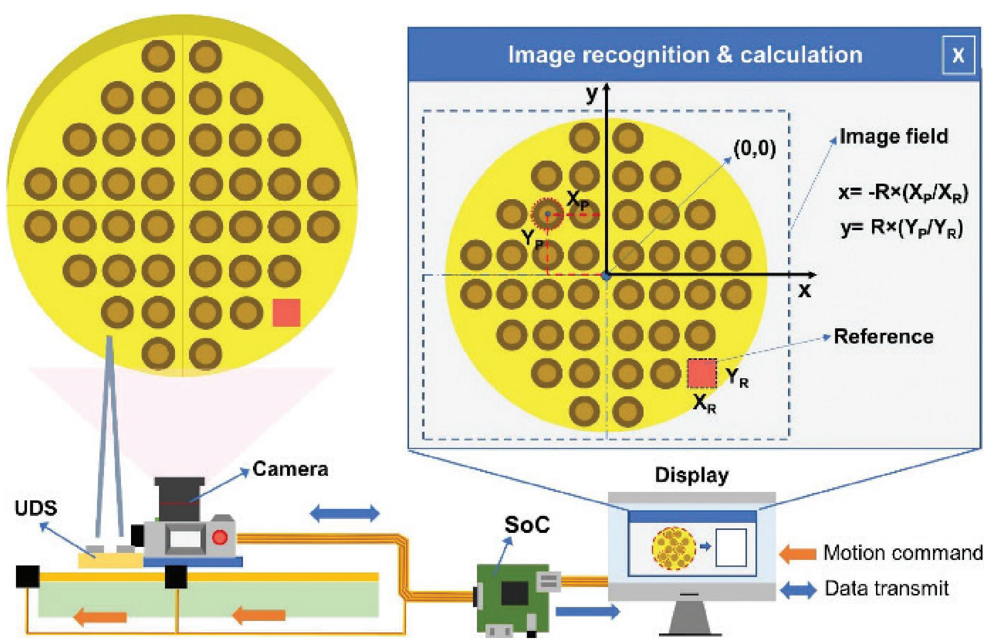


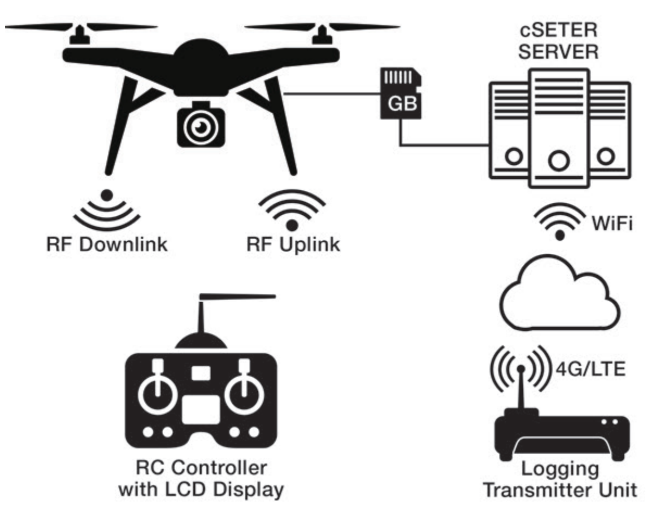
Image processing steps for recognizing geometry and location of tubes' inlets.

Autonomous Aerial Power Plant Inspection in GPS-Denied Environments

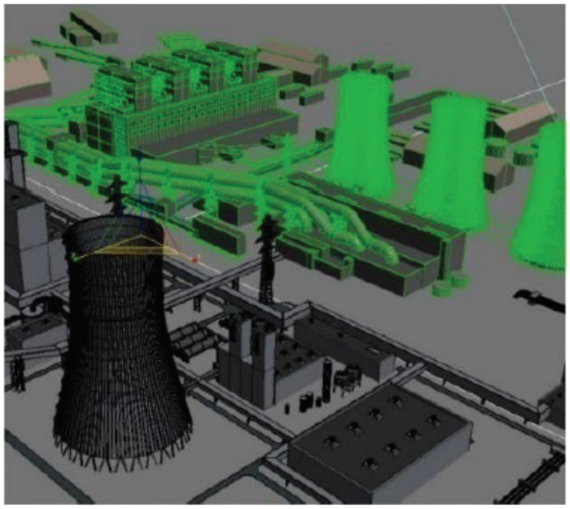
Performer	University of Texas at El Paso
Award Number	FE0031655
Project Duration	09/01/2018 – 08/31/2021
Total Project Value	$ 400,000
Collaborator	Southern Research
Technology Area	University Training and Research

University of Texas at El Paso (UTEP) researchers will test and validate the performance of UTEP's global positioning system (GPS)-denied inspection system, outfitted with electro-optical and infrared inspection sensors, in a representative coal-fired power component that will be determined in conjunction with the El Paso Electric Company. Researchers will use rotary wing flying robots for outdoor inspection and airships for indoor inspection of GPS-denied environments to test the system's guidance and navigation and obstacle avoidance capabilities. The objectives are to develop computer assisted design (CAD)-based inspection profiles for space-constrained and GPS-denied areas of a power plant; test and validate the capability to keep a pre-set distance from complex surfaces (within sub-15 centimeter tolerances in all six directions); and test and validate the capability to perform an automated inspection of uneven vertical and horizontal surfaces in enclosed and GPS-denied areas.

The aerial system will leverage current robotic-based inspection technology in power plants by potentially increasing the area and the types of structural components that can be inspected with unmanned aerial systems; access dangerous and difficult-to-reach structures; inspect areas where GPS is not available; and enable inspection of cluttered and space-reduced areas, internal and external components such as cooling towers and flue gas stacks, and areas with high ash content without disturbing particulate matter.



Data logging and telemetry system.



Model of a power plant (courtesy of Turbosquid).

ABBREVIATIONS

°C .... degrees Celsius
3D .... three-dimensional
AI .... artificial intelligence
Al_2O_3 .... aluminum oxide; alumina
As .... arsenic
AUSC .... advanced ultra-supercritical
CAD .... computer assisted design
Cr_2O_3 .... chromium (III) oxide
DANCE4CFDD .... Deep Analysis Net with Causal Embedding for Coal-fired power plant Fault Detection and Diagnosis
DOE .... Department of Energy
ECT .... eddy current testing
ECVT .... electrical capacitance volume tomography
EPRI .... Electric Power Research Institute
FE .... Office of Fossil Energy (DOE)
FWP .... Field Work Proposal
GE .... General Electric Company
GPS .... global positioning system
HBCU .... Historically Black Colleges and Universities
Hyper .... Hybrid Performance Facility
IASM .... Integrated Additive and Subtractive Manufacturing
I&C .... instrumentation and control
IFOS .... Intelligent Fiber Optic Systems Corporation
IIoT .... industrial internet of things
IT .... information technology
LIBS .... laser-induced breakdown spectroscopy
LiDAR .... light detection and ranging
LTI .... lizard-inspired tube inspector
MEMS .... microelectrical-mechanical system(s)
MESA .... merged environment for simulation and analysis
mm .... millimeter(s)
mV .... millivolt(s)
NDE .... non-destructive evaluation
NETL .... National Energy Technology Laboratory
NRECA .... National Rural Electric Cooperative Association
OMI .... Other Minority-Serving Institutions
OT .... operational technology
OTBA .... operational technology behavioral analytics
P2P .... peer-to-peer
PID .... proportional-integrative-derivative
R&D .... research and development
RF .... radio frequency
RGA .... Raman gas analyzer
RUL .... remaining useful life
SAW .... surface acoustic wave
SBIR .... Small Business Innovation Research
sCO_2 .... supercritical carbon dioxide
SDN .... software-defined networking
Se .... selenium
SiC .... silicon carbide

ABBREVIATIONS

SOFC .... solid oxide fuel cell

TBC..thermal barrier coating

TRL ....technology readiness level

UCR ....University Coal Research

U.S. ....United States

UTEP .... University of Texas at El Paso

W ....watt(s)

WBG .... wide band gap

NOTES

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https://netl.doe.gov/coal/crosscutting

https://energy.gov/fe/plant-optimization-technologies

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