Project No. 03-01-SR108 – *An Advanced Diagnostic and Prognostic System for Gas Turbine Generator Set with Experimental Validation*

FACT SHEET

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Peter Lukens – Undergraduate Student, 2004 HEET Summer Intern Program (July 2003 – August 2004)

II. PROJECT DESCRIPTION

A. Objectives

A series of five goals are pursued to achieve the project's objectives.

- Develop an advanced statistical based modular diagnostic and prognostic strategy for multi-domain systems which features an adjustable sensitivity level.
- Design a health management system for gas turbine power generator sets. The real-time algorithms shall detect, isolate, and estimate system degradations as well as predict their occurrence for maintenance scheduling. The available sensor data shall be fused to create a comprehensive map of the system's operation.
- Use the Clemson University Central Energy Facility and Energy Systems Laboratory to monitor a Taurus 60 or Mercury 50 gas turbine generator set with selectable sensor signals and sampling rates. The experimental data will be used to validate the diagnostic and prognostic modules, and compare its performance with the existing on-board diagnostics.
- Identify additional sensors that may be integrated into the turbine system to supplement the available information for the diagnostic and prognostic modules.
- Introduce an "Undergraduate Research Award" in the Department of Mechanical Engineering at Clemson University to recruit junior and/or senior college engineering students to participate in the research program.

B. Background/Relevancy

The Reliability, Availability, and Maintainability (RAM) technical area of the High Efficiency Engines and Turbines (HEET) program encompasses the design of gas turbine health management systems. A variety of diagnostic and prognostic systems have been developed for turbine engine health and usage management. The introduction of real-time diagnostic and prognostic capabilities on gas turbines can provide increased reliability, safety, and efficiency. The diagnostic module is responsible for the prompt detection of system degradations followed by the isolation, or classification, of the failure, and determination of the magnitude. Prognostic activities are focused on the prediction of anomalous plant behavior such that maintenance measures may be performed to permit continued operation. Typically, the diagnostic algorithm operates in a parallel manner to the plant controller and uses the same available sensor data to monitor the plant. Similarly, the prognostic module interfaces with the diagnostics and may perform a statistical analysis of the operating trends using regression methods.

C. Period of Performance

36 months starting 07/2003 and ending on 07/2006 (extended to 12/2006)

D. Project Summary

The objective of this project is to deal with the location and determination of pending and actual system anomalies, or degradations, to ensure the proper operation and reliability of gas turbine installations. The project encompasses seven tasks.

Task 1: **Analytical and Empirical Mathematical Modeling**

An important requirement for health monitoring systems is the availability of mathematical model as an estimator of the plant's operation under normal conditions. To create the model, specific gas turbine subsystems have to be described including the compressor, the combustion chamber, the fuel system, the turbine, the starter motor, the generator and the shaft dynamics. These descriptions allow the monitoring algorithm to check the total output parameters of different subsystems such as temperatures, pressures and speed. The mathematical model also facilitates the investigation of design parameter changes and their impact on the plant's performance. Two important considerations are: (i) the required model database (i.e., availability of system parameters), and (ii) the real-time execution needs which demand a mathematical description that can be executed with an acceptable integration time step. The resulting dynamic models are a combination of analytical and empirical descriptions. These models are validated using experimental data gathered from the Clemson University facility.

Task 2: Real-Time Turbine Sensor Data for Analysis

The research team together with the Clemson University Facilities and the Energy System Laboratory staffs had achieved the connection from the Mercury 50 PLC host computer to the research workstations located in the Energy Systems Laboratory. The Mercury 50 connection is permitting remote data streaming. This one-way link (i.e., data reading only to prohibit interference with plant operation) permits: (i) an adjustable data sample rate (e.g., $\Delta t = 1, 10, 60, 120$ seconds), and (ii) selection of the sensor signals to monitor. Special software is used to transfer directly the turbine sensory data into a Matlab array for real time analysis.

Task 3: Sensor Fusion for Data Analysis

The sensory information may easily encompass 180 points (e.g., sampled hourly) which can overwhelm a computer's data storage and through put processing capabilities. One of the first tasks when developing a diagnostic strategy is the selection of a smaller subset of key information which may be fused to monitor the complete system in real-time. Thus, an important task is identifying a manageable subset of sensors for use in the diagnostic algorithms through the mathematical model to develop a comprehensive operating map of the gas turbine's operating space.

Task 4: Diagnostic Module Design

The initial starting point for the diagnostic module will be the implementation of a limit and trend checking strategy to directly monitor the signals for departures from acceptable operating ranges. The completion of this preliminary task will allow future comparisons with the advanced diagnostics, as well as an understanding of the factory installed diagnostic package. Next, a model-based failure detection, isolation, and estimation algorithm can be designed. An innovations-based fault detector is created using a "no fail" system model to predict the ideal system behavior and compare it with the actual plant performance. The failure isolation and estimation tasks are implemented using a series of parallel fault filters as well as innovative stochastic methods.

Task 5: Prognostic Module Design

The prognostic system shall attach to the diagnostic module and interpret the diagnostic information to predict three useful quantities: (i) time to possible failure, (ii) predicted time to component degradation for maintenance scheduling, and (iii) remaining useful life. The initial prognostic approach will be short and long-term statistical trending of the diagnostic data to determine the time when an adaptive threshold level will be transgressed. The accompanying statistical analysis permits confidence bounds to be associated with each prediction such that design parameter and operating condition uncertainties may be fully considered. The available maintenance and useful life database can be used at this point to compute the two additional quantities which will allow the turbine operator to make better informed decisions regarding operation.

Task 6: Experimental Testing

The previous tasks are validated using numerical and experimental endeavors. The numerical activities will be pursued via Matlab based computer simulations. For experimental testing, software is used to transfer the Mercury-50 turbine data into the Matlab environment, so that real time data acquisition and algorithm execution may be achieved. The experimental validation of the previous tasks, is performed at the Clemson University Campus Facility and Energy System Laboratory in close cooperation with their technical staffs.

Task 7: Industry Interactions

One of the research project's goals is to develop strong academic/industry interactions. The team is working with Solar Turbines (San Diego, California) through teleconferences and fellowship program. In addition, discussions have been initiated with Woodward FST (Greenville, South Carolina) to explore fuel subsystem diagnostics.

III. PROJECT COSTS

$ 319,479

IV. MAJOR ACCOMPLISHMENTS SINCE THE BEGINNING OF THE PROJECT

- Achieved a model free trend checking diagnostic algorithm (12/2003).
- Demonstrated real-time data streaming between the Mercury 50 gas turbine and the Energy Systems Laboratory using OPC technology with MATLAB® Interface (03/2004).
- Created a compressor map of the Solar Mercury 50 gas turbine based on actual blade geometry and experimental data (07/2004).
- Completed the real time data streaming for Taurus 60 to allow possible study (07/2004).
- Undergraduate research group member completed HEET Summer Intern Program at Solar Turbines, San Diego, CA (09/2004).
- Established a sensory architecture of 28 signals for diagnostics/prognostics (12/2004).
- Developed a dynamic (transient) model for the gas turbine incorporating thermodynamic features as well as a hypothetical mass capacitance component (04/2005).
- Created an initial methodology for the prognostics module (05/2005).

- Verified and validated the dynamic model with experimental data (06/2005).
- Achieved a model-based fault detection algorithm based on Kalman filtering validated with experimental fault (12/2005).
- Achieved a prognostic technique based on statistical regression principles for parameters behavior forecast (02/2006).
- Achieved a novel multivariate signal comparison technique for fault detection and isolation with validation with the real fault (06/2006).
- Achieved a prognostic technique based on wavelet analysis (06/2006).

V. MAJOR ACTIVITIES PLANNED DURING THE NEXT 6 MONTHS

- Completing the real time implementation of the diagnostic module with experimental results with various fault scenarios.
- Completing the prognostic algorithm derivation and validation with extended turbine runs.
- Turbine consultant, Dr. Ting Wang, will provide experimental data for longer runs
- Issuing a comprehensive technical report for the project

VI. MAJOR ACTIVITIES PLANNED IN OUTYEAR (06/2006 to 06/2007)

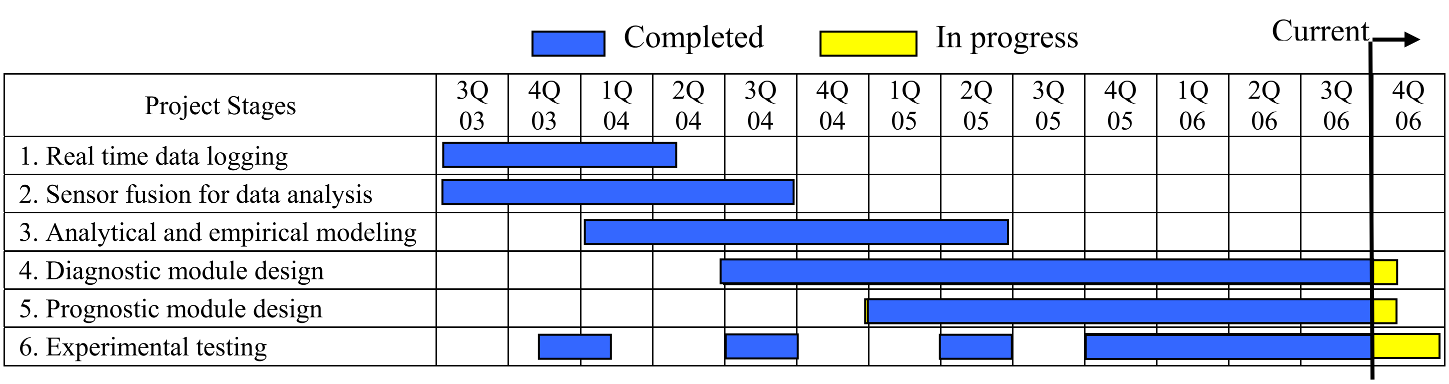
- Not applicable (final six months of the project)

VII. ISSUES

Identification of long term normal operating data and short term faulty condition data.

VIII. ATTACHMENTS

1. Project Execution Timeline



- All tasks are progressing according to schedule.
- More fault cases validation cases for the derived diagnostics and prognostics algorithms are projected for the upcoming period.

2. Clemson University Mercury 50 gas turbine generator set

Figure 2.1 Outside view of the Mercury50 Combustion Chamber

Figure 2.2 Allen-Bradley PLC – Main controller for the Mercury 50

3. Sample of Model Validation Results

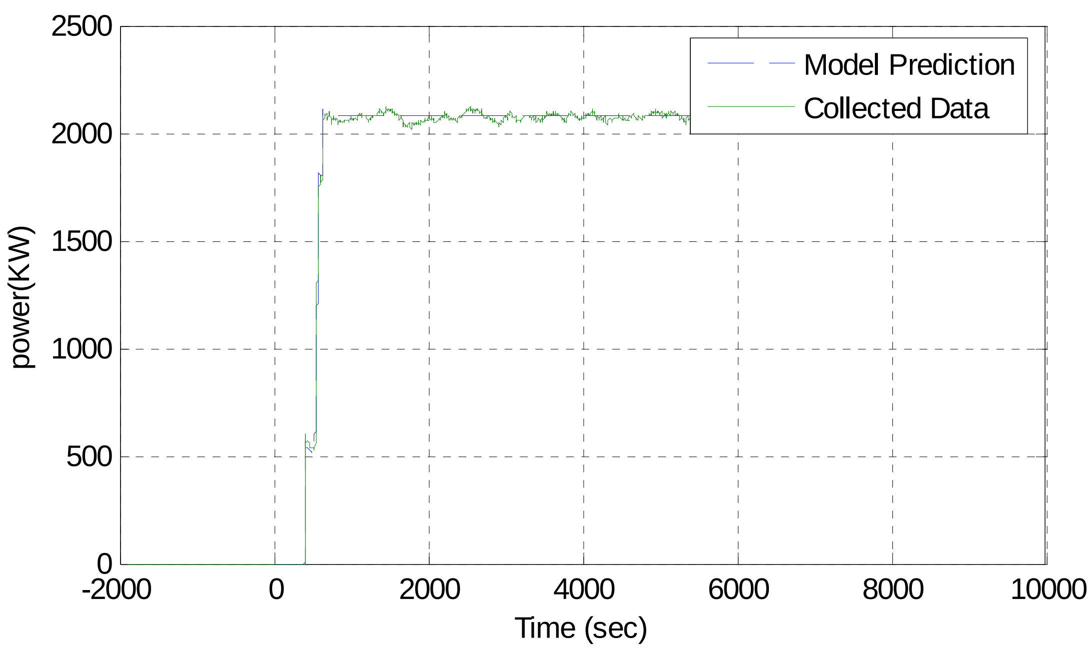


Figure 3.1 Matching results of the model output and actual experimental data for the generated power

4. Sample of Diagnostics Results

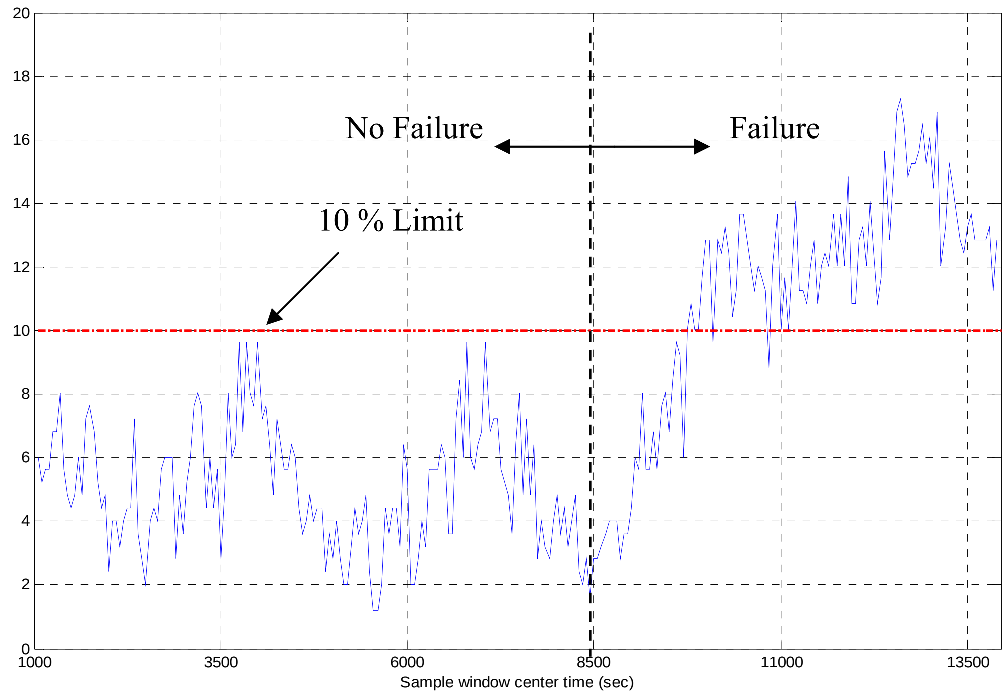


Figure 4.1 Test results for model-free detection based on a multivariate signal (TRIT, PCD and power) comparison for an experimental fault run and demonstrating the fault violation

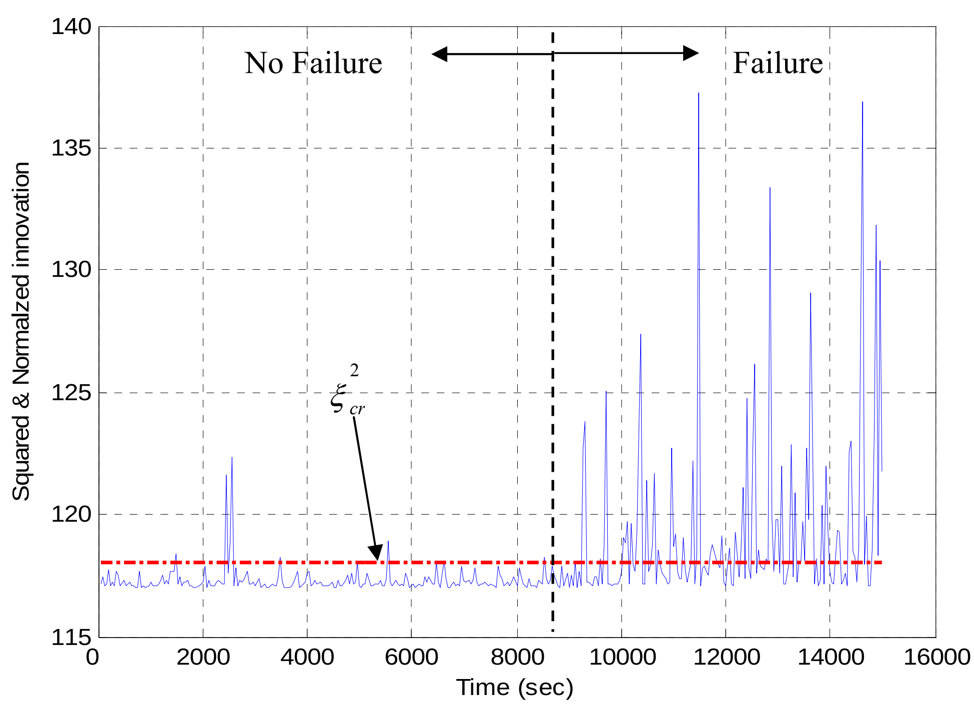


Figure 4.2 Test results for model-based detection based on analyzing the innovations of a Kalman filter based on the linearized gas turbine model at the full load operating point for the same experimental fault

5. Sample of the Prognostics Results:

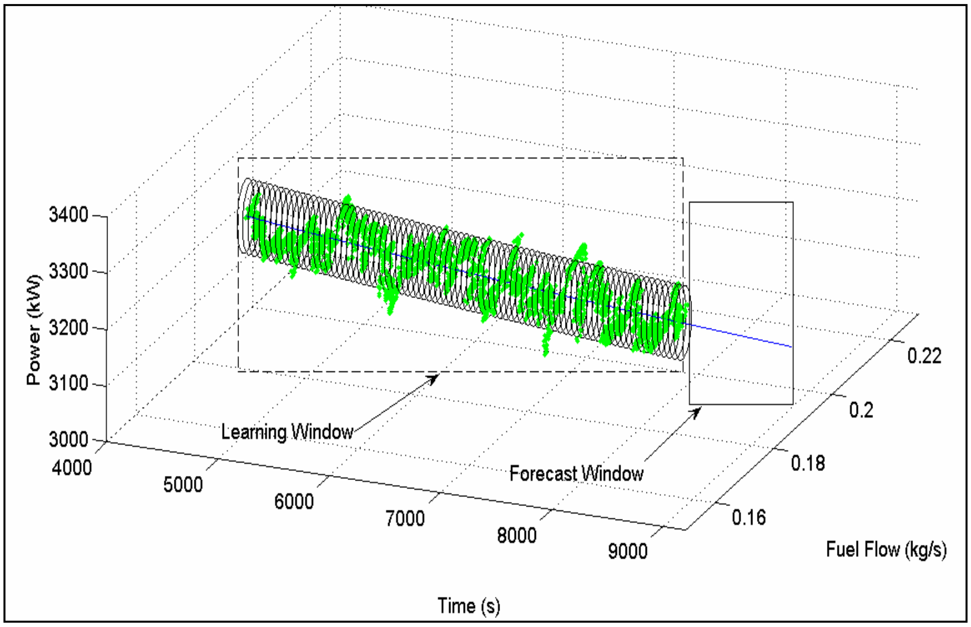


Figure 5.1 Forecast of fuel flow and power generated versus time for the gas turbine for an additional period of 1000 seconds using regression method

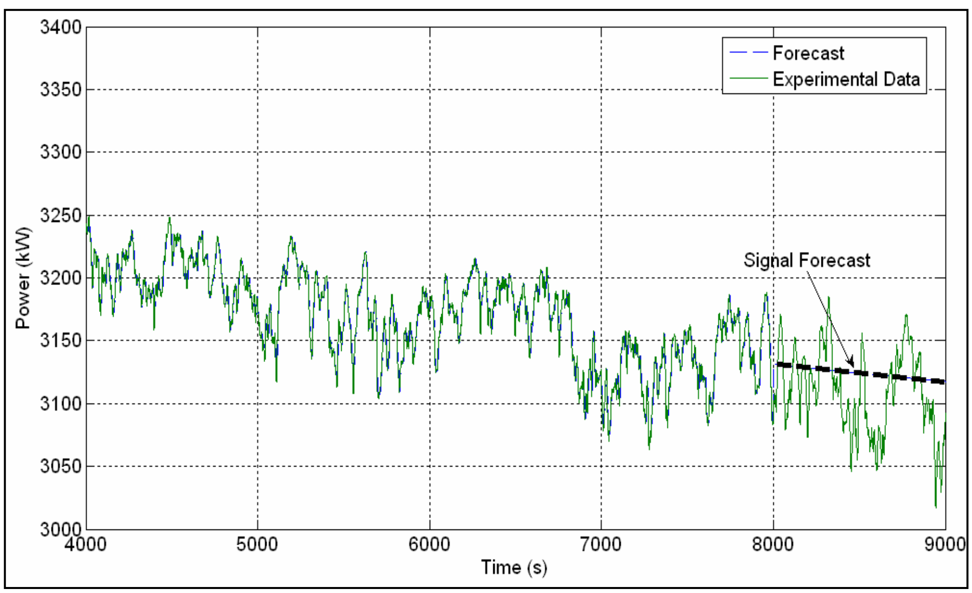


Figure 5.2 Forecast of power generated versus time for the gas turbine for an additional period of 1000 seconds using wavelets method

6. Signal Connectivity and Data Acquisition Diagram

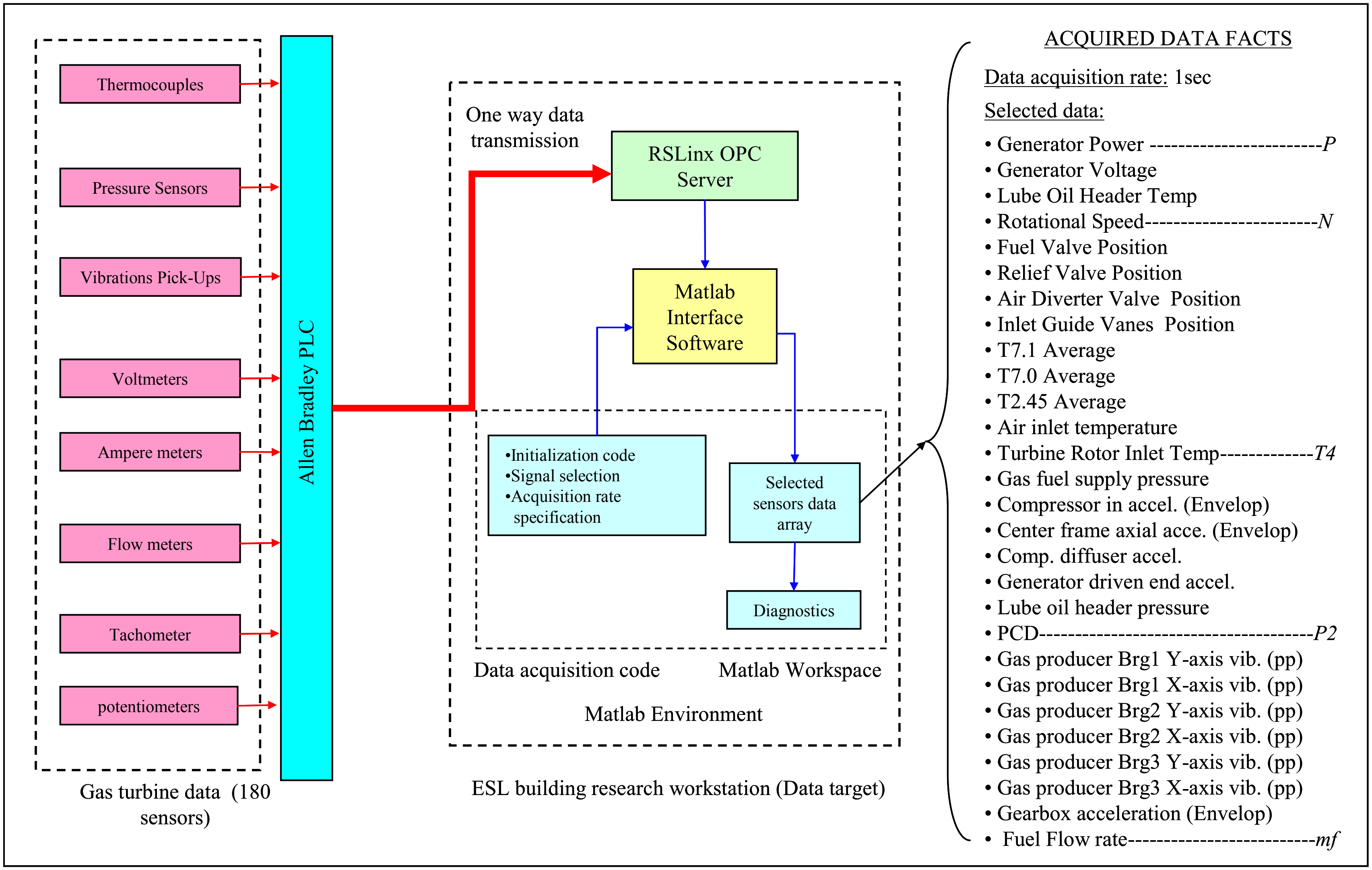


Figure 6.1 Data connection and manipulation for real time logging and processing for both the Mercury 50 and the Taurus 60 gas turbines with a list of the selected sensors for the analysis