EMBEDDED EXPERT SYSTEM FOR
SPACE SHUTTLE MAIN ENGINE MAINTENANCE

BY:

J. Pooley, W. Thompson, T. Homsley, and W. Teoh, PhD

SPARTA, Inc.

4901 Corporate Drive

Huntsville, Alabama 35805

J. Jones and P. Lewallen

NASA Marshall Space Flight Center

Huntsville, Alabama

ABSTRACT

Space Shuttle Main Engine (SSME) maintenance, whether preventive, scheduled, or unscheduled, is a major escalating cost item. Significant progress has been made in the NASA and Air Force communities toward performance of the health monitoring function in instrumentation, analysis techniques, and envelope (trends and rate of change) monitoring. Current techniques require that domain experts be integrally involved in the analysis session and make on-line decisions to direct analysis. The SPARTA Embedded Expert System (SEES) is an intelligent health monitoring system that directs the analysis by placing confidence factors on possible engine status, then recommends a course of action to an engineer or the engine controller. This technique can prevent catastrophic failures or costly rocket engine down time because of false alarms. Further, the SEES has potential as an on-board flight monitor for reusable rocket engine systems. The SEES methodology synergistically integrates vibration analysis, pattern recognition, and communications theory techniques with an artificial intelligence technique - the Embedded Expert System (EES). This integration affords a robustness via the analysis techniques with an ability to resolve conflicts by the expert system techniques.

INTRODUCTION

A critical element of the Space Shuttle Main Engine (SSME) program is the development of a turbo-pump health monitoring system (HMS). A HMS that could predict incipient failures and permit routine maintenance to be scheduled based on performance indicators would dramatically reduce the need for refurbishment, improve equipment availability, and make maintenance more cost-effective. The key functions of an effective HMS are shown in Figure 1.

- **RECOGNIZE AND CATEGORIZE PERFORMANCE**
  (Baselining Of Performance Standards)
- **RECOGNIZE AND CORRELATE INDICATORS OF IMPENDING FAILURE**
  (Incipient Failure Prediction)
- **RECOGNIZE AND CORRELATE INDICATORS OF NEED FOR REMEDIAL ACTION**
  (Scheduling Of Routine Maintenance In A Cost-Effective Manner)

Figure 1. HMS ESSENTIAL FUNCTIONS

Significant progress has been made in the NASA community toward performance of the HMS functions. There have been relevant advances in instrumentation [4,1], analysis techniques [2,5], and in detection of anomalies and failures [3]. Each of these advances has demonstrated individual attributes useful for an HMS to correlate failure modes with turbo-pump components at risk. However, an integrated HMS that uses and updates the SSME data base is possible through the use of emerging AI techniques. AI techniques, specifically a rule-based expert system, can enhance the functions of an HMS. SPARTA has developed and adapted a set of algorithms to produce an innovative application of Artificial Intelligence techniques. The keystone of this application is an expert system that uses confidence levels to resolve conflicts among compound data, and that heuristically trains on each data set to derive (or modify) classification rules. This expert system has been named SEES, an acronym for SPARTA Embedded Expert System.

SEES ARCHITECTURE

The SEES architecture is shown in Figure 2. In SEES, conventional computation methods are used to reduce the raw data to a manageable "derived" data set, and to extract pertinent information (signatures) from the derived data set. This information is then used by the SEES to derive rules, with the help of domain experts/knowledge engineers, to establish a knowledge base. In future phases, SEES will use this set of rules to determine engine conditions during SSME testing.

MAJOR COMPONENTS

As can be seen from the architecture in Figure 2, there are three major subsystems to the SEES HMS: The SEES front end (SFE), the embedded expert system (EES), and the supportfunction library (SFL). The SFE processes the raw data to screen obvious anomalies and to derive the reduced data set, then generates from it an appropriate signature. The process of data screening, reduction and signature generation is the unique and proprietary innovation of SEES. The embedded expert system (EES) uses this signature and the reduced data, with the help of the SFL and the rule set in its knowledge base, to infer the operating conditions at a given instant, deduce the mean time to failure and recommend maintenance schedules. The SFL, as its name implies, is a set of supporting functions for the rest of the HMS.

SEES FRONT END (SFE)

The SFE is comprised of signal analysis techniques that convert raw count accelerometer data to Engineering Units and transform the data to the frequency domain using Fast Fourier Transforms (FFT) to derive a power spectral density (PSD) for input to a Data Conditioning Module. The Data Conditioning Module processes the PSD signal to remove the extraneous components. Finally, the conditioned PSD is evaluated as a candidate for signatures derived during this processing (by the Pattern Matcher) or binned to be considered for establishment of another signature.

SEES SUPPORT FUNCTION LIBRARY (SFL)

The SFL consists of the algorithms that transform reduced data into symbol structures for use by the Development Engine and/or the Inference Engine to accomplish inference and control. This transformation is accomplished by applying communications theory and image processing methods to the SFE conditioned data.

SEES EMBEDDED EXPERT SYSTEM

The Embedded Expert System (EES) is an integral part of the HMS. The EES is a rule based knowledge system that uses forward chaining strategy, and has the ability to recognize and categorize performance, incipient failure and the need for remedial action. It consists of a development engine, a knowledge base, an inference engine, and a user interface.

The Development Engine

The development engine is a subsystem of EES which is intimately related to the knowledge acquisition process; it allows a knowledge engineer to transcribe the knowledge gained from the domain expert into a set of rules that make up the knowledge base. A basic characteristic of the SEES problem in analyzing SSME vibration data is the volatility of signatures and the importance of high rate vibration data. While some rules can be developed, the evaluation of data in real-time leads to the requirement to merge information from multiple sources. This leads to the use of the blackboard architecture for storing intermediate hypotheses, the use of a certainty factor merging heuristic and rule-use counting as a "rule-critic".

The SEES Knowledge Base

Based on SPARTA's study of the training sets, we expect the knowledge base to be quite large. Our investigation indicated that signatures may be extracted and meaningfully classified. Thus, the rule set may be ordered in an appropriate manner (e.g., a rule tree) to reduce search space. The nature of the data is such that one can seldom specify a diagnosis with absolute certainty. Thus in SEES, certainty factors will be used to reflect uncertain information. These certainty factors can be either computed algorithmically by the development engine based on derived or existing knowledge, or estimated by domain experts or knowledge engineers.

The SEES Inference Engine

The SEES HMS is basically data driven. Thus, a forward chaining strategy is appropriate. The incoming data, although reduced by the SFE, is still quite complex, and entering the HMS at a high rate. The EES inference engine must and will have the capability to invoke functions in the SFL for further data reduction. Perhaps one of the more important tasks of the inference engine is to determine when an unknown situation (i.e., not in the rule base) occurs. It should be able to coordinate with the domain expert or knowledge engineer and pass the new information to the development engine to create new rules, or store the information to accomplish the same at a later time off-line when a domain expert is available. The inference engine must provide information to the explainer to produce explanation on demand. The explainer is a subsystem of the user interface and can provide explanations as to how a conclusion is reached. This can be accomplished in a variety of ways; the one selected by SPARTA is to leave the time history of SEES events in the blackboard for post mortem examination.

SEES User Interface

The user interface is the component of an expert system that acts as an interface between the expert system and the user who is not necessarily a domain expert. Thus, it should have the capabilities to: (1) Solicit input from the user, (2) Provide output to the user - this output may be in the form of questions, recommendations or conclusions, and (3) Provide explanations on demand. One important aspect that can be implemented is a possible data link between the user interface and the SSME controller. This would serve as a means to assume control of the engine in unusual situations, such as when an imminent engine failure has been detected, and an immediate engine shutdown becomes necessary to prevent catastrophic failure. This feature is, of course, not needed for off-line testing.

IMPLEMENTATION

Preliminary investigation to date has been carried out using a VAX780 computer in FORTRAN. It is anticipated that the final system will be implemented in FORTRAN or C to run on a MASCOMP computer. This computer is chosen because of the outstanding data acquisition capabilities which is a critical aspect of SEES. Equally important is the fact that a variety of languages and utilities are available commercially for this micro-supercomputer. A decision has to be made as to the language used to develop the embedded expert system (EES). One can choose the more traditional approach of using LISP or PROLOG (both of which are available to the MASCOMP, and both can interface with the rest of the system if it is written in C. We have decided

to use RULE MASTER by Radian Corporation. This is an expert system shell that would allow us to develop EES rapidly, and can be integrated to the rest of SEES easily.

PRELIMINARY RESULTS

The vibration time series is analyzed in a discrete data format. The data is first transformed into a power spectral density (PSD). Each discrete PSD is the power average over a small time interval at a frequency with a certain bandwidth. The power level of a frequency line is then temporalized. Figure 3 shows the amplitude time history of one important frequency band. The accompanying SSME power profile shows the shift from 100% to 104% power level. The amplitude of the time history shows a marked decrease at that time. Other bands show an increase at ramp up to 104%. The characterized signatures consist of a covariance matrix, C, which measures coupling between components of the sample vectors and the mean sample vector, M. A signature is a measure of the turbo-pump's performance profile at a given load condition. When a turbo-pump is operated at a load condition for an extended period, its performance may degrade from nominal to anomalous. This degradation is measured by the HMS and characterized into a class ensemble of signature, at a load condition. Two signatures characterized from the SSME test are presented in Figure 4. The spectral components of these signatures are very complicated; therefore, AI techniques must be used to classify data.

CONCLUSIONS

Preliminary analysis has shown that the SEES development engine successfully extracts signatures from SSME test data that can be formulated into rules for the SEES knowledge base.

REFERENCES

[1]   Barkhoundarian, S. and A.T. Zachary, "Condition Monitoring For Space-Based Reusable Rocket Engines", ASME Winter Annual Meeting, New Orleans, LA, December 1984.

[2]   Coffin, T. and J.Y. Jong, "Signal Detection Techniques for Diagnostic Monitoring Of Space Shuttle Main Engine Turbomachinery", NASA Technical Report 66938-01, February 1986.

[3]   Evatt, J.C. and W.W. Palmquist, "Failure Control Techniques for the SSME", NAS8-36305, Phase I Final Report, Rockwell International.

[4]   Hampson, M.E., J.J. Collins, M.R. Randell, and S. Barkhoundarian, "SSME Bearing Health Monitoring Using a Fiberoptic Deflectomer", NASA Conference on Advanced Earth-to-Orbit Propulsion Technology, Huntsville, Alabama, May 1986.

[5]   Jong, J.Y. and Thomas Coffin, "Diagnostic Assessment of Turbomachinery by Hyper-Coherence Method", NASA Conference on Advanced Earth-to-Orbit Propulsion Technology, May 1986.
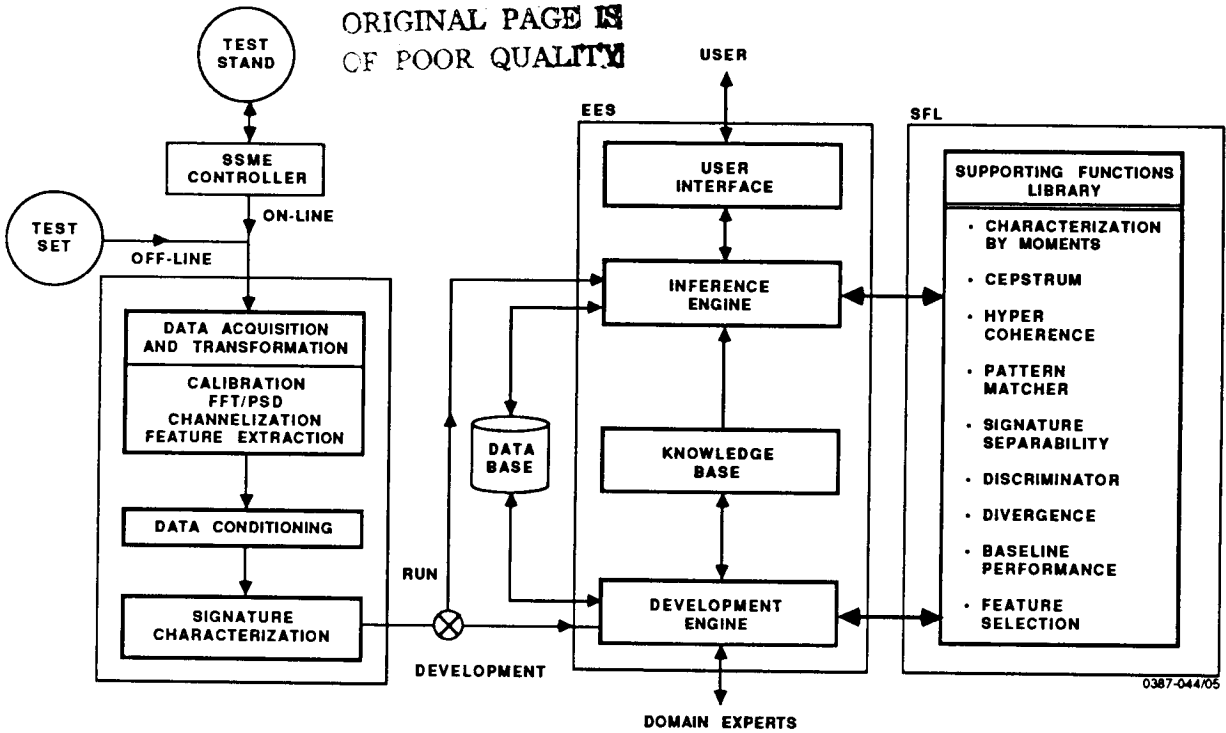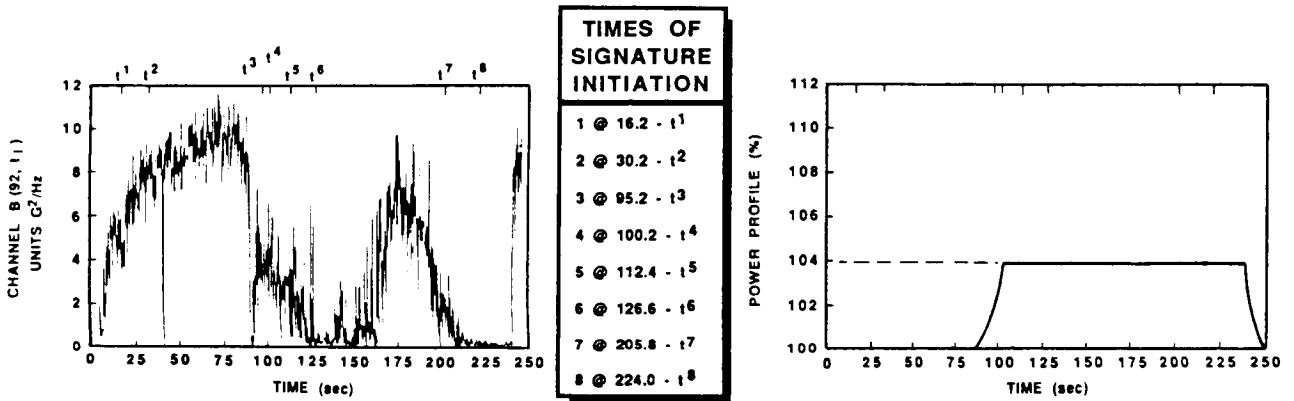
FIGURE 2. SEES - HMS ARCHITECTURE

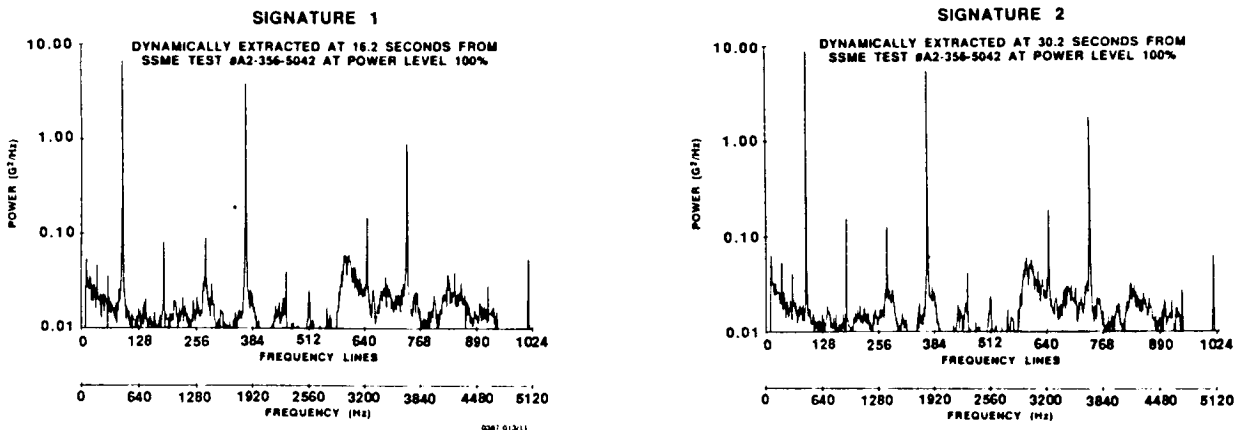FIGURE 3. TEMPORALIZED DATA OF CHANNELS FROM SSME TEST #A2-356-5042

FIGURE 4. TYPICAL SSME SIGNATURES

0387-013/14

119