ADAPTIVE DIAGNOSTIC SYSTEM

**Project Final Report
Transit IDEA Project 2**

Prepared for
Transit IDEA Program
Transportation Research Board
National Research Council

August 31, 1998

Prepared by

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San Francisco Bay Area Rapid Transit District

INNOVATIONS DESERVING EXPLORATORY ANALYSIS (IDEA) PROGRAMS MANAGED BY THE TRANSPORTATION RESEARCH BOARD

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Adaptive Diagnostic System Project

IDEA Project Final Report

Contract Number: TRANSIT- 2

Prepared for

Transit IDEA Program

Transportation Research Board

National Research Council

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August 24, 1998

TABLE OF CONTENTS

LIST OF FIGURES

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LIST OF TABLES

EXECUTIVE SUMMARY

The Adaptive Diagnostic System (ADS) Project sought to integrate state-of-the-art, off-the-shelf hardware and software components with custom-designed software and hardware interfaces to provide a cost-effective general testing platform for use at the San Francisco Bay Area Rapid Transit District (BART). Specific objectives of the Project were threefold:

1. To develop a general purpose hardware/software framework using an Intel PC to control five VXI-bus-based test instruments, four programmable power supplies, and programmable switching relays and matrixes. The software of the framework is to be written in the National Instruments Lab Windows/ CVI graphically-based C language software development environment.. Such a framework is to find use for both automated routine acceptance testing, and for troubleshooting, using specially developed diagnostic software tools.

2. To develop a generalized neural network module utility as one such diagnostic tool, to be used for isolating component failures from pattern recognition of test waveforms.

3. To incorporate a variety of graphically based aids for the technician, including context-sensitive component layout photographs and diagrams, circuit schematic diagrams, and sample waveforms.

The above was to be developed initially to service two particular Units Under Test (UUT) in the BART Electronic Repair Shop, as vehicles for testing and evaluating the ADS. These UUTs are both frequent items of repair that present particular challenges for BART technicians.   Formalized alpha tests were specified for measuring quantitatively the productivity improvements that were obtainable with the ADS as applied to the two UUTs. Two consulting firms were retained to assist in the ADS development: Innovative Technologies Inc., a firm specializing in the development of automated test equipment, and. Marcus Thint Ph.D. of Intelligent Machines Inc., a specialist in neural network and fuzzy logic software.   The Principle Investigator was Steven Mullerheim of the BART Research and Development Division.

The Project was quite successful in achieving its main technical objectives. The ADS general framework provided most of the basic features desired. It employed excellent graphical user interfaces, and was capable of providing a rapid and precise automated test of one of the two UUTs. The architecture of the software was developed in such a way that it could be adapted easily to test other UUT's, and to incorporate other test instruments.

The neural network diagnostic module was developed and refined to the point that it could recognize with high probability waveforms that were discernable by the human eye. Using a single generalized architecture, the module produced neural networks that were trainable to recognize two rather different classes of waveforms associated with the two UUTs: modulated carrier, and transient response to a step function input. Principal development effort was associated with the design of the feature reduction preprocessing functions, and the training and testing software

The Project was quite ambitious, and not surprisingly, did not meet all goals within the allotted schedule and budget. Areas still requiring completion are: formalized testing; development of and linkages to data files; integration of the neural network module into the general ADS framework; and testing of the neural networks with actual circuit-generated (as opposed to simulated) waveforms. None of these are impediments to putting the system

system to productive use in its present state of development. The principal challenges of the Project henceforth are not technical but institutional. Further implementation of the technology within BART will require a commitment in principle and of resources to pursue the development of automated testing tools. Once such a decision is made, major inroads in application and enhancement of the Adaptive Diagnostic System can be expected.

IDEA PRODUCT

The product concept is to combine VXI hardware architecture under control of PC-based software with neural network-based artificial intelligence to create a powerful, general purpose testing and troubleshooting tool that will have wide application both within BART and the transit industry as a whole.   Such a tool is needed in the typical transit agency where there is a wide variety of electronic repair assemblies, each of which is repaired infrequently, and for which the cost of specialized test equipment is prohibitive.

The product is to make extensive use of state-of-the-art commercial products that have powerful and flexible capabilities. These include: industry-standard VXI programmable instrument modules and Intel-based PCs as the hardware platforms, the MS Windows operating system, a Microsoft WINDOWS-based graphically-based C programming environment: LabWINDOWS/CVI for the control and display of programmable instruments; and O'INCA, a graphical environment for developing neural network and fuzzy logic systems that generate C code. The programs all use graphical user interfaces, which makes them easy to program and use.

The general-purpose, programmable, automated tester that is the goal of this Project can find wide use not only in the transit field, but in electronic and electromechanical repair facilities generally where there is a need to routinely repair a variety of equipment units, and there is no special-purpose test equipment available for testing these units. The capabilities being sought will focus on circuitry that is a mix of analog and digital circuitry, and operates below 50 Mhz, as is commonly found in the transit industry. Excluded from the scope are purely digital circuits, for which off-the-shelf test equipment is more readily available, and circuits operating at frequencies above 50 Mhz

HARDWARE FRAMEWORK

The original concept chosen by BART for the hardware architecture is shown in Fig. 1. This involves the use of four programmable power supplies and a VXI 13-slot cradle populated with a resource manager module, five test instruments, a switching matrix module, and a power relay module. All of these are to be controllable from a PC through a GPIB interface. The PC is also interfaced with a printer for the provision of written reports.

Subsequent to the development of the original product concept and the purchase of the hardware, advances have occurred in VXI instrumentation technology, that would suggest some modifications and enhancements be made in the product concept, as follows:

1. MXI Interface. The GPIB interface was selected early in the Project as a mature interface that was originally developed for stand-alone instrumentation; however, it was found to suffer from being very slow. At present the MXI interface for VXI cards has become established as a superior interface that offers considerably greater speed, as well as some internal intelligent capabilities. This should be the selection for future systems.

2. Bus Emulator VXI Module. A relatively new VXI instrument module that has become available is the Bus Emulator, that allows connection to and probing of microprocessor bus-based I/O cards. Such I/O cards are becoming a very common type of circuit board in new transit equipment procurements, for which improved testing and diagnostic tools are badly needed. A Bus Emulator module is advocated as a desirable addition to the Adaptive Diagnostic System architecture.
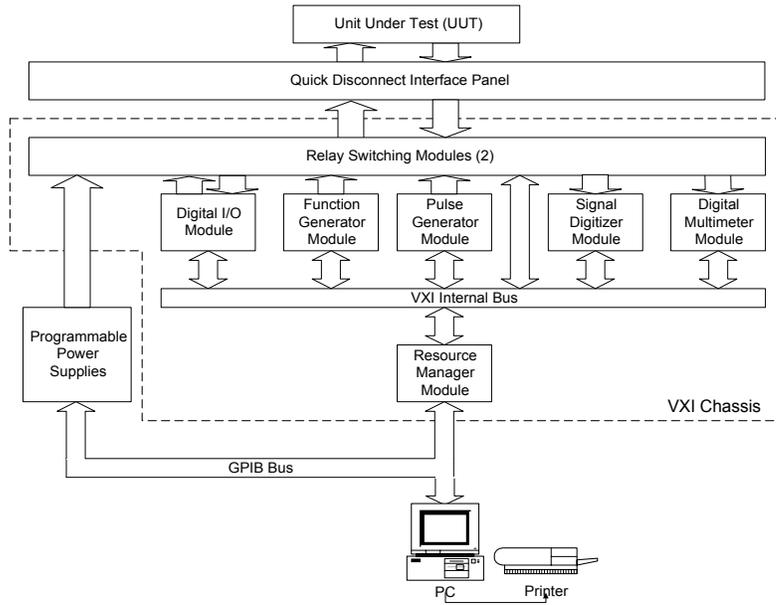
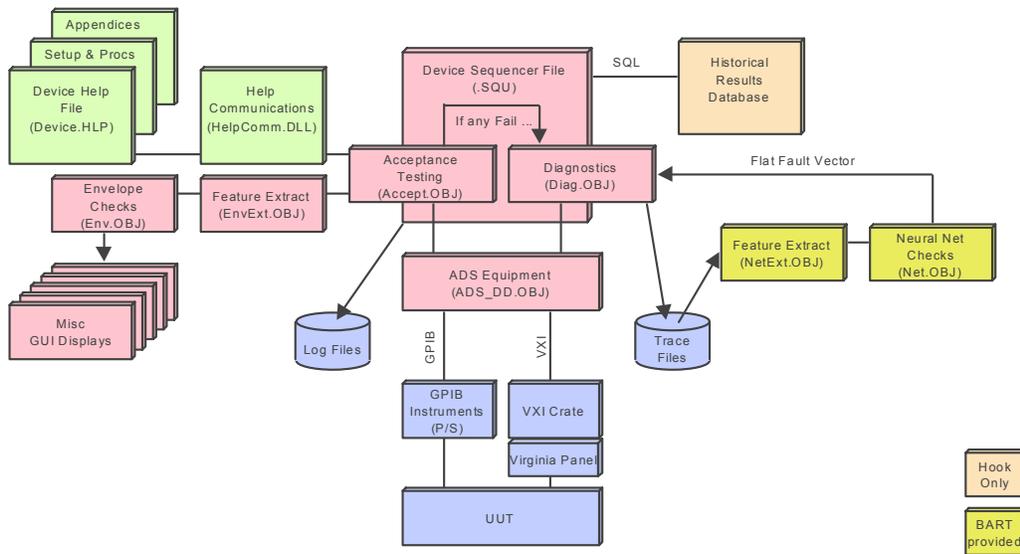*FIGURE 1 Adaptive Diagnostic System Hardware Framework*

FIGURE 2. Adaptive Diagnostic System Software Architecture

SOFTWARE ARCHITECTURE

The software architecture chosen for the ADS developed jointly by the consultants of the Project and BART, is as shown in Fig.2.   Specific features are as follows:

1. Modularity. All functions are developed as modules that can be assembled as part of system integration for particular needs. The high level modules are developed in terms of generic functionality that can be applied to other applications and transit properties as well.

2. Test Executive module. A generic Test Executive module with fixed windows and architecture calls application-specific sequence files, graphics files, help menus, and subordinate utilities. This module is developed around the Test Executive C-code product that is already being marketed by National Instruments.

3. General purpose utilities. A variety of general-purpose utilities are provided, which include setup functions for test instruments, power supplies and switching matrices, measurement and display functions, file read and write functions, error handling and reporting, and browsing. These, in turn, draw upon support utilities within the Windows 95 operating environment, and hardware supplied by National Instruments for each of the VXI instruments used.

4. Diagnostic utilities. The only diagnostic function utility developed at this time is the neural network module (described below), to be treated as a callable function for providing diagnosis of measured waveforms.

5. Data files. Two data files are incorporated for each UUT: (a) log files to maintain a complete history of tests, outcomes, and technician comments; and (b) trace files to store non-standard waveform signatures associated with failures of analog and digital circuitry. The data files are of a flat file format, which can later be imported into a variety of database programs, recompiled for such programs, and used for off-line analysis. The waveform trace files are to be accumulated and used periodically for off-line training of the neural networks associated with specific test points.

Although the hardware and software are to be of a general-purpose design, specific development is required for each new UUTapplication, as follows:

1. Hardware interface. An interface adapter module for the Virginia Panel hardware with associated cable harness and test jig needs to be provided for each UUT.   This may need to be accompanied by some minor interface circuitry. Associated with this interface hardware is a specification for routing of signals through the relay and switching matrices.

2. Test sequence software. High level C-based software for test sequences is required for controlling application-specific test sequences.   This software works in conjunction with universal library functions already developed for controlling a variety of elements, including: test equipment initialization; interconnections through relay matrices; reading of inputs, display of outputs; mathematical calculations; timing of events; and handling of errors.

If other test instrument modules are needed to accommodate more complex UUT's (e.g., a

Bus Emulator module) development effort is also required for associated new instrument function calls, graphical user interfaces, error handling, etc..

NEURAL NETWORK MODULE

The neural network software developed under the program was to be of a single generalized architecture that: (a) could be adapted by training to recognize reliably a variety of signal waveform categories; and (b) would use a relatively simple structure containing a minimal number of nodes to minimize training time. These goals were to be met by the use of a feature extraction "engine" that reduces the approximately 1000 data points of a signal waveform, to less than 50 for input to the neural network. The classes of waveforms to be recognized were to include simple periodic functions, modulated carriers, and digital circuits bit streams. The resulting generalized neural network software architecture with the associated feature extraction module, developed jointly with Intelligent Machines Inc., is as shown in Fig. 3.

> **Comment [MT1]:** Move to later section for discussion (see page 10)
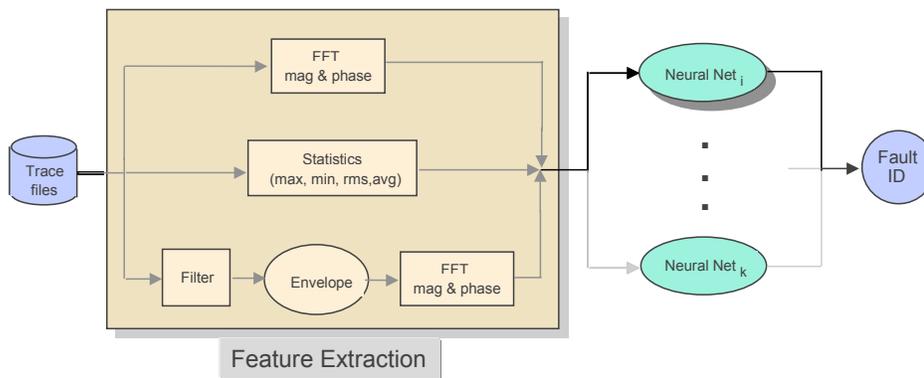
FIGURE 3 Data flow associated with the Neural Network Module

INNOVATION

BART staff searched initially for such a general purpose testing system from the major test equipment manufacturers, but found no such product. One reason for this lack of availability is that the tools, hardware platforms and software development environments that make development of such a system at reasonable cost are all relatively recent. A second reason is that the demand for new test equipment serving the types of equipment being targeted, namely digital/analog equipment in the range below 50 mHz, is relatively small at this time, since new equipment tends to be microprocessor-based and better served by other types of diagnostic systems.

The neural network design is one that has general application for many uses, but is one that neither our neural network consultant, nor we were able to find in commercial of-the-shelf products.   Again, this is probably because the design of such networks for the particular

application being pursued is somewhat specialized, and differs in requirements from that of more common applications.

INVESTIGATION AND DEVELOPMENT

The Project began on March 28, 1995 with a $73,348 grant from the Transportation Research Board, and an even larger commitment from the San Francisco Bay Area Rapid Transit District (BART) in the forms of equipment purchase and staff support. The Principal Investigator was Steven Mullerheim of the BART Research and Development Department. The program used outside consultants for portions of the development, as follows: Intelligent Machines, Inc., a private firm specializing in the applications of artificial intelligence software, for the neural network development; and Innovative Technologies Inc., a developer of integrated hardware/software testing subsystems which use MS Windows/Intel PC-based platforms and software tools, for the general test framework. The Project built upon the prior experience and accomplishment of the various parties in the fields of automated test equipment and artificial intelligence, using BART's needs as a focus for technology and application development.

> **Comment [MT2]:** Only for an initial short period – subsequently received majority investment from foreign (Chinese) company, so I don't think that qualifies for DBE status

The Project involved two stages, with successful completion of the first required before authorization was granted on the second. These stages were defined as follows:

- Stage 1. Fabricate a general purpose tester (prototype) and examine the feasibility of incorporating artificial intelligence / neural network for identifying typical electronic failures, including failures in transit equipment.

- Stage 2. Integrate hardware and software for the tester. Perform suite of operational tests and demonstrate the efficacy of the automated general-purpose tester for troubleshooting and maintenance of transit equipment electronics.

The approach to be used in developing and evaluating the product was to apply it to two subassemblies being serviced by BART's Electronic Repair Shop for which the tester would find good application:

- Preamp/mux assembly. This assembly is a combination of several subcircuits: (a) a single-stage frequency-contoured amplifier for signals in the audio range; (b) a transmitter/encoder and receiver/decoder of pulse modulated audio signals for transmission through the BART train trainlines. The Preamp/mux assembly was considered a good candidate for evaluating general testing capabilities of the Adaptive Diagnostic System, since it has a representative mix of low-frequency analog and digital circuits, and also, has been a frequent repair item that is time consuming to test. The amplifier stage portion of the assembly, furthermore, was also considered a good candidate for evaluating the neural network, since it is easy to simulate using a circuit simulation program, and allows evaluation of the effects of specific component failures.

- XA-3 Board. The board contains a variety of circuits, one of which, a commutated capacitor filter, is complex and produces varied waveforms which are difficult to analyze. The commutated capacitor filter is used for filtering track signals as input from the track signal preamplifier circuit. The normal signal output produced in response to track signals involves a beat signal created by mixing a local oscillator on the board with an external modulated

modulated carrier input signal, and is of a class that can be described as "modulated carrier". This is approximately a biased sine wave signal, with a sinusoidal beat frequency that is quite random in frequency and phase. Signals associated with component failures represent distortions of this normal signal, but still preserve the randomness in frequency and phase of the envelope. The complexity of the XA-3 board commutated capacitor filter circuit and its associated waveforms made them good candidates for evaluating the effectiveness of the neural network program for identifying failures.

The design and testing of the two portions of the product, the general-purpose tester and the neural network, being independent of one another, were undertaken in parallel. Development and implementation of these shall be described separately.

ADAPTIVE DIAGNOSTIC SYSTEM FRAMEWORK

Prior to the beginning of the TRB program, BART had already procured a variety of components for the Project based on the available versions of products at that time. These components included: the 13-slot VXI cradle, VXI instrument modules, power supplies, Virginia Panel interface hardware, Lab Windows 3.0 software and associated instrument drivers. By the time Innovative Technologies Inc. had started work on designing the software architecture during Stage 1, a variety of changes had occurred in the maturity of the various components, and it became desirable to procure new versions and to design based on these versions. Changed components included the following:

- MS Windows 3.1 progressed to MS Windows 95

- National Instruments CVI version 3.0 progressed to version 4.01

- National Instruments instrument software drivers superseded Tektronix drivers

- The Tektronix Resource Manager module , which was flawed and became obsolete was replaced with a superior National Instrument module

All of these changes, particularly the progress of MS Windows and National Instruments CVI, which involved major architectural changes to the computer operating system, had profound effects on the design of the software architecture. Shown in Fig.2 above is what emerged as the Stage 1 design that was proposed for implementation.

An objective of the Adaptive Diagnostic System framework design was to make maximum use of hardware and software components that had already been developed by outside parties for other applications. Principal among these parties was Innovative Technologies Inc. who had developed for others, and were continuing to develop, software-based test equipment that used a similar architecture. A second major source of developed hardware and software was National Instruments, a company that specialized in graphics-based test and instrumentation hardware and software. Their Test Executive C code was used as the basis for the Test Executive design for BART. The interrelationships of these various sources were as shown in Fig. 4.
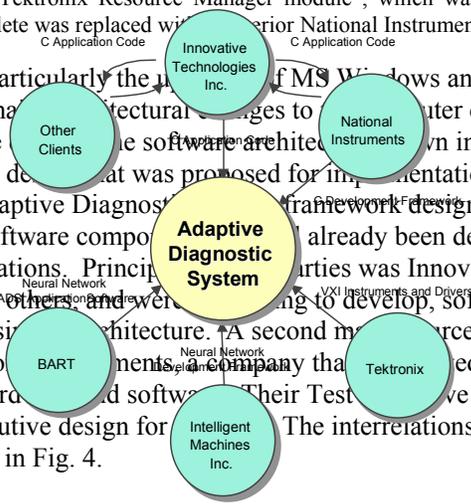
FIGURE 4 Development Sources and Interrelationships

For both development and demonstration purposes, the design of the ADS featured two operating modes, in which the ADS could work with either "virtual" hardware or actual hardware. By means of the virtual hardware mode the software "engine" could be debugged and demonstrated independent of connection to actual hardware; conversely, with the actual hardware connection, debugging and demonstration of hardware interfaces would be facilitated.

Instrumentation modes were also of two types: Virtual Test Instruments, and Virtual Instruments. Virtual Test Instruments are those that are automatically called within the Test Sequence program for a particular Unit Under Test, wherein the program chooses the instrument, its settings and displays, provides the user with the displays and queries he needs, and then closes at the termination of the measurement. A Virtual Instrument is a manual instrument that the user can select and control, via the Graphical User Interface, which will allow him to make measurements with probes.

During Stage 1, the architecture shown in Fig. 2 was developed, and hardware and preliminary software components of Virtual Instruments were developed and demonstrated. In Stage 2 the remainder of the software and hardware design was completed using the services of Innovative Technologies Inc.

The result was a workable hardware/software system ready for testing. Preliminary testing consisted of using technicians unfamiliar with testing of the preamp/mux assembly to perform an acceptance test using the System. A properly functioning assembly was used for such tests, since diagnosis was not an objective at this point. All instruction needed to perform the tests were to be obtained from the screen messages /displays.

NEURAL NETWORK MODULE

Fig. 5 depicts the neural network software module in its intended context within the ADS. As can be seen, the module is designed to be called as a diagnostic function within the ADS Lab Windows/CVI framework, reading waveform trace files, and yielding as output a list of probable faults sorted in terms of likelihood.

FIG. Neural Network integrated into
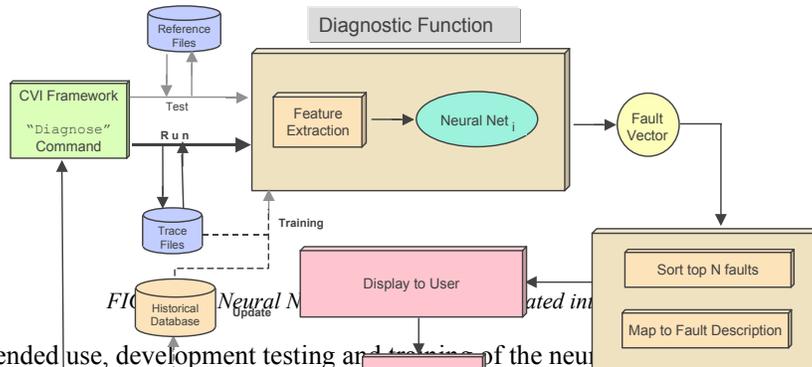
In its intended use, development testing and training of the neural network comes from stored waveforms derived from both simulated and actual circuit diagnostic measurements. Diagnostic waveform data is accumulated over time in historical files, which are used to periodically retrain the network and thereby improve accuracy.

Development effort for the neural network module focused on five areas:

- design of the neural network architecture;

- design and refinement of feature reduction functions;

- design of simulation software for generating waveforms to be used in training and testing of the module;

- design of the training and testing software used to evaluate module performance; and,

- execution of the testing program and compilation of results.

Several of software components of the above were consolidated in a graphically-based program designed to streamline the design process. A screen snapshot of the program's Graphical User Interface is shown in Fig. 6.
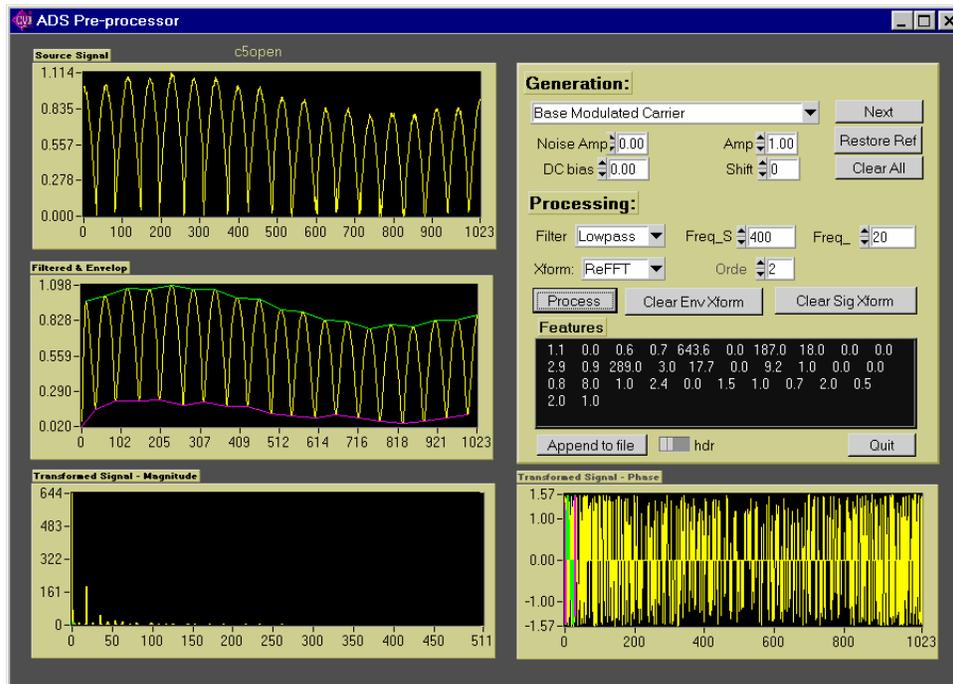
FIGURE 6 Feature Extraction Development Program Graphical User Interface

As shown in Fig. 6, a variety of waveform features were evaluated for inclusion as nodes in the neural network. During Stage 1, in which the neural network architecture was being designed, the modulated carrier type of waveform was chosen for research, being considered an extreme type of pattern to characterize. One set of features required for this type of waveform was that which characterized the waveform envelope. An envelope extraction function and associated filters for both top and bottom envelopes were therefore developed and optimized for this purpose, as are depicted in Fig. 6.

With both the envelope and the carrier information, further feature reduction was required. This was accomplished with a series of scalar measures of raw signal magnitude (maximum, minimum, mean and RMS), with a multiplicity of Fourier series magnitude and phase measures derived from the unprocessed signal and also, from the upper and lower envelope functions. This resulted in the set of 32 features listed in Table 1 which were chosen to evaluate as inputs to the neural network.

Feature Index	Description
1	Maximum of signal amplitude
2	Minimum of signal amplitude
3	Mean of signal amplitude
4	Root-mean-square of signal amplitude
5	First signal harmonic above threshold (set as 20% of extremum)
6	First signal harmonic index (its frequency)
7	Second signal harmonic above threshold
8	Second signal harmonic index
9	Third signal harmonic above threshold
10	Third signal harmonic index
11	Average noise magnitude (set as 10 additional harmonics at tail-end)*
12	Root-mean-square of signal phase
13	Number of phase components above threshold (set as 20% of extremum)
14	Index of region of maximum phase component density#
15-23	Same as 5-10, 12-14; repeated for top envelope of waveform+
24-32	Same as 5-10, 12-14; repeated for bottom envelope of waveform+

(* Beginning of 'tail' of the frequency spectrum is currently set as 10*average frequency of three principle harmonics
Spectrum is divided into eight regions, and density of phase components above threshold is computed
+ Feature 11 is excluded for envelopes because low-pass-filter has been applied)

TABLE 1 Neural Network Input Node Features

During the development of the diagnostic subsystem, considerable effort was devoted to the feature extraction module to ensure that the neural network's decisions are based on meaningful (physically relevant) criteria for the problem domain. As "universal approximators" neural nets can learn an arbitrarily complex mapping between its input and output parameters; however, the solutions it produces (and its basis for reasoning) would not be sound unless its input data is recognized to be acceptable by domain experts.

The resultant features in Table 1 provide: (i) data reduction from the original waveforms digitized at 1024 points each, and (ii) confidence that the trained neural network has learned meaningful relationships between probed waveforms and fault classes, since the network is "looking at" physically significant waveform characteristics in both the time and frequency domains. Note that although the human designer engineers feature selection, the fault classification problem remains non-trivial – the neural network must learn how the 32 input parameters relate to various fault classes.

The neural network itself, developed using the O'INCA neural network/fuzzy logic
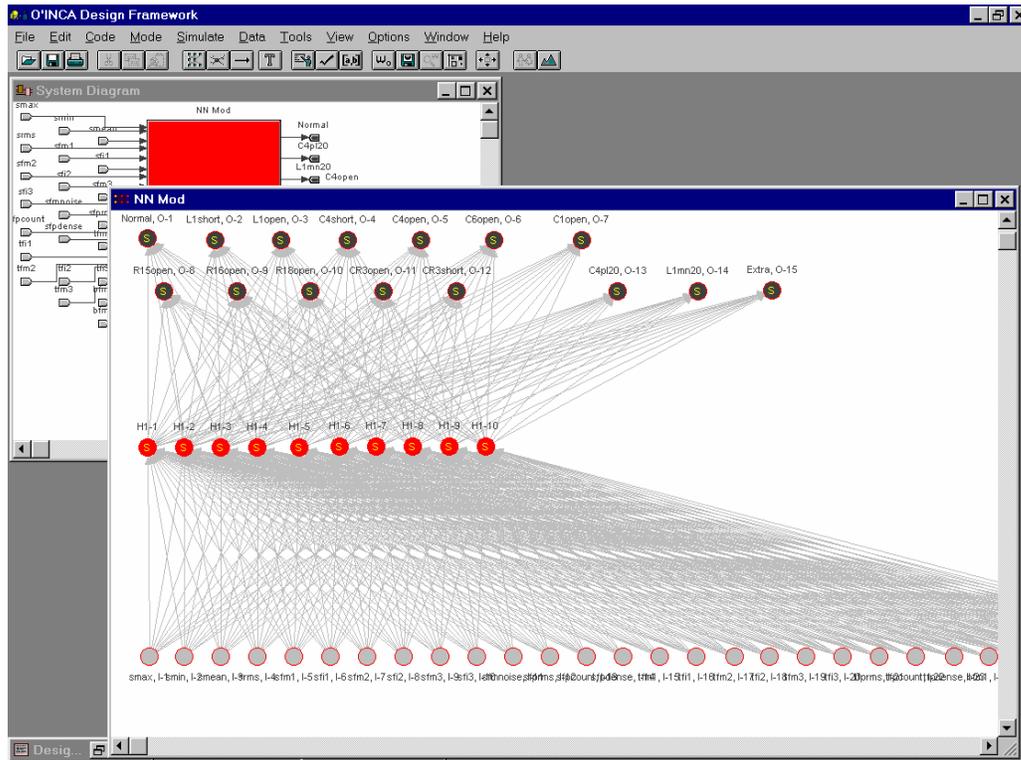
development program, is as shown in Fig. 7. The network incorporates the feed-forward, backward error propagating architecture that finds common use. A single hidden layer involving ten nodes was employed, a design choice that was arrived at using rules of thumb and testing. Starting with a number of hidden output nodes equal to the number of output fault vectors, nodes were reduced in number to the minimum that would achieve desirable levels of accuracy.

FIGURE 7 Neural Network Architecture

During Stage 2 , the development activity was focused on testing, evaluating and refining the neural network module design, and on integrating it within the Adaptive Diagnostic System framework. For testing we chose to use simulated rather than actual hardware

signals since they were easier to generate, and also, could better isolate deficiencies of the neural network module. Two sets of test signals corresponding to two separate neural networks, were used for the evaluation: the XA-3 board (modulated carrier type) and the preamp (ringing transient). The waveforms associated with nominal signals for each of the failure states, and each output node of the neural networks, are shown in Fig. 8.

For training and testing, noise was injected, and the various parameters used to generate the signal were randomized within component tolerances for each signal type and fault class, to create the spread of variations that could be expected with actual hardware.   Signal parameters varied for the two circuits were as follows:

XA-3:   carrier frequency, envelope frequency, phase and amplitude,
Preamp: transient frequency, amplitude, phase

Design decision was made to use separate neural networks for the two UUTs. The reasoning relates to theoretical (information capacity of the neural network) and practical aspects such as training time. A "different" neural network in this domain implies a neural network that is trained on a different set of fault waveforms and fault classes as applied to different UUTs. The architecture of the neural net itself remains unchanged, except for the number of output nodes which corresponds to the number of fault classes.

In this application where a neural network is used as a diagnostic function call, a different neural net and its associated weight file could be easily uploaded as part of a standard set-up sequence for each UUT (or even each test point for a given UUT). Consequently, to improve accuracy of diagnosis, decrease training time, and prevent unwarranted overloading of the neural network, two neural nets were used for the XA-3 and Preamp boards.   For each of the two neural networks, performance was evaluated during the
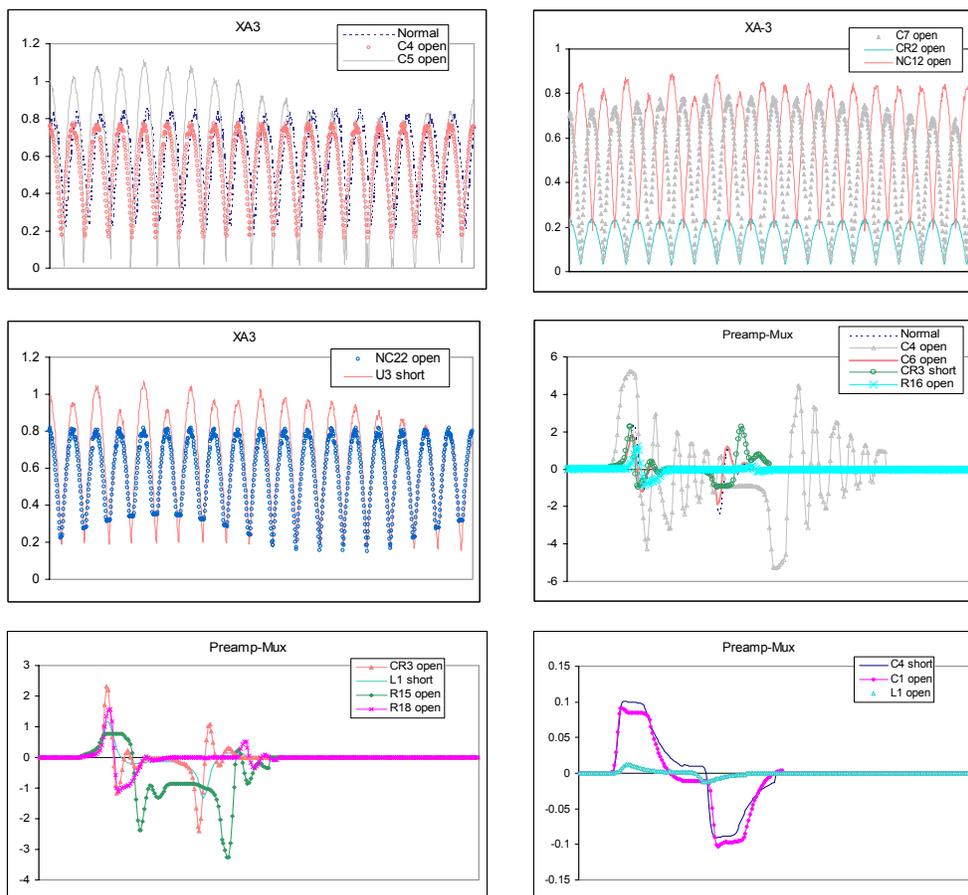
training process with one set of waveforms, and then during testing with an independently generated set.

FIGURE 8 Nominal Waveforms for Simulated Fault Conditions

Initial training of each of the networks was performed using an automated program that read the randomized waveforms, performed the feature reduction, and calculated the resultant weighting functions for each of the network nodes. The number of waveforms and the training time (on a Pentium 130 PC) associated with each were as shown in Table 2.

Circuit	Number of Waveform Classes	Number of Waveforms used for Training /Testing	Approx. Training Interval
XA-3	8	328 / 252	2 hours
Preamp	12	120 / 120	1 hour

TABLE 2 Training Data for Sample Circuits

RESULTS OF INVESTIGATION
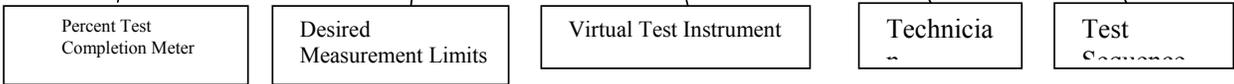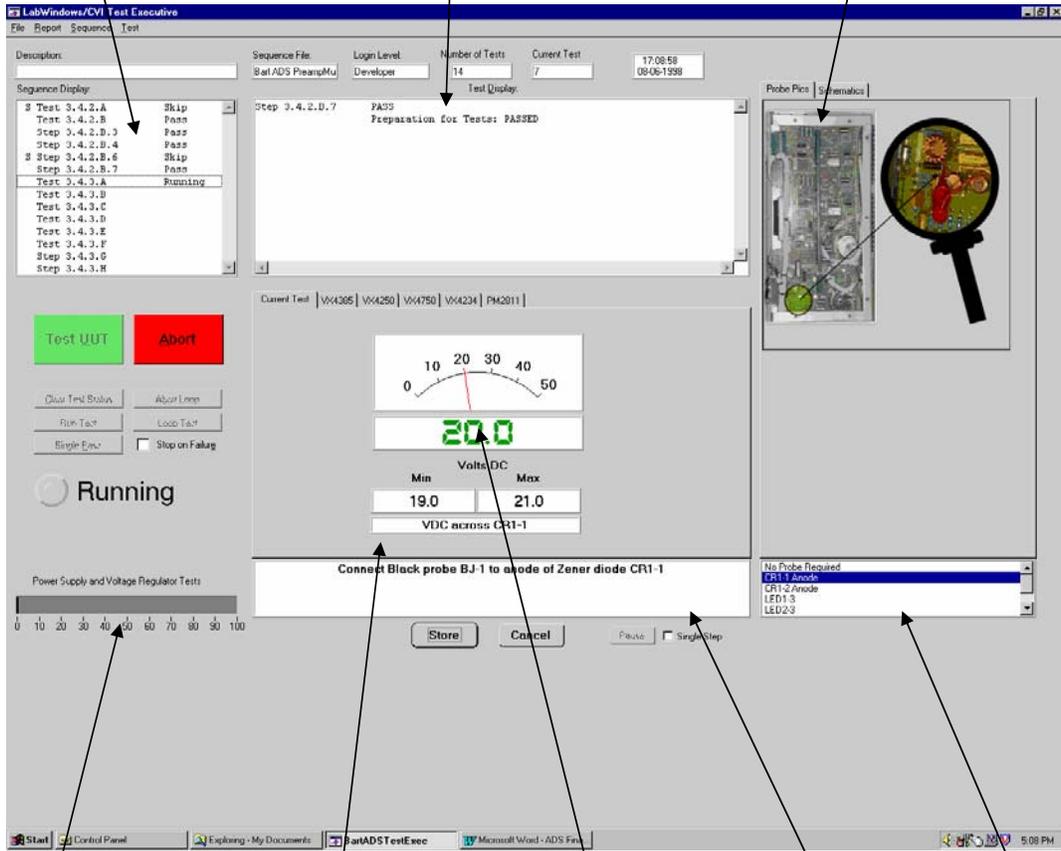
ADAPTIVE DIAGNOSTIC SYSTEM FRAMEWORK

Work was completed in developing the hardware and software framework for the Adaptive Diagnostic System and for its application to the Preamp/Mux Assembly, although constraints of schedule and budget required that the refinement of the design and formal performance testing be postponed. No fundamental design problems were encountered. Preliminary testing performed by the Principal Investigator and the technicians of the BART Electronic Repair Shop revealed a few discrepancies in certain displays and in certain recommended procedures, which were corrected quickly and easily.

Although the benefits of the ADS have not been quantified, their potential is clear. Specific areas of benefit were seen to include the following:

- Reduced technician training time. The use of on-screen instructions, with abundant graphic support in the forms of context-sensitive color photographs, schematics, instrument readouts, and measurement limits eliminates the need for testing manuals and training. Several tests were performed automatically that were formerly performed manually. All of these made prior training unnecessary.

- Reduced testing time. The above features appeared to reduce testing time significantly, although this aspect was not measured in controlled tests.

- Increased testing accuracy. Testing accuracy is improved by enforcing total repeatability of signal injection magnitudes, and of pass/fail thresholds. Also, enforced adherence to a testing sequence, and logging of test results to a permanent file minimizes the opportunity for technicians to take "short-cuts".

- Reduced cost of test equipment development. Innovative Technologies Inc. made estimates of the cost to develop acceptance test applications of the ADS for future Units Under Test. This would involve for each UUT at a minimum, development of new test hardware interfaces and test jigs, and new sequence software. Where new test VXI instruments are required (such as a bus emulator for bus-based A/D/ and D/A function circuit boards) additional development and cost would be entailed for the new instrument drivers, displays and functions. The overall development cost estimates were found to

to range from $27K to 52K for new UUT applications; and an additional cost range of $50K to 100K to procure and develop software associated with new VXI instruments. While these costs are not insignificant, they still are less than that of development of custom hardware and software for new stand-alone test equipment.

The Test Execution System can be better visualized using the operator's displays, shown in Fig. 9 in the following pages.

| Test Sequence Overview | Test Display | Diagrammatic and Photographic Testing Aids |

| Percent Test Completion Meter | Desired Measurement Limits | Virtual Test Instrument | Technician | Test Sequence |
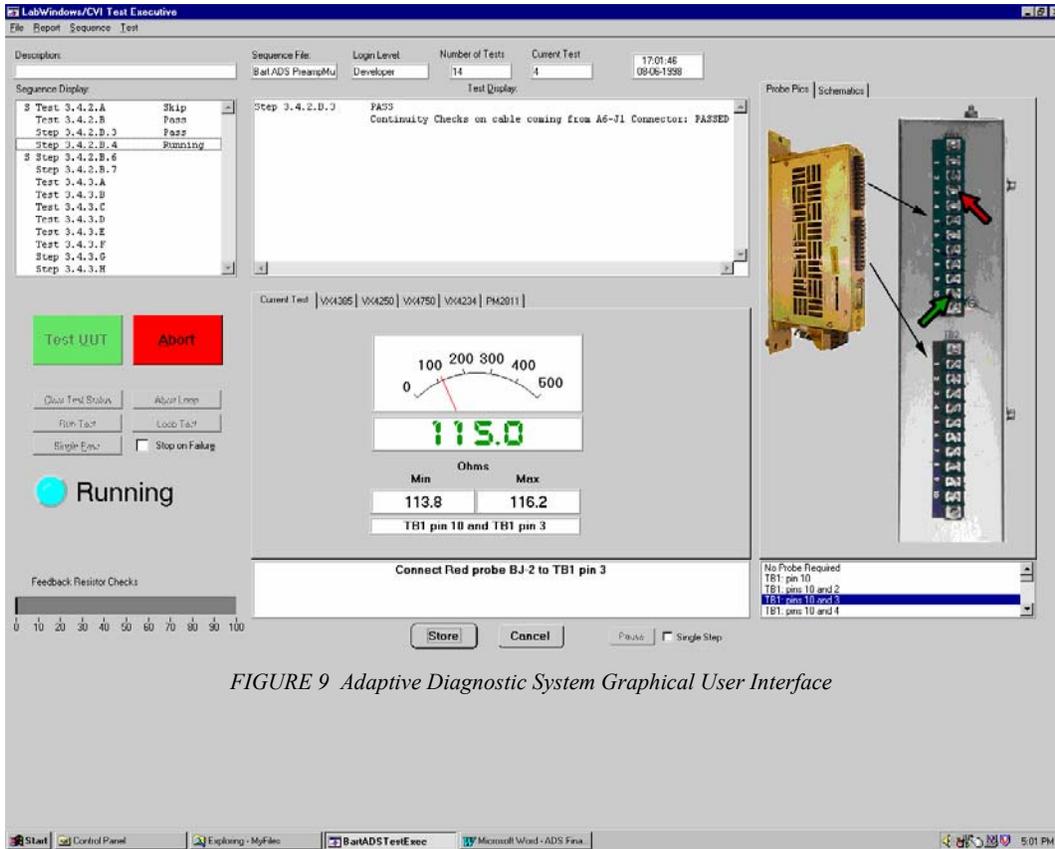
FIGURE 9 Adaptive Diagnostic System Graphical User Interface
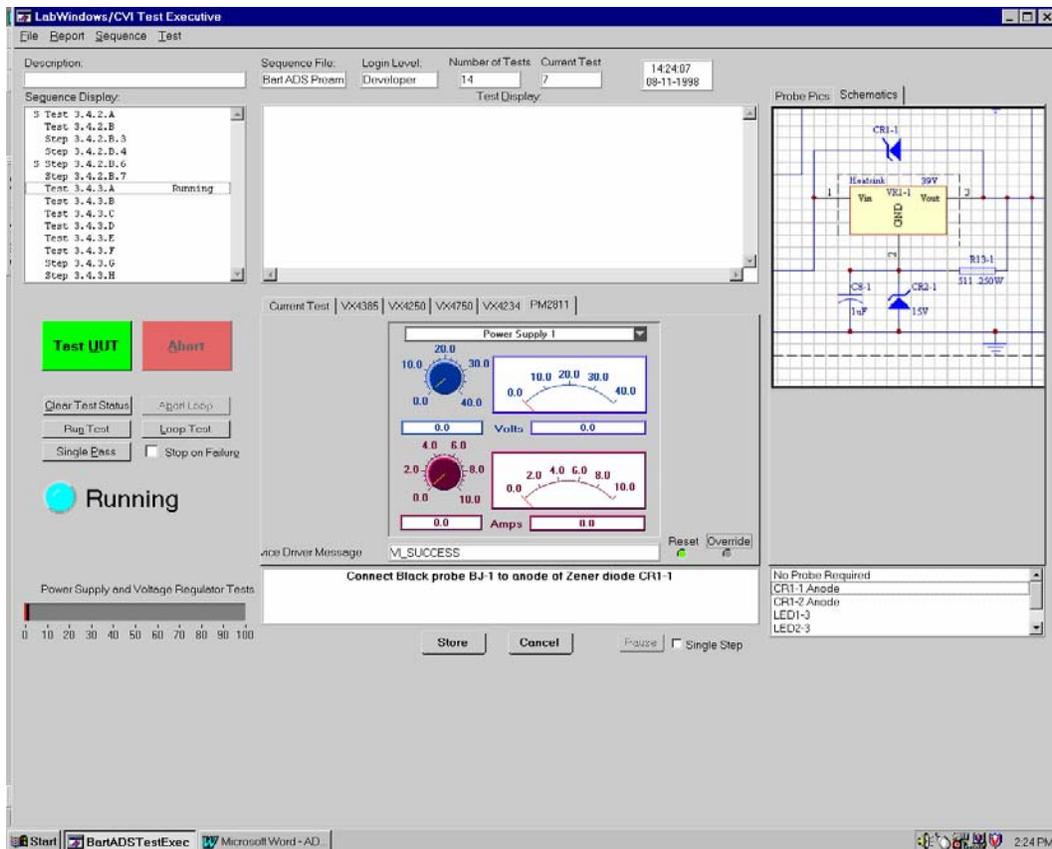
FIGURE 9. Adaptive Diagnostic System Graphical User Interface (continued)

NEURAL NETWORK MODULE

The neural network module design performed admirably in identifying waveforms of both categories for those classes that were readily discernable by the human eye. For those fault classes where the waveform differences were slight or undetectable, the network module was able to reliably reduce the choice to two fault classes. Table 2 below shows the statistical performance experienced:

Circuit	% of Correct Fault Identification to	% of Correct Fault Identification to

	One Class	Two Classes
XA-3	90%	98%
Preamp	70%	90%

TABLE 3 Performance of Neural Network Module in Identifying Fault Classes

Note that the statistics in Table 3 above represent average performance over the entire test data set. Test data is mutually exclusive from the training data (i.e. the neural network has not seen the test data before) and it is randomly selected from the total population of available data. As indicated in Figure 13 below, mis-classification rate for a particular fault may be higher, but can be improved via biases in the training data.

These performance indicators should be viewed with respect to the potential utility of the neural network module – in practice, if poor performance is detected during the testing phase, the diagnostic module can be improved with further effort from the designer. For example, an additional neural network could be used to segregate and learn the cluster of "problem faults" and decrease information load on the one neural net. However, our descriptions reflect results without such problem-specific optimization.

Examples of waveforms for fault classes that were easy to discern by the neural networks are given in Fig. 10, while those that were difficult to discern are shown in Fig. 11.
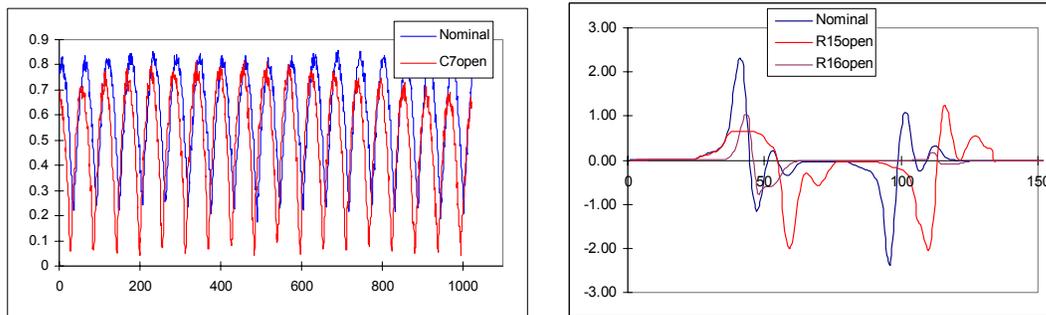
FIGURE 10 Waveforms That Are Easy to Distinguish by Neural Network Module
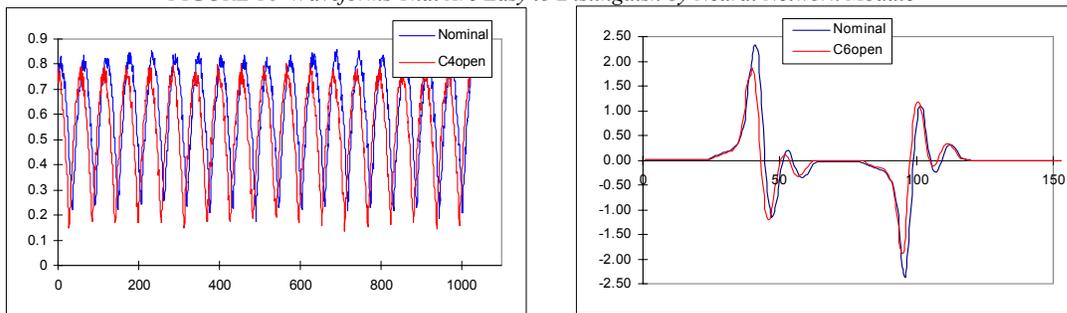
FIGURE 11 Waveforms That Are Difficult to Distinguish by Neural Network Module

The computational "pattern distances" as seen by the neural network were examined and were found to show a correspondence with differences that were discernable by graphical inspection. This can be seen in Fig. 12 below for the XA-3 set of waveforms. For example, the CR2_open signature is distinct from others, whereas distances between each of the other waveforms are similar (and therefore poses a more difficult pattern recognition problem):
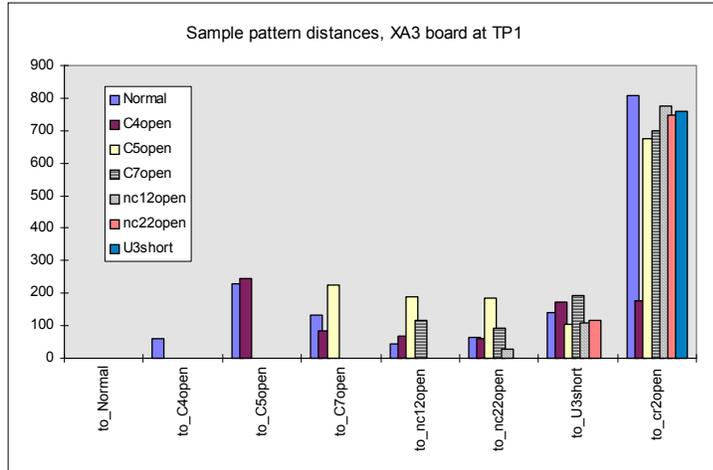
FIGURE 12 Sample Pattern Distances for Various Fault Classes of XA-3 Circuit

It was also determined that by biasing training towards waveforms that had small computational distances between them through use of more samples, performance for those fault classes could be improved, albeit with some degradation on other classes. Fig. 13 below involving a total sample training and testing pass of 580 waveforms demonstrates, for example, that while nc22open produced the highest error during pass 1, performance on that fault class could be improved with more training, but at the expense of error for the other classes.
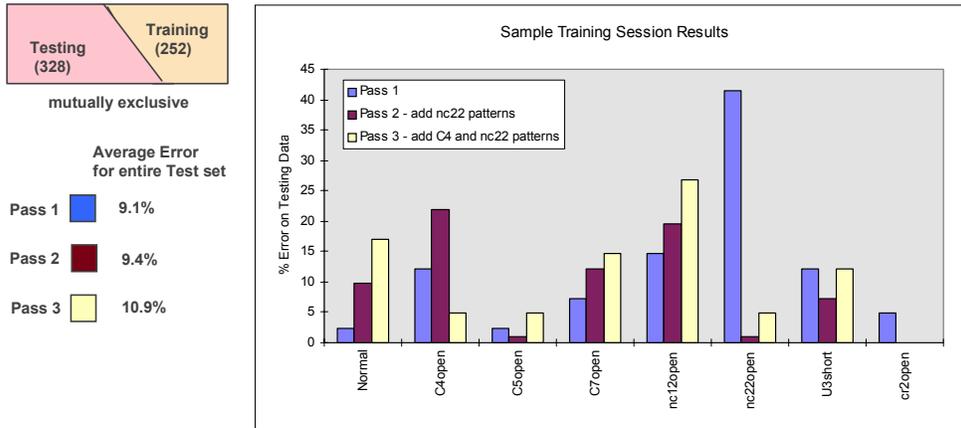
FIGURE 13 Sample Training Results for Various Fault Classes of XA-3 Circuit

25

ATTAINMENT OF PROGRAM OBJECTIVES

The scope of the ADS Project was ambitious for the schedule and budget involved., and of necessity, had to be somewhat curtailed. Fig.'s 14 and 15 show the various development objectives of the program, and the extent of their completion, for the general ADS framework and neural network modules portions, respectively.   The Project encountered no technical barriers that could not be overcome, but did experience institutional impediments. Among these impediments were procurement delays and restrictions, personnel and organizational changes, budget cutbacks, and shifting organizational priorities. Many of these are problems inherent in the performance of R & D by public agencies.   The rapid change of technology is also a widespread problem.

Sytem Design	Application to UUT	Hardware Design	System Integration	Refine/Test
System Architecture Design	Review Existing Test Procedures	Map Test Set to VXI Interfaces	Start Development/Test of Test Sequences	Review/Refine Features
Choice of Software Tools	Develop Revised Test Script	Fabricate Panel and Wiring Harness	Complete Development/Test of Test Sequences	Perform Alpha Test in Shop Environment
Windows Interface Design	Map Tests to System Resources	Checfk/Debug Interfaces	Develop/Test Neural Net Link	Refine
Equipment Interface Design	Develop Help Files		Develop Database Save Link	Perform Features and Productivity Tests
	Develop Graphics and Appendices			

FIGURE 14 Development Tasks and Status for the ADS Framework

As can be seen from Fig. 14 above, several improvements are still required to complete the development of the ADS frameworks. One of these is the creation of data storage files and associated data base links for storing and retrieving test data and associated waveform files.   Another is the addition of browser help files, which include context-sensitive technician comments, sample waveforms, and circuit schematics. A third is formal testing and debugging. Lack of these enhancements should not stand in the way of using the system productively in its present state, however.

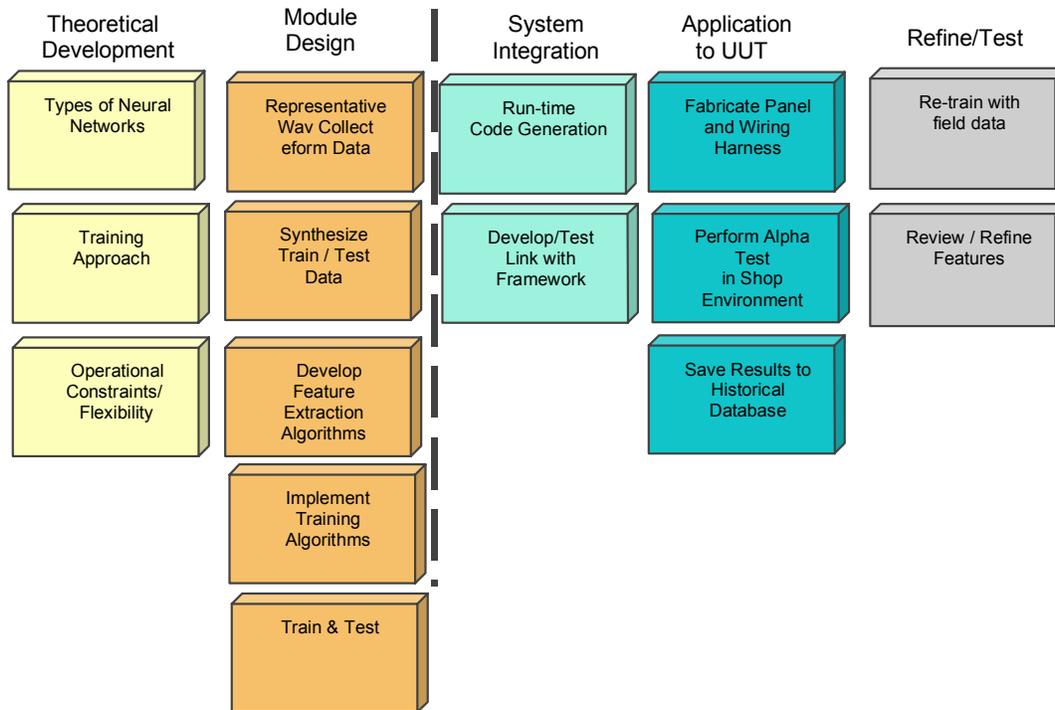| Theoretical Development	Module Design	System Integration	Application to UUT	Refine/Test
Types of Neural Networks	Representative Wav Collect eform Data	Run-time Code Generation	Fabricate Panel and Wiring Harness	Re-train with field data
Training Approach	Synthesize Train / Test Data	Develop/Test Link with Framework	Perform Alpha Test in Shop Environment	Review / Refine Features
Operational Constraints/ Flexibility	Develop Feature Extraction Algorithms		Save Results to Historical Database	
	Implement Training Algorithms			
	Train & Test			

FIGURE 15 Development Tasks and Status for the Neural Network Module

PLANS FOR IMPLEMENTATION

BART as an organization still has to make a determination as to whether it wishes to further the development and use of the Adaptive Diagnostic System. Specific decisions relate to: (1) completing development for its application on a trial basis to testing of the Peamp/Mux Assembly; (2) expansion of its application to other Units Under Test; and (3) enhancing its testing capabilities through the addition of new test instrument hardware and software modules.

To progress to items 2 and 3 above will require a commitment by BART to developing internal engineering capabilities dedicated to automated testing. The BART Research and Development Division believes that such an investment will reap good returns through enhanced productivity and accuracy of maintenance and repair operations. Such a capability has become even more critical now that BART has expanded its fleet and with it, the number of repairable electronic assemblies it needs to service. The Principle Investigator working with BART shop technicians and with its software developer/consultant, devised a preliminary set of tasks that could be the focus of such an Adaptive Diagnostic System deployment. This list of tasks, with associated cost estimates, is presented in Table 4.

More generally, and with consideration to use of the Adaptive Diagnostic System beyond

Item	Estimated Labor Cost	Estimated Material Cost	BART Priority
General ADS Framework Development			
Linking databases	$10K		High
Creating Virtual Instruments (VI) for existing hardware	$5K per VI		High
Addition of new VXI Instruments with software	$35-50K	$15-50K	High
Diagnostic Subsystem Development			
Guided probe linking of nodes and resources	$50K		Medium
High-level automation of Neural Net training/testing	$15K		Medium
Develop hybrid Rule-Based & Neural Net system	$50K		Low
Application to New Units Under Test	$25-50K per UUT	$2K per UUT	
XA-3 Board (Vehicle Speed Code Receiver Board)			High
Vital Relays (Interlockings and Vehicle ATC)			Medium
XA-7 Board (Vehicle ID and Program Stop Receiver)			High
Fare Collection Equipment Boards			Low

BART applications, candidate areas of enhancement for the System are as shown in Fig. 16.

TABLE 4 BART ADS Development Tasks and Associated Cost Estimates
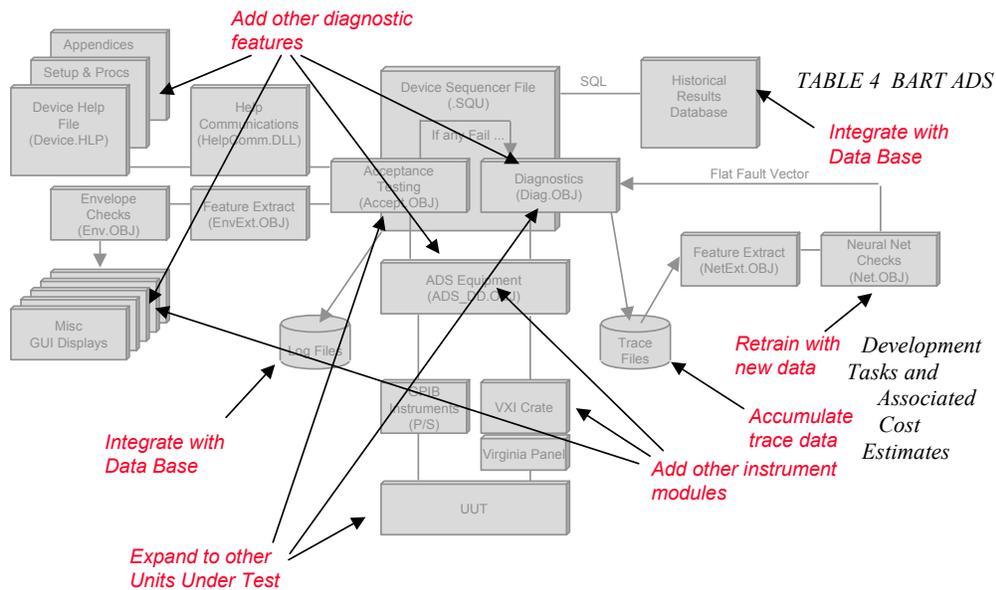
FIGURE 16 Future Enhancement Areas for Adaptive Diagnostic System

CONCLUSIONS

The Adaptive Diagnostic System has provided BART with the foundation for a general automated testing framework which can find productive application to the Preamp/Mux Assembly with minor additional work. It also has significant potential for expanded application and functionality, wherein its generalized and flexible design attributes can be exploited. To reap the benefits of the System, however, BART will need to make a commitment to pursue its continued development and use. Such a decision will require that the repair and testing needs of BART be accurately assessed, and that cost-benefit analyses be made of the ADS against other testing and diagnostic alternatives.

The principal value of the System would appear to be for routine acceptance testing and repair of analog and logic types of assemblies, including relays, in the frequency spectrum below 50 mHz. This is particularly true of assemblies that must be tested to meet certain functional performance requirements. Other types of assemblies, such as microprocessor boards, are best served by the use of built-in tests and commercial testing systems specifically intended for such assemblies.

The neural network module as designed met the particular objectives of the Project admirably. It appears to be a promising tool for waveform recognition, based on the two types of waveforms that were investigated. One other type of waveform that still needs to be studied is the digital pulse train. This was selected as a candidate waveform for the Project, and is believed to be one that could also be well identified with the present design.

A remaining issue for application of neural networks to component failure diagnosis is that of training. Electronic circuits have an almost infinite variety of failure states. In the absence of empirical data from actual repair records, as is the case initially, discretion needs to be used in selecting for training that subset of failures which is most likely. There is also the task of finding a means for generating or simulating the waveforms corresponding to those failures. These tasks are often non-trivial, as was found for the case of the XA-3 circuit, which is difficult to both analyze and simulate. The frequency of occurrence of a particular failure state for a UUT needs to be sufficiently high to justify the investment in training for that state. Of course, once data becomes available for actual failures, such data can be used for the training.

The neural network module is only one of several diagnostic tools that could be incorporated into the ADS. Others include rule-based tools such as expert systems, guided probe systems and fuzzy logic systems. The neural networks and rule-based systems can be combined; for example, one of several neural networks can be selected based on answers to some simple queries of the technician by a rule-based system.   Use of rule-base tools can also narrow the application of the neural network sufficiently that training of the network becomes less of an issue.

BART offers its assistance to other transit properties wishing to gain the benefits of its designs and experience. This can be best accomplished through direct contact with the Principle Investigator, Steven Mullerheim, as follows:

> Telephone: 510-869-2417
> Fax: 510-287-4777
> E-mail: (smuller@sinewave.com)