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ELECTRONIC CIRCUIT DIAGNOSTIC EXPERT SYSTEMS—A SURVEY

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Abstract—The electronic circuit diagnostic problem is roughly formulated and subdivided into six subproblems. Current literature and patents are surveyed with respect to the above six subproblems. Some of the existing expert diagnostic systems as well as expert diagnostic shells are described and their limitations are outlined. A review of the relevant terms from AI is included. The bibliography list contains some 300 references.

1. INTRODUCTION

This paper discusses artificial intelligence methods in circuit pack testing. Testing requires investment of labor, capital and information about testing techniques. The added cost of testing in the circuit pack production line is justified by several reasons: first, the defective products are not shipped; second, testing helps to develop product repair methodology; and, finally, testing helps to discover manufacturing problems, e.g. low yield due to a single fault may occur because of malfunctioning insertion robot, a bad batch of components, or a badly designed in-circuit test.

The interested reader should refer to Towill (1987) and Williams *et al.* (1982) for overviews of automatic testing.

1.1. Fault categories

Defects in circuit packs, in general, come from three sources: bad components, damage to components or the circuit board, and mistakes in the manufacturing process. Since "different things go wrong at different times because of different reasons" (Pynn, 1986), determining an optimal manufacturing and test strategy becomes a challenging task.

Roughly speaking, one can define three different fault categories: device faults (e.g. unoperative capacitor) assembly faults (e.g. solder shorts, missing components, misoriented components, etc.) and operational faults, such as timing problems arising from apparently good components that fail to work together. According to this somewhat arbitrary fault categorization, a two-stage test strategy has been adopted by most circuit pack manufacturers: the inspection test stage and the functional test stage.

Inspection test is designed to examine the circuit pack for proper construction and it consists of shorts test, in-circuit test, and visual test. The in-circuit test examines the function of each device separately from others. Functional (system) test is designed to examine the operation of the pack and thus tests the function of assemblies of components.

As the complexity of the circuit pack grows, the role of testing becomes more important and the testing process becomes more difficult. The area of design for testability is becoming a popular topic by necessity (Williams and Parker, 1983). With the advent of computer technology, automatic test equipment—the equipment for programmed application of sequences of stimuli, measurement, and comparison of the results to the expected values—became the accepted norm. The issue of software development for such automatic test equipment becomes both increasingly important and difficult as the complexity of the circuit packs grows.

1.2. Automated diagnostics

The ability of software to generate stimuli and to draw conclusions about the defective components for a given circuit pack is a subtle issue dependent on the experience of the test engineer responsible for programming of the automatic test equipment. If the test is to perform two basic tasks, i.e. verification (knowing whether everything is functioning as expected), and diagnosis (identifying what causes the unexpected behavior, so it can be fixed) then it is the diagnosis which becomes an increasingly difficult task as a result of the growing complexity of the circuit packs.

1.3. Importance of diagnostics

Diagnosis of an electronic circuit usually refers to the process of determining the faulty component(s) that cause an undesired behavior (output) of the given circuit for some (correctly) given input. Importance of diagnosis stems from both practical and theoretical considerations.

1.3.1. Practical considerations. The practical considerations are primarily of an economic nature: there is a monetary value associated with every component in the pack, as well as a monetary value associated with the processes of assembly and soldering of the pack. Thus, when a pack is declared faulty, it is desirable to replace only the faulty components.

Moreover, the process of identification of the faulty components (the diagnostics) consists of a series of tests each of which has an associated cost, expressed in such parameters as test setup time, component destruction, etc. The process of identification of the faulty components and their subsequent replacement should not be overly expensive. Thus,

Observation 1: Diagnostics of circuit packs is primarily an economic problem (Barber and Yau, 1986). Currently this problem is solved in the majority of cases by humans who are called test analysts or diagnosticians. Training of such human analysts is expensive. Their performance depends on the accumulated experience. Indeed,

Observation 2: There are human experts that are extremely successful in the area of diagnostics. Therefore, it is very desirable to have computer programs which are capable of performing diagnostics. However,

Observation 3: Diagnostics problem (i.e. the construction of a computer algorithm which is capable to perform diagnostics) is NP-hard (Hyafil and Rivest, 1976; Ibarra and Sahni, 1976; Karp, 1972).

1.3.2. Theoretical considerations. Therefore, in the absence of a better alternative, we resort to the construction of programs that perform approximate diagnostics. In other words, we are willing to give up some of the precision of the final description of the faulty component(s) (solution) in order to gain in the length of time spent to obtain that solution. Moreover, in many cases, in the absence of rigorous mathematical methods to simulate the complex decision making processes which are performed by the human diagnosticians, we are forced to invent different heuristics in order to obtain in some sense similar diagnostic performance. Therefore, the development of such programs is related to the field of computer science which is commonly known by the name of artificial intelligence.

This relation is further extended to the fields of control systems, since, as we shall show later, a diagnostics problem is also a planning or control problem. Moreover, approximate solution approaches often employ probabilistic and fuzzy reasonings, thus relating the research in diagnostics to operations research and information theory. The time complexity considerations in the diagnostic and related algorithms requires applications and further developments of the results belonging to the field of computational complexity. And, of course, the area of application is related to electrical engineering. Diagnostics belongs to the intersection of all of the above fields. Hence the theoretical importance of diagnostics.

1.4. Current approaches

Two basic approaches and their combinations are currently utilized in industry for conventional diagnostic software development: the fault dictionary approach and the guided probe approach. The fault dictionary approach requires simulation of the faulty behavior of the system and subsequent storage of the simulation results (as well as the fault assumptions) in the fault dictionary. A "misbehaved" output of the pack under test can therefore be looked up in the fault dictionary. Basically, two problems prevent the fault dictionary approach from being the widely accepted testing method. These are the overly extensive memory requirements and the diversity of the faults. As a result, the fault dictionaries are usually incomplete and ambiguous.

The guided probe approach requires only simulation of the correctly functioning circuit pack. The basic tool in utilizing this approach is the blame-shifting mechanism applied after each measurement. The upstream (from the test point view) components in the circuit are blamed only when the measurements do not agree with the expected results. The efficient sequencing of measurements becomes the main problem when implementing the guided probe approach.

1.5. Outline of the overview

In order to appreciate and put into perspective the contributions of the earlier published results on diagnostics, it is convenient to view them with relation to different aspects of the diagnostics problem. Such a perspective not only allows us to compare different approaches but also provides us with the opportunity to identify yet unsolved problems. The rest of the paper is organized as follows: first we state the diagnostics problem in a more formal way so as to allow its subdivision into six subproblems. Then we give a brief overview of each of the subproblems and the tools that are used in their solution.

2. PROBLEM STATEMENT

A circuit pack (plant) $P = P(S, B)$ is modeled by its structure S and its behavior B. Structure $S = S(C, T)$ is defined by the set C of components and topology T on the set C. Behavior $B = B(IO, R)$ is defined by two mathematical models: (1) IO model describing the input–output relationships of every $c \in C$ and (2) R model describing the reliability of every $c \in C$.

A component $c \in C$ is called faulty if its observed behavior b_0 is different from b_e, the expected IO behavior ($b_e \in IO$).

Problem 1 (*Diagnostic Problem*). Given a multicomponent plant P and a symptom indicating an anomaly on the expected IO behavior, identify the subset $C_f \subset C$ of faulty components.

However, the identification part of the above problem is itself a complex process. In particular it involves repetitive generation of hypotheses and their support or disposal. Proving or rejecting a hypothesis requires in turn to perform sequences of measurements and subsequent sequences of symbolic computations. Therefore, the identification requirement of Problem 1 can be satisfied by recursively solving the following:

Problem 2 (*Classification Problem*). Given a symptom and the results of previously performed measurements, obtain an estimate of the faulty subset C_f (generate hypothesis), and

Problem 3 (*Planning Problem*). Given an estimate of C_f, obtain the minimum expected cost plan (sequence) of measurements, so that when performed, the initial hypothesis will be either proved or rejected.

Note 1. The actual reasoning technique employed to prove or reject a hypothesis, although an important issue by itself, serves only a secondary role.

Diagnostic expert system exploits diverse sources of information to detect failures in a given unit under test (UUT). The relevant information is concerned with the function of the different components, their interconnection, signal characteristics and their paths, and component reliability measures. Moreover, since usually the initial information is insufficient to diagnose correctly, a number of additional observations (tests) is needed to complete the diagnosis. The description of available tests, their diagnostic value and costs is yet another kind of information necessary for diagnosis. Knowledge representation is the term used for the schemes of storing the different kinds of information in order to allow for its efficient processing, i.e., failure detection and cost-efficient test sequence generation. Knowledge has to be adequately represented for quick manipulation, for ease in modification, for specifying distinctions between different concepts, and for viewing of multiple levels of abstractions.

Knowledge representation is inherently related to the ways the knowledge is used. Different problem-solving strategies which use the knowledge base define the inference engine of the diagnostic expert system.

Problem 4 (*Reasoning Problem*). Find an efficient way of reasoning about electrical circuits. (Such reasoning involves manipulation of data structures which represent both structural and behavioral data.)

Note 2. Both Problem 2 and Problem 3 involve requirements to reason along both structural and behavioral lines. Such computational requirements require novel approaches for solution of

Problem 5 (*Representation Problem*). Find an efficient way of representing plant $P = P(S, B)$. Efficiency of representation is determined by its level of completeness, consistency, transparency, and computability (Winston, 1984).

When solving Problem 1 by using heuristic approaches and in particular by utilizing knowledge of human experts, one can not overestimate the importance of

Problem 6 (*Knowledge Engineering Problem*). Find efficient ways to extract the heuristics about circuit pack troubleshooting from human experts.

And, when interfacing to analysts at the shop floor level, one must also face

Problem 7 (*User Interface Problem*). Find efficient ways to conduct a fruitful dialog with the human analysts performing diagnostics.

We have identified six problems which belong to the field of artificially intelligent testing. Now we turn to the approaches and tools which are being used to solve those problems. It is more convenient first to address the problems of representation and reasoning, then the planning and classification problems, and, finally the issues about knowledge engineering and user interfaces.

3. REPRESENTATION AND REASONING PROBLEMS

Basically two approaches and their combinations have been used to solve diagnostics problems: the rule-based (shallow modeling) approach and the conceptual (deep) modeling approach. Many diagnostic systems have their knowledge in the form of rules, representing separate and modular chunks of knowledge, e.g. "Observations $\Rightarrow$ Hypothesis". Often such knowledge may be contradictory, incomplete, or too large to be manipulated efficiently. In such cases one models the domain or system under consideration and reasons with this model to generate diagnostics. Such models have been called causal, conceptual, or deep models.

3.1. *Performance notions*

The choice of the correct approach or their combination depends on such factors as size and complexity of the diagnosed system, its reliability on the one hand, and its criticality and stability on the other hand.

System size is usually defined in terms of the number of line replaceable units (LRU). System complexity reflects the size of the effort required to track down a fault and it is a function of the number of feedback loops, number of outputs and inputs to LRUs, etc.

Reliability of the diagnosed system is defined as the cumulative reliability of its LRUs. Note that the more reliable the system is the more difficult is the diagnostic task.

The criticality of the diagnosed system is defined in terms of the length of time interval length within which the diagnosis must be completed. Stability of the diagnosed system is defined by the number of modifications to the system per unit of time.

3.2. *Rule-based appoach*

The rule-based approach can be further subdivided into deterministic decision trees, single relevant rule, and multiple relevant rule methods.

3.2.1. Deterministic decision tree. The deterministic decision tree method is based on the construction of a hierarchy of questions in such a way that each combination of answers can be interpreted as a leaf on the decision tree. The main advantage of this approach is in its simplicity and in its suitability to the systems of high criticality. However, this approach is limited to the systems of low complexity and high stability.

3.2.2. Single relevant rule. The single relevant rule approach is based on searching the rule base for the single rule which can be applied in a given situation or can confirm a given hypothesis. Since such search procedures can be applied recursively, they have been called forward and backward chaining respectively. The advantages and disadvantages of the single relevant rules are similar to the ones of the deterministic decision trees. However, when applying this approach one must be aware of the requirements to maintain a valid rule base, i.e. no two rules may apply to the same situation (consistency), and each situation has to be covered by a rule (completeness).

Optimality of the rule base is obtained by ordering the rules in such a way that the expected time to search for the relevant rule is minimized. An entropy-based approach is usually utilized to obtain the optimal ordering of the rule-base. Sometimes a cost is associated with the firing action of the rule or/and with the satisfaction of the antecedent of the rule (i.e. query of the user, test setup time, etc.). In such cases the optimality of the rule-base becomes a difficult problem. The requirements of consistency, completeness, and optimality are very difficult to satisfy in advance when dealing with systems of low stability and high complexity.

3.2.3. Multiple relevant rules. To resolve the above problem, the multiple relevant rules approach has been developed by several authors. This approach requires application of a heuristic to evaluate the chaining strength of the rule on a particular situation as well as a heuristic to combine the strengths of several rules when forward or backward chaining is involved. A basic expert system building tool (a shell) has been recently patented (Hardy *et al.*, 1987) by Teknoledge. The tool includes interactive knowledge base debugging, question generation, legal response checking, explanation, and certainty factors. (Its source code in Prolog takes 7 pages and is available in the patent documentation.) However the expert systems based on this approach and having several hundreds of rules again exhibit great difficulties in maintaining their knowledge base. Also the multiple relevant rules approach does not contribute to the problem of knowledge acquisition for the systems of low stability.

3.3. Conceptual modeling approach

Conceptual modeling approach takes into consideration the original system description rather than using the knowledge compiled by humans into a decision tree or a set of rules. The conceptual modeling approach can also be subdivided into normal functioning modeling and fault functioning modeling. The overall diagnostic strategies and their relationships were described in Chandrasekaran and Milne (1985), who used a hierarchy of four levels: structural, behavioral, functional and pattern matching. Given structural representation (list of components and their connectivity; Forbus, 1987; Bylander and Chandrasekaran, 1985) using qualitative simulation and consolidation proposed methods to generate the behavioral description. To generate a functional description of the device using the behavioral description, one may use the approach of de Kleer which is based on teleological (device intentions based) reasoning. The pattern matching diagnostic strategy can be applied after compiling (by a human expert or by a machine) the functional description of the device.

Deep (structural, behavioral and functional) modeling can also be used to declare the innocence of certain components of the unit under test (UUT; Scarl *et al.*, 1987), or to *explain* the observed malfunction (Kuipers, 1987).

Using de Kleer's (1983) approach, given a low level electronic description of the components, one is able to deduce the outputs of the circuit, and consequently diagnose faults in it. Davis (1983) proposed computing the function and the inverse of each component and then utilizing them to propagate of combination of inputs to compute the outputs or *vice versa*. Digital troubleshooting becomes possible by comparing the expected values with the computed ones.

A formal language for UUT description has been developed by (Chandrasekaran, 1985) who compiles the above description into a set of production rules which are used for diagnosis.

Milne (1985) uses structural reasoning at both the fault isolation to a functional area and possible faults proposal stages. Using his "responsibility theory" appoach only four basic diagnostic rules are needed: two rules to propose faults using description of structure and another two using description of function.

Forbus (1981) develops a qualitative reasoning methodology to derive the diagnostic rules given a structural description of objects and their topology. Bylander and Chandrasekaran (1985) propose a methodology to develop the description of behavior of composites of components based only on the descriptions of the components.

4. PLANNING PROBLEM

Goel (1980) has shown that the number of tests needed to pinpoint a fault is at worst linear in the number of components. However, as we observed earlier, generating the best test sequence is NP-complete (Ibarra and Sahni, 1976).

A test generation algorithm which uses the design information has been proposed some 20 years ago by Roth *et al.* (1967) and it is called the d-algorithm. The d-algorithm is based on activating simultaneously all the paths to the observable point in the system. Such an approach is impractical for nowadays circuits because of its high computational requirements.

An algorithm of Cantone (1985) for deciding which test to perform is based on maximizing the ratio of information gained and expected cost, computed over the available subcircuits. The algorithm is based on the gamma-miniaverage method (Slagle and Lee, 1971). A combination of structural information (topology of components) and compiled knowledge (cost of test and components' failure rates) is used to further isolate the fault to a single functional area.

The DART algorithm (Bennett *et al.*, 1981) exploits the heirarchy of the circuit in order to deal with the issue of exponential growth in the number of computations. Within each level DART deduces the suspects by reasoning backward to find a justification for a symptom and generates additional tests by working forward from a behavioral rule for one of the suspects to observable outputs. For more on planning see also Allen *et al.* (1983), de Kleer (1977), Hyafil *et al.* (1976), Ibarra *et al.* (1976), Konolige *et al.* (1980), Loveland (1979), McDermott (1981, 1982), Poage *et al.* (1964), Rosenchein (1981), Sacerdoti (1977), Shirley (1983), Slagle *et al.* (1971), Vere (1983) and Warren (1976).

5. CLASSIFICATION PROBLEM

The diagnostic mode of reasoning is a term used by Kim and Pearl (1985) to describe the inference process of updating the causal model of beliefs due to modifications in the model of symptoms. Kim and Pearl (1985) describe a computational model for causal and diagnostic reasoning which is a generalization of the Bayesian methods previously applied to decision trees (DDI, 1973).

5.1. Bayesian methods

Diagnostic reasoning requires construction of means to assign and update a blame measure to parts of the model, based on the observed behavioral deviations of the physical system. The classical Bayesian probabilistic approach suffers from the following shortcomings: (1) the need to establish *a priori* probability of success of a test; (2) the need to establish *a priori* failure rates of the components; (3) the approach is only applicable when the events are mutally exclusive; and (4) conditional probabilities for every combination of evidence must be computed since the independence of evidence cannot be assumed.

The Dempster–Shafer (Shafer, 1976) theory of evidence has been proposed to remedy some of the above problems. The theory still suffers from shortcomings 1, 2 and 4. Recently Thompson and Wojcik of Westinghouse patented a "Method and Apparatus for System Fault Diagnosis and Control" (Thompson and Wojcik, 1987). A domain-independent set of metarules is constructed which is able to build a rule network through which belief is propagated to detect defects.

5.2. Multiple-fault assumption

The multiple-fault assumption poses an additional difficulty in diagnostics problems. Peng and Reggia (1987) developed a probability based approach to guide the backward chaining in such a way that the more likely situations are considered first. By only using the input/output description of the components and the connectivity information, de Kleer (1986) developed a procedure to incrementally accept or rule-out possible faults. See also Edgar *et al.* (1984).

Fuzzy logic applications for failure analysis were tried by Kitowski and Ksazek (1985). The applied method involves solution of fuzzy equations derived from a failure-symptom fuzzy relations matrix.

Sensor-based systems for realtime monitoring present particularly stringent requirements for expert diagnostic systems. A rule-based system utilizing multiple sensors for obtaining data about chemical parameters was recently patented (Kemper *et al.*, 1987; Westinghouse Electric). The system is utilized to monitor a steam turbine–generator power plant.

5.3. Learning

Learning of diagnostics systems has been explored only at the compiled knowledge base level reasoning: Pazzani (1987) developed a failure-driven learning mechanism to update the rule-base when a diagnostic failure occurs.

6. KNOWLÉDGE ENGINEERING PROBLEM

Problem 6 (knowledge engineering) has been addressed in Cheeseman (1984), who considered the problem of expert systems learning from data. In particular he proposed a method for extracting information from data to form the knowledge base for a probabilistic expert system. A rule acquisition method for a diagnostic expert system has been recently filed for European Patent (Alexander *et al.*, 1986) by Tektronix. The method includes a grammar for acceptable patterns which are automatically converted to rules. The rule acquisition process includes parsing of an input sentence as it is received and guiding the expert through the sentence creation. The system is implemented in Small Talk and Prolog.

7. USER INTERFACE PROBLEM

Problem 7 (user interface) is considered in Simmons (1985) and Taie *et al.* (1987) who addressed the issues of graphical and animated representation of functioning of devices. See also Richer and Clancey (1985) and Brown *et al.* (1981).

8. OPERATING IMPLEMENTATIONS

Several diagnostic expert systems have been developed in industry during the last few years. A review of the capabilities and limitations of some of the completed projects is given to exemplify the theoretical discussion of the applicable methods given above.

ADVISR (Cooper *et al.*, 1987) is a rule-based expert system developed by AAI Corporation, running on IBM PC/AT, working in conjunction was ATLAS test program software, and designed to indicate faults on a Navy AN/USM-UUG (V) automatic tester. A single-fault assumption is made as well as the assumption about fully-reliable connectivities.

ADS (Magliero *et al.*, 1987) was developed by Harris Corporation as part of the Navy Integrated Diagnostic Support System. ADS integrates several knowledge representation paradigms such as pre-computed fault-trees, design topology, logical parameters historical records, and production rules. Test selection is done by maximizing the "expected" entropy to cost ratio. The system is implemented in ADA.

FCMDS (Bursch *et al.*, 1987) is developed by Honeywell Inc., in Lisp. FCMDS uses frame representation for its knowledge base which is subdivided into Causal Model KB and Test KB. The Causal Model includes the design toplogy. The Test Base contains the basic procedural knowledge for performing tests. Test selection is done similarly as in ADS. Test interpretation procedures involve proprietary algorithms to manipulate failure likelihood measures attached to LRUs. This allows for multiple-fault assumption.

APU MAID (McCown *et al.*, 1987) is developed by Allied-Signal Aerospace Company (Bendix). It has a temporal, event-based description of the diagnostic target system, The system is viewed as a sequence of functional events composed of location and context, e.g. time and causality. A failure model is obtained as an event-based description. The rest of the system is implemented in a rule-based fashion. The rules describe the relationships among events, components and parameters.

FIS (Pipitone, 1986) is developed at the NRL's Center for Applied Research in AI. It is based on the fault model which is a qualitative causal model composed of a block diagram of the UUT combined with a set of causal rules for each block. Processing hypothesized test failures through the fault model produces an "ambiguity" set of possibly faulty components. A rule-based test cost generation is used to evaluate the variable costs of the tests. The best test is chosen similarly to the ADS. It is written in Lisp and runs on Sun.

AI-Ferret (Maguire, 1987) is developed at Hughes Aircraft Company. It is written in Interlisp-D and Loops and runs on Xerox 1109 AI workstation. It is basically similar to FIS and it has been successfully applied to diagnose the TOW missile system. The resulting rule base contains 3950 rules while the connectivity model contains over 900 functions (modes).

Haidex (Firdman, 1987) is another diagnostic expert system developed at Hughes. It is based on the conceptual model of the normally functioning system and the set of deviations from the normal function. The inference engine generates a troubleshooting strategy by decomposing the UUT into its subsystems. It is developed in Zetalisp and runs on Symbolics 3670.

MYCIN (Shortlife, 1976) is one of the first expert diagnostic systems designed at Stanford to recognize bacterial infections in blood samples. It is based on purely rule-based approach and it contains about 700 rules. Each rule has a confidence factor associated with it and the inference engine is provided with an *ad hoc* computation scheme to combine the factors when using backward chaining. Other MYCIN and medical applications related papers include Adams (1976), Benbasset *et al.* (1976), Ben-Bassat *et al.* (1980), Bjerregard (1976), Blois (1980), Bosyj (1975), Cantazarite *et al.* (1979), Chandrasekaran (1982), Chandrasekaran *et al.* (1979, 1980), Charniak (1983), Cooper (1984), Elstein *et al.* (1978), Flehinger (1975), Gomez *et al.* (1981), Gorry (1973), Kolodner *et al.* (1987), Kulikowski (1970, 1980), Lipkin *et al.* (1985), Miller *et al.* (1982), Mittal (1980), Mittal *et al.* (1979), Patil *et al.* (1981), Patrick *et al.* (1981), Regia (1982), Regia *et al.* (1985), Rubin (1975), Szolovitz (1978) and Weiss *et al.* (1978).

Some other expert systems (AFHRL, 1984) include ARBY/NDS (DUCK) for communications networks troubleshooting, ACE for preventive maintenance of telephone cables, LES (frame-based with about 50 rules) for electronic maintenance, STAMP, IDT (Shubin *et al.*, 1982), CRIB (Hartley, 1984) and CRITTER (Kelly *et al.*, 1982).

9. SYSTEM BUILDING TOOLS

The core of an expert system has a knowledge base and an inference engine that operates on the knowledge base. User interface is considered at two different levels: when developing a system, and when deploying it. Some of the important concepts are summarized below.

9.1. Knowledge representation

There are three important aspects of knowledge representation which must be available in any diagnostic system building tool. These are: object descriptions, actions, and certainties.

The most convenient way to represent objects is by frames which are tabular data structures (records). A frame consists of slots which are filled with either data about objects or relations to other frames. A built-in inheritance mechanism allows to inherit or override the information from other frames.

Actions are used to modify the relevant database. Actions are usually implemented by rules or procedures.

The degree or correctness of data and/or knowledge is usually expressed by means of belief functions, certainty factors, or probabilities.

9.2. Inference approach

The inference approach in a typical diagnostic expert system may be a combination of forward and backward chaining, hypothetical reasoning, and blackboard mechanism.

9.2.1. Chaining. Backward chaining is a method of evaluating hypothesized conclusions to see whether they are supported by the evidence. It is usually implemented via *if–then* rules, starting with rules that have the hypothesized conclusions as their consequents. The set of rules is then searched for those in which the antecedents include the previous conclusions. This process (backward chaining) is continued until the hypothesis is proved. If the proof is unachievable, then some other hypothesis may be tried.

Forward chaining starts with the present data with is matched with the antecedents until a relevant rule is found. The consequent of that rule determines the new present data and the process of matching is repeated until a desired conclusion is reached.

9.2.2. Hypothetical reasoning. Hypothetical reasoning (truth maintenance) refers to the solution in which hypotheses have to be assumed when initializing the search (e.g. forward or backward chaining.) Nonmonotonic reasoning refers to the ability of retracting the consequences of the assumptions which have been found untrue during the search process. Different tools handle nonmonotonic reasoning by using viewpoints, contexts or worlds, or nonchronological backtracking. Hypothetical reasoning literature includes Doyle (1979), and McDermott (1980, 1982).

The blackboard mechanism (Hayes-Roth, 1983) refers to a common data structure shared by a group of cooperating expert systems. An agenda often is used to control the development of the solution on the blackboard. This mechanism is especially useful when several competing solutions are developed in parallel.

9.2.3. Pattern matching. Pattern matching is usually required in two mechanized reasoning instances: when matching rule atecedents to the current knowledge situation to fire the best applicable rule, and when matching partially filled frames to the existing knowledge base to determine the current knowledge.

9.3. Expert system shells

A diagnostic expert system development tool is required to have the following capabilities: (1) *Knowledge representation*: structured rules, certainty factors, frames; (2) *Inference engine*: forward chaining, backward chaining, backward chaining, blackboard-like, truth maintenance, pattern matching; (3) *Developer interface*: KB editor, menu, check for consistency, graphics representation of KB, graphics utilities to build end user interface, debug; and (4) Interface to general-purpose programming language (e.g. C).

Unfortunately, none of the available products in the current market have all of the above features, although all of the products have many features in addition to the above list. The only products that come close to our requirements are ART, KEE and Knowledge Craft (see Expert System Shells List). However, the cost of these tools is in the range of $10,000–$65,000, besides additional expensive training.

9.4. Diagnostic tools

Two commercially available special purpose diagnostic expert system tools have been developed recently, namely, IN-ATE, and AI-Test. We give a short outline of their characteristics.

9.4.1. IN-ATE. IN-ATE (Cantone *et al.*, 1985) provides an excellent menu-driven syntax for specifying fault diagnosis expert rules. It also allows specification of the signal flow and uses it when searching for the defective component. In additon it has frames-based knowledge representation and a mechanism to perform probabilistic reasoning.

The system does have an interface to C, and it does have capabilities for automated testing the knowledge base consistency. It runs however only on a Macintosh computer. The system does not have a separate electronics theory and measurements related data-base. Therefore, each test point must have all the relevant information. Thus, some duplication of information and difficulties in knowledge acquisition are inevitable.

9.4.2. AI-Test. AI-Test (Ben-Bassat *et al.*, 1987) is developed by Intelligent Electronics and runs on IBM-PC/AT. AI-Test is comprised of two knowledge bases—the Universal Knowledge Base which contains general information relating to electronics theory, kinds of measurements (DC, frequency, etc), signal types, etc. and the UUT-specific knowledge base which includes the block diagram of the UUT and tests descriptions.

The inference engine interprets the test results (by updating the model of beliefs) and chooses the next best test. No mechanism is provided to update the initial failure rates of the components. Also, the choice of the appropriate kind of test at a specific test point must be performed by the user. An AI system should be able to suggest the most informative test description automatically. The user interface has been improved greatly since the last release.

10. CONCLUSIONS

New circuit pack manufacturing technologies (e.g. surface mount) contribute further to the complexity of the circuit pack and thus make the testing even more difficult. For example a new approach in electronic design is the Built-In-Self-Test (BIST) approach (Agarwal, 1987). This approach has the positive features of testing the equipment at its normal operation speed, as well as running the test in parallel on all the devices. Thus a malfunctioning device can in principle declare its faulty condition faster and seemingly reduce the difficulty of the diagnostic task.

10.1. New challenges

As happened before, the new technology has posed new testing challenges. In particular, BIST technology requires separate independent testing of the built-in test equipment. Failing to test the built-in hardware may result in two kinds of errors: a correctly functioning device declaring itself as faulty and thus being replaced for the wrong reason (such repeated mistakes will later be propagated to mistakes in the process control) and a misbehaving device declaring itself as being healthy, thus postponing the troubleshooting to later stages and therefore increasing the manufacturing and maintenance costs.

10.2. Drawbacks of the rule-based approach

Since the success of MYCIN, the rule-based approach has been implemented several times in circuit pack diagnostics. The mechanisms that proved useful in medical applications were automatically applied in the electronics industry. However, in this industry only part of the knowledge (general electronics laws) is static, while the rest of the knowledge changes with every new design and with every new batch of components. Moreover, the usually available statistical data is not present any more. One the other hand, another kind of data (connectivity and signal paths) is available. These differences must be recognized and utilized (e.g. IN-ATE and AI-Test) in order to develop a successful expert system.

10.3. Classification and planning problems

The diagnostic problem is still far from being resolved and it is currently an area of active research and development. In particular in the area of the classification problem there is a lack of computationally efficient schemes to propagate the results of tests. A prevailing assumption is the "perfect info" assumption underlying the construction of most of the diagnostic expert systems. The mechanisms for dealing with partial, unreliable, and contradictory results are mainly based on the Dempster–Shaffer theory. The conditional probabilities (correlation data), which are usually available in medical applications are not generally available in electronic circuit pack diagnostics applications. Thus, the applicability of the "classical" belief propagating schemes is questionable. This issue requires a separate investigation in light of dealing with structural circuit description in addition to rules. The issue of dealing with noisy data also requires a specialized effort.

In the area of the planning problem there is lack of mathematically sound basis for the best test selection. Most of the existing systems either do not address the issue of test planning or use an ad hoc method. Computational efficiency is another issue which must be addressed separately.

10.4. Deep knowledge representation and reasoning

Although it is now quite obvious that a purely rule-based approach is not practical, there are not many pragmatic ways to implement a deeper kind of knowledge besides the connectivity of the circuit pack. The area of knowledge representation and reasoning currently receives most of the AI community's attention. Yet it is still unclear to what extent qualitative reasoning and functional knowledge can be used for practical applications. Consequently all of the existing diagnostic expert systems implementations are using a combination of rule-based and connectivity knowlege with a mechanism for belief functions manipulations and an *ad hoc* (entropy vs cost based) best test selection heuristic. Thus, efficiency of such systems is difficult to assess.

10.5. Learning and user interface

The least amount of work is done in the areas of learning and user interface. It seems that the most desirable approach to "engineer" knowledge is via a mechanized interview of the design engineers. Experiments have not been performed, nor have tools been constructed to achieve such goals.

10.6. More open problems

Only one system (AI-Test) has implemented a separate global electronics knowledge base containing generally true facts about electronic circuits behavior, possible tests, etc. However, there is no known technique to match the best test to its proposed location and to its time occurrence. This test matching problem solution could provide an important aid in diagnostic expert system construction. And finally, applications of new technologies (e.g. neural networks) have yet to be examined.

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A PARTIAL LIST OF EXPERT SYSTEM SHELLS

1. ART, Inference Corporation, 5300 W. Century Blvd, LA, CA 90045, U.S.A.
2. KEE, Intelli Corp, 1975 El Camino Real West, Mountain Views, CA 94040, U.S.A.
3. Knowledge Craft, Carnegie Group, 650 Commerce Court, Station Square, Pittsburgh, PA 15219, U.S.A.
4. Picon, Lisp Machine, 5 Tech Drive, Andover, MA 01810, U.S.A.
5. S. 1. M. 1, Teknoledge, 1850 Embarcadero Rd, P.O. Box 10119, Palo Alto, CA 94303, U.S.A.
6. KES, Software Architecture and Engineering, 1600 Wilson Blvd, Suite 500 Arlington, VA 22209, U.S.A.
7. Nexpert Object Newron Data Corp., 444 High St., Palo Alto, CA 94301, U.S.A.

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