A Qualitative Circuit Simulator

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Abstract

The work described here is part of a larger project which is investigating various issues related to diagnosis and failure prediction in the context of automotive manufacturing. In particular, our goal is to produce prototype intelligent tools which will assist in the analysis of potential faults and hazard situations in evolving electrical circuit designs. This will offer support for the important engineering task of Failure Mode Effects Analysis (FMEA). Current techniques for FMEA are slow and tedious, and have to be carried out by professional engineers whose time is expensive.

This paper reports on the design and implementation of a qualitative electrical circuit simulator that can effectively model the structure and behaviour of systems under analysis. The simulator assigns labels to open and short circuit branches, finds current paths and determines directions of flow.

1 Introduction

This paper describes some ongoing work which is investigating qualitative reasoning techniques for application in the domain of automotive electrical systems. Our main aim is to produce a prototype system that can form the basis of an intelligent tool to support engineers engaged on a particularly demanding analysis task: Failure mode effects analysis (FMEA). The purpose of an FMEA study is to attempt to predict the possible effects of faulty components on the rest of the system [1]. This kind of analysis is of growing importance in, for example, the automotive industry, where increasingly complex electrical, electronic and mechanical systems are being combined in safety-critical applications. FMEA work is often carried out during the design stage as it is important that designs are analysed for hazardous and safety-critical situations. This is an extremely tedious process because it demands detailed and systematic examination of all aspects and parts of the design. However this work must be carried out by professional engineers because it requires extensive experience of the domain. These two factors, painstaking work and expert judgement, indicate the great value that an automated tool will have in this area. We envisage a tool that can explore much of the detailed analysis and report back when decisions based on application criteria have to be made.

The work we describe here is part of a larger project which is investigating various issues related to diagnosis and failure prediction in the context of automotive manufacturing. This paper reports on our present work directed at the domain of electrical wiring systems. A major part of the project involves the design and implementation of a simulator that is able to model the structure and behaviour of the electro-mechanical aspects of wiring systems.

2 The Limitations of Heuristic Methods

The impetus for the present investigation comes from the fundamental nature of the FMEA problem. FMEA is the analysis of potential faults, and their effects and consequences, on a system design. At first, this may appear to suggest that heuristic-based expert systems are an appropriate technology to apply to this problem. However, an examination of the available methods shows severe limitations. Because such first generation expert systems rely on the fact that the effects (and consequences) of potential faults are already known, these systems are inappropriate for problems where any combination of system variables might be the subject of analysis. For failure analysis the large number of fault scenarios can lead to combinatorial explosions.

Although FMEA experts do refer to information which can be heuristic in nature, for example “the failure rate of wires is very low”, the type of reasoning used to determine the behaviour of a system, when a particular fault mode is present, relies on the expert’s understanding of the domain. That is, the expert must resort to first principles in order to determine the effect of a particular fault mode. Very often,
in man-made devices, the sort of knowledge that the human expert will use is related to the structure of physical objects in the domain plus relevant technical knowledge — in a chemical processing plant, for example, the expert might be concerned with the structure of the plant (tanks, pipes, valves, etc) and the chemical reactions taking place inside the plant.

To deal with this problem we have investigated model-based reasoning techniques as an approach for building FMEA and diagnosis tools.

3 The Electrical Domain

The engineering applications considered in this paper concern electrical systems built from electro-mechanical components. The source of this interest originates in manufacturing, in particular the manufacture of products with discrete component parts. We are interested in electrical circuits with electro-mechanical elements such as relays, lamps, diodes, motors and switches — an example being an automotive electrical wiring system. We concentrate on this application as it forms a major concern of our industrial collaborators.

As automobile electrical systems become more and more complex it becomes very important to prove the reliability and safety of a design; failures can be spectacular if safety-critical issues are not considered. Example of safety-critical electrical systems include: anti-lock braking systems, computer controlled engine management systems and, less glamorous but no less important, fusing arrangements for the lights. The problems of complexity will soon increase greatly as "drive-by-wire" cars begin to appear within the next few years.

As a major step towards FMEA for electrical systems, we have developed a qualitative circuit simulator which allows the exploration of the effects of certain types of failure on the rest of the circuit. We argue that some form of simulator is invaluable in applications where unique solutions have to be deduced from first principles or where deeper reasoning based on the design or structure of a problem is required. For FMEA we need this kind of more sophisticated reasoning process if we are to achieve powerful and flexible tools for decision making.

4 Model-Based Reasoning

Model-based reasoning takes knowledge about the entities, structures and interactions in a particular domain and uses that knowledge as a foundation for reasoning processes. The key feature is that a model is maintained which mirrors the important structure and features of the domain, so that analyses and predictions may be carried out with a high degree of authenticity. This is in contrast to heuristic-based systems where the knowledge is derived from patterns of input-output associations and often bears little relation to the physical structures in the domain.

Many current model-based diagnostic systems generate fault hypotheses using information available within the model of the system under diagnosis. This is done by comparing predictions about the behaviour of modified versions of the model with the observed symptoms. Any modification that can generate all the symptoms is considered to be a possible explanation for those symptoms (for example [2], [3], [4], and [8]). This approach can also be used for fault prediction and evaluation by changing the properties of one of the devices and observing the resultant system behaviour.

The kind of model suitable to support such reasoning must have certain properties. The model should represent the structure and function of the device and should also record causal relationships between its components. This kind of model is not like numerical or mathematical models, which are designed to solve particular exact problems such as thermal or stress analysis, but instead can represent and operate on the interesting properties, changes of state and internal processes that occur in electrical and mechanical devices (see [7]).

5 Qualitative Reasoning

When deciding to construct a simulator for electrical circuits, one of the first questions which was addressed was whether or not it was necessary to be able to produce precise numerical values for the various voltage and current levels at each point in the circuit. Methods for doing quantitative computation already exist, e.g. by using packages such as SPICE. However, this kind of solution would not accurately model the type of reasoning that seems to be employed by engineers when performing this kind of process. In this particular application domain, and for the purposes of FMEA, it is qualitative changes in electrical circuits that are of most significance. Such changes are seen in short circuits and open circuits, and we wish to find their effects on the rest of the electrical system. These effects are of much greater importance than finding the exact values of current and voltage at various points in the circuits. Short and open circuits represent changes to the topology of the circuits being analysed, and the simulator described in this paper can quickly identify such conditions. When presented with a simple circuit diagram, or even part of a more complex one, an electrical engineer will usually be able to say general things about the direction of current flow, the existence of short-circuits, and so on, without doing any precise numerical calculations at all. This "back of an envelope" reasoning is also usually very quick. We wish to investigate the utility of this kind of "coarse" reasoning an
so have chosen a qualitative as distinct from a quantitative
approach.

Qualitative reasoning involves representations of quantities in terms of coarse symbolic values; typically, a variable might be allowed a value from the set \{ + 0 - \}. Despite the apparent crudeness of this notation it has proved surprisingly powerful for representing the essential structure of a given model. Research is currently very active in this area and qualitative reasoning has been applied to control theory, feedback systems, all kinds of engineering, and medical and biological systems.

An advantage of causal and qualitative representations is that they can deal with non-linearity and discontinuous phenomena. Thus, structural changes (e.g. extra wires added into a circuit) are no different in their consequences for the model from changes in the value of variables (e.g. a current increases in magnitude). This is because the structure of the system is an integral factor in the deduction of behaviour.

Although there are many problems, these techniques have considerable promise because the representations offer a degree of authenticity at the most basic level of modelling.

5.1 A Qualitative Circuit Model

Using a model-based approach, an object-oriented model of electrical circuits has been constructed. In this, the various components, such as connectors, wires, bulbs, and resistors are directly represented by instances of objects in the simulator. However, resistances are represented not by numerical values, but by one of three qualitative values: \{0, \ell, \infty\}. These correspond to short circuit, load and open circuit. Zero-load components represent items such as wires and connectors which have no significant resistance; load components represent those which do have a relevant resistance, while the qualitative resistance value of infinity is used to represent components through which there is no significant current flow, such as at open switches or blown fuses.

The qualitative approach seems to be suitable for many of the kinds of faults which engineers are interested in when doing FMEA. "Stuck-at" faults are common, where a particular point on the circuit is "stuck" at the value of supply positive or negative. These failures represent changes in the topology of the circuit due to short- and open-circuit faults. Since the behaviour of the model is deduced in part directly from its underlying structure, structural changes of this type are not difficult to handle using the qualitative model. (Notice how a numerical package would be used in this situation. Any changes in connections, however small, would require at least some of the equations to be reformulated, followed by a complete re-run of the package.)

5.2 A Qualitative Circuit Algorithm

Having constructed a model of the structure of an electrical circuit, we next design and build appropriate reasoning processes. For electrical circuit analysis we need a suitable ontology that supports some of the methods of conventional circuit theory. One approach is to use the circuit equivalence theorem of Thévenin. However, the qualitative version of this theorem offers very little information as all resistances become candidates for change when any perturbation occurs in a resistive mesh. It seems that a minimum of Kirchoff's and Ohm's laws are necessary to support reasoning about the behaviour of qualitative models of circuits.

![Figure 1: A simple circuit](image)

In order to give some of the flavour of our technique, consider the very simple circuit in figure 1. Our algorithm works by treating the circuit as a graph of nodes, where all physical components are represented as nodes and electrical connectivity is represented by arcs.

A procedure (mark-shortest-path) is given two nodes, start and goal, and finds a path through the network that connects these. This is a form of best-first search and is based on Dijkstra's shortest path algorithm. The algorithm computes the least-cost distance from the start for each node. A shortest path is defined here as a path with a minimum number of load components, i.e. of least resistance. A load qualitative resistance at any node in the circuit represents a cost, or distance increment in the path from the source to the sink; nodes with zero resistance add nothing to the distance. By performing this process from both positive and negative terminals through the circuit, it is quickly possible to identify short and open circuits.

Figure 2 shows the example circuit as a graph. The circuit can be seen to have two paths. Tracing along each path from one of the terminal nodes to the other, it is clear that one path is shorter than the other. This is the "primary path". For each junction node on the path, two numbers in the form p/n give the distance from the positive battery terminal and the negative battery terminal (or source and sink) respectively. An interesting property is that the sum of these two values (the total path resistance, "tpr") remains constant along the primary path. From this, not only can the primary path be identified, but the direction of current flow along it can be determined using the convention that if the first of the two figures increases when the second decreases, a movement to a point "nearer" the sink node has taken place. (The primary path, and the direction of
flow are denoted by solid arrows in figure 2). Where it is not possible to reach one of the source or sink nodes, that component of the \( tpr \) is marked infinite. No current can be flowing on that path.

If there are no non-zero values for the distances from the source and sink nodes on a path, then that path is a short circuit. This case is quickly found and can be flagged.

Extending this idea further, secondary paths (denoted by dashed arrows) can be identified as any in which the nodes have a total path resistance greater than that of nodes along the primary path. Careful case analysis of the transitions between junction nodes can allow current directions to be inferred in many cases.

Introducing a simple fault in the circuit shown in figure 2 produces the situation shown in figure 3. A new primary path has now been established and what was previously the primary path is now the secondary path. Using the qualitative scheme, the flow across two of the nodes can no longer be determined unambiguously.

The algorithm is a combination of breadth-first enumeration of branches, together with a deep search along each successor branch from start. The deeper search uses best-first order but it only returns a single path — this gives direction to the search process and prevents erroneous labelings. The result of applying this algorithm to a network is to give a qualitative current value to each arc entering or leaving a node and also define the direction of flow.

There are several advantages to this method. First, the process proceeds in a layered manner — only after the most serious cases have been detected are the lesser, and more subtle, events pursued. Thus power shorts across the supply and large open circuit networks are found first; then primary flow paths are determined; followed by secondary paths; and, finally, the ambiguous branches, as seen in bridges across equi-potential points, are processed. Another feature is that after the initial assignment of values for the whole network it is a relatively easy matter to compute changes in currents due to short or open circuits in localised parts of the network. It is possible to use focusing schemes to localise the sections of the net where changes occur, and we are developing incremental methods for this purpose. Finally, the labelling scheme for qualitative currents at junction nodes offers information for identifying potential future current flow. For example, at an open switch it is possible to decide if current will flow if the switch is closed simply by examining the qualitative values at the switch terminals.

At first, the efficiency of the algorithm appears to be not very high: \( O(n^3) \), for \( n \) nodes. This is because best-first is a memory intensive method and the shortest path search is repeated for all paths through the network. However the topology of most electrical networks with single source and sinks, i.e. typical of automotive electrics, is such that for any given branch the opportunities for very wide breadth are
limited. This means the efficiency should be much better in practice than indicated above and we have experienced quite acceptable speeds in our prototypes. On the positive side, the search does guarantee to find the shortest path, and does not involve extensive back-tracking. We are working on a better formulation of the algorithm so that scanned paths are saved for the next shortest path cycle instead of repeating whole process each time.

6 Further work

The model-based qualitative simulator described above represents the “core” of an intelligent FMEA circuit tool and we are investigating extensions for effective application. There are two main developments necessary: the use of an architecture to control and coordinate the analysis process, and the recruitment of additional non-circuit knowledge from external sources.

We have designed and developed architectures for both diagnosis and FMEA [5], and are currently examining methods for linking different domains together and integrating the simulator with higher-level, more functional reasoning.

In order to perform the final stage of the FMEA process information about non-electrical relations between components, and data on the likelihood of fault occurrence, together with detection rates and application specific criticality information will all need to be incorporated. We have carried out research into augmented model-based reasoning [6] and intend to build these additional layers of knowledge into our next prototypes.

We believe the careful use of additional knowledge and coordinated reasoning will resolve the problems of ambiguity and complexity that can occur with qualitative systems while capturing their inherent modularity, flexibility and strong intuitive mapping onto real engineering devices. We see FMEA as an important testing ground for a range of intelligent support tools for design and analysis engineers.

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References


