Incremental Automated Diagnostics

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Abstract

This paper describes how the effects of possible component failures on an electrical system can be predicted through simulation of the correct behavior of the system, and repeated simulation of versions of the system containing faulty components. The results of such simulation are useful both for failure mode and effects analysis (FMEA), and for diagnosis.

Such results have been used commercially for FMEA for a much longer time than for producing diagnostics. This has led to techniques for reducing the amount of engineer effort needed to repeat the FMEA when changes to the design occur, a modified process we have termed "incremental FMEA". This modified process significantly reduces the amount of engineer effort needed to evaluate the consequences of minor changes to a system design.

This paper shows how the results of FMEA are also being used to generate diagnostics, and applies incremental FMEA techniques to the diagnostic challenges of variants and of producing diagnostics as a system evolves over time. The idea of incremental diagnostics should reduce the amount of effort needed to produce different versions of related diagnostics in a similar way to how it reduced the effort needed for repeated FMEAs.

Introduction

The production of vehicle electrical diagnostics is an increasing challenge for automotive manufacturers, whether in the form of workshop manuals or of computerized assistance to automotive technicians.

There are several reasons why the production of electrical system diagnostics is becoming more challenging:

The complexity of vehicle systems is increasing. There has been a continuing trend towards greater complexity in car electrical systems for several decades, because of greater numbers of features, because of the use of electronic control units (ECUs), and because of the pressures for greater vehicle efficiency and reduced emissions.

Variants of vehicles demand different diagnostics. On many vehicles, some features such as passenger air bags are optional. Other features, such as daytime running lights, are only mandatory in certain countries. Different variants of a vehicle may exhibit different failure behavior for the same root fault, and demand different diagnostics. Producing different diagnostics for different variants can be a great deal of work.

Optimization of designs. After a new vehicle design is produced, the design may change for several reasons. A generic problem with the design may been found and fixed for future releases of the vehicle, or sets of components in the design may be replaced with more economic components in order to reduce the cost of the vehicle. If the diagnostics have already been produced (which they should have), then the diagnostics are unlikely to be changed for such changes.

This paper describes how automatically generated diagnostics can not only reduce the cost of producing diagnostics in the first place, but can also reduce the challenge of variants and of design optimization to the production of accurate diagnostics.

Our research group at Aberystwyth has produced a number of automated electrical design analysis tools, for failure mode and effects analysis (FMEA) (Price00), for sneak circuit analysis (Price and Hughes), and for design verification (McManus et al.). The tools have been adopted by automotive companies as a basis for performing design analysis during electrical systems development.

This paper describes how the results from FMEA are being used by automotive companies as a basis for diagnosis, and how they can reduce the impact of variants and design optimization on the cost of producing accurate diagnostics.

The rest of the paper is structured in the following way:

- Section 2 provides an overview of how simulation can be used to calculate the effect of a failure on the overall operation of an electrical system.

- Section 3 explains how knowledge of the relationship between a failure and its effect on the overall system forms a basis for diagnosis.
- Section 4 explores how FMEA generation can be streamlined when identifying the effects of incremental changes on the failure behavior of a schematic.
- Section 5 shows how the incremental FMEA information can be used to produce diagnostics for variants and to update diagnostics when a circuit design has been optimized during production.
- Section 6 discusses some of the issues for practical diagnostic systems raised by this work.

Automated Analysis of Failure Effects

Failure mode and effects analysis (FMEA) is a design discipline where every possible failure on a design is considered, and the effects of the failure on the operation of the overall system are calculated, in order to identify severe, frequently occurring failures, and eradicate them from the design if possible.

AutoSteve (Price00) uses simulation to generate a textual report giving the effect of each possible component failure on the behavior of the overall system. This is achieved by performing a simulation of the correctly behaving system under changing input conditions and abstracting the results to the level of functions of the system. The result of the simulation is a statechart of the possible behaviors of the system. For the simple electrical example in figure 1, the generated statechart would look like figure 2.

In order to explore failure behavior, the simulation is repeated for versions of the system containing components with faulty behavior. For a version of the circuit in figure 1 where wire W18 supplying the right fog lamp has failed, the statechart is shown in figure 3.

The effect of the failed component can be extracted by comparing the two statecharts. So, for the example of wire W18 failed open circuit, it can be seen that the only difference is in the state on the far right. Instead of both fog lamps being illuminated, only the left fog lamp is lit, so the effect of the failure is that the Right fog lamp does not illuminate when both the switches are closed.

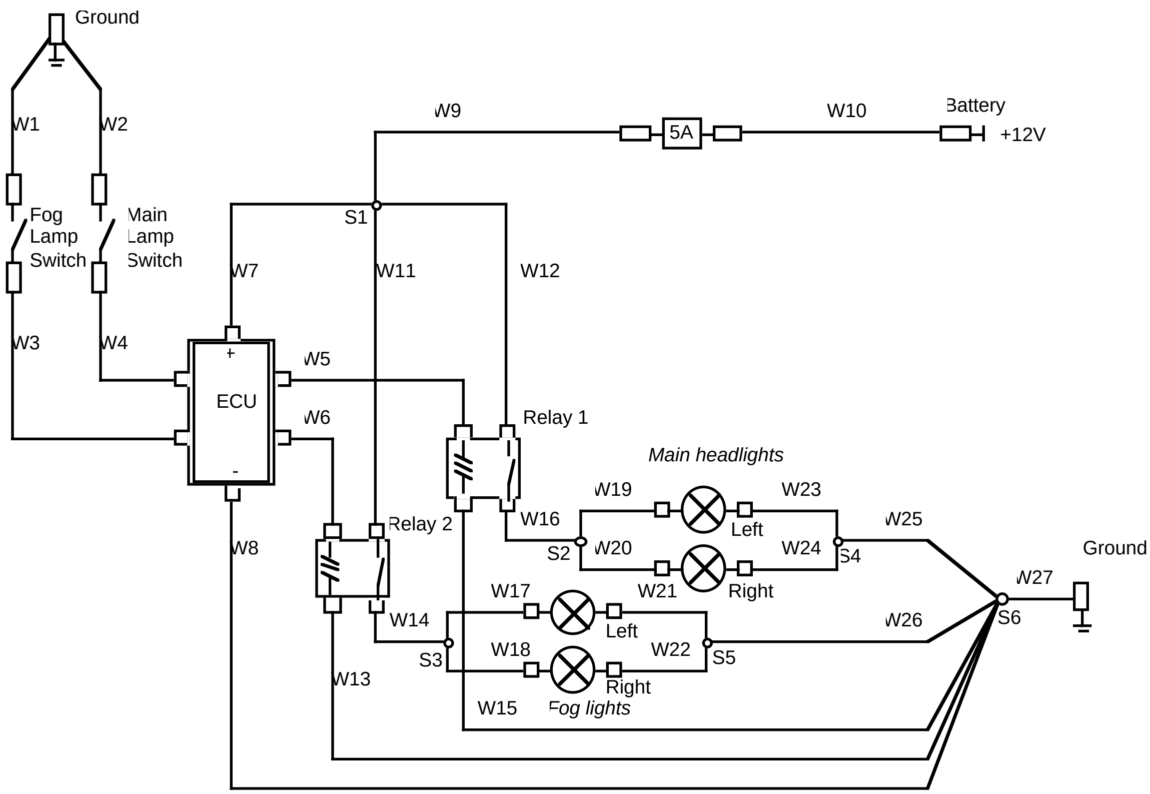

Figure 1: Main beam and fog lamp example circuit

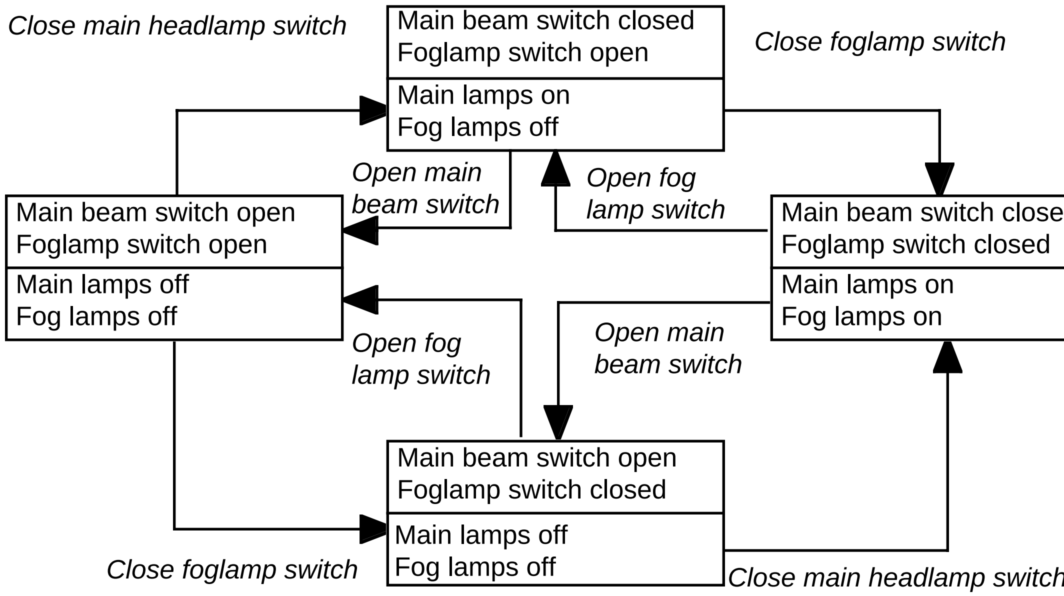

Figure 2: Statechart for good system behavior

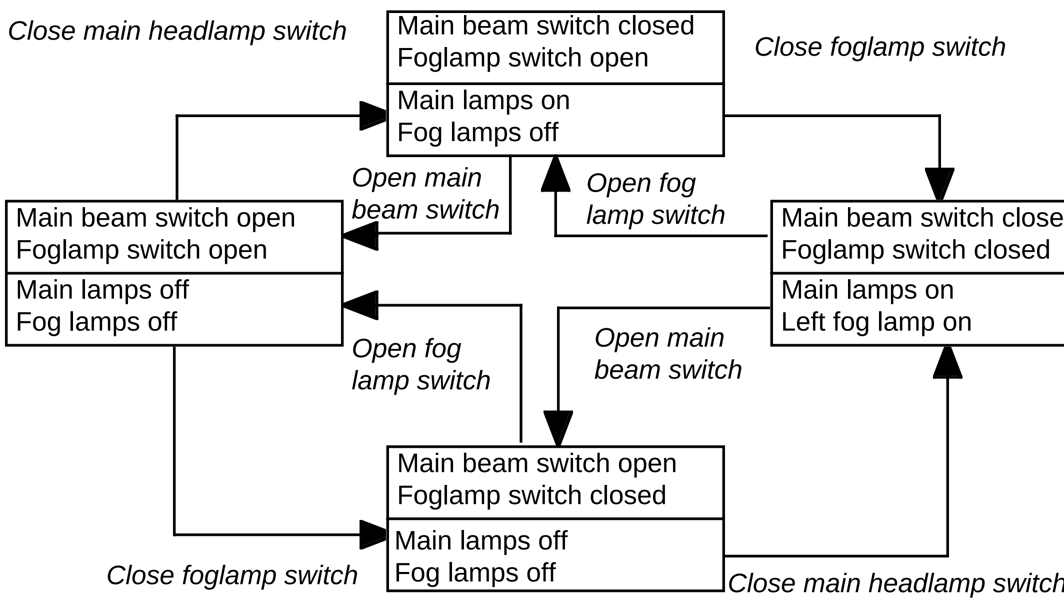

Figure 3: Statechart for system behavior with wire W18 failed open circuit

The simulator normally used in AutoSteve is a qualitative simulator (Snooke); it does not need exact resistor values, but is able to produce results using resistor values of zero, load and infinity. This is appropriate for design analysis, because it means that useful results can be produced as early as possible in the product lifecycle. However, more accurate results can be produced by the time that the engineers are ready to produce diagnostics, and so AutoSteve can also work using the commercially available SABER simulator. This produces numerical results, and abstracts them to the same functional level reports as are produced from the qualitative simulator.

Part of the process of performing FMEA is for the engineer to consider the effects of each failure, and see whether any changes to the design are needed to mitigate the effects of the failure. This means that each link between component failure and system failure effect has been considered and validated by a design engineer. This is reassuring when considering the use of such information in diagnosis.

Use of FMEA results for diagnosis

For FMEA, analysis begins with each potential failure on each component, and generates the possible effects of the failure. Many different failures may have the exact same effect. For example, failure of wire W22 or of the right fog lamp itself would have the same effect as the failure of wire W18 shown in figure 3. The important end result of FMEA is a table of failure/effect pairs for every possible potential component failure. This is a simplification, as each pair will also have associated information that could be of interest for diagnosis, such as the likelihood of occurrence of the component failure, but the most important information is the failure/effect pair.

For diagnosis, the effects or symptoms are the starting point. Typically, the driver of a vehicle will detect a problem - a lamp fails to illuminate, or the engine is slow to respond to the throttle - and they will want to know what component failure caused the observed behavior in order to repair the system. The contents of the table of failure/effect pairs can be rearranged to produce a list of all component failures that could cause each specific effect. This is discussed in more detail in (Price and Taylor).

More recently, we have been working with an automotive manufacturer to explore the use of AutoSteve FMEA results for the production of both workshop manuals and computer-based service bay diagnostics. The workshop manuals deal with the electrical systems that are not electronically monitored from an electronic control unit (ECU), and start from driver-level symptoms.

We have studied typical diagnostic trees within the manuals. They guide the technician to runs of wires that might be responsible for a specific failure. The FMEA results can be rearranged to produce results equivalent to those produced by engineers. The results from the FMEA also cover more obscure combinations of symptoms that are ignored when the lists are generated by hand. Because the symptoms are generated from an electrical FMEA, some failures are not included, because they cannot be simulated. For example, in a radio system, failure of the radio to work because the aerial is no longer connected would not be covered.

The result of this work is a process for producing diagnostic manuals from FMEA results as follows:

- Obtain the on-line schematic for the system from design staff.
- Run the automated FMEA software on the schematic (all component models for doing so will have been produced during design).
- Automatically generate the text and diagrams for the manuals from the FMEA and the schematic.
- Arrange in suitable order for the manual.
- Add any additional failures that are not electrical.

Where electrical systems are monitored by an ECU, online fault detection software will detect most problems, and generate a diagnostic trouble code (DTC) indicating the symptom. DTCs give a more exact indication of likely problems, and when the service bay technician connects the car to a diagnostic computer, software guides the technician in pinpointing the problem. The software directs the technician in the order in which tests should be carried out, taking into account such factors as likelihood of a specific failure and the cost of performing a particular test.

Automating the production of software for pinpointing the failure causing a DTC is more difficult than automating diagnostic manuals, but is worth doing because producing the software by hand is so much work. The process for achieving this is:

- Obtain the on-line schematic for the system from design staff.
- Add descriptions of functions corresponding to each relevant DTC (the original functions monitored corresponded to the user-level symptoms, not the symptoms that the DTCs detect).
- Run the automated FMEA software on the schematic (all component models for doing so will have been produced during design), generating the set of failures that could cause each DTC to fire. For each DTC:
  - Automatically order the possible failures by their likelihood.
  - Allow the user to change the order. This cannot be done automatically as there is no information about cost of tests.
- Generate the code for the diagnostic system from the ordered set of failures that could cause each DTC to fire.

The processes outlined above significantly reduce the amount of time needed to produce diagnostics. As the FMEA system works efficiently for multiple failures (Price and Taylor), it can also produce diagnostics that cover multiple failure cases.

However, there is a good amount of work to be done in order to diagnose variants of systems, and to reflect changes to the design of a system over its lifetime. The next two sections describe how the FMEA software deals efficiently with incremental changes to a design, and how that strategy can be extended to provide an efficient answer to the problem of variants and changing designs.

Incremental FMEA

In (Price96), we describe how the consistent nature of the FMEA produced by AutoSteve makes it possible to produce incremental FMEA results showing the difference that has been made to a design by a set of design changes. The first time an FMEA is run on a system, it might take an engineer a day or so to absorb all of the implications of the FMEA report generated by AutoSteve (as opposed to a month or two to generate such results by hand for a complex system). When a change is made to the system, perhaps as a result of a problem being identified by the FMEA report, then the FMEA can be re-run, and automatically compared row by row with the previous set of results.

The results of comparing the FMEAs fall into four categories:

1. The results are the same for the same component failure in each case. This covers the majority of cases, and can be ignored as the engineer has already considered this.

2. The results no longer exist, because the component has now been deleted. This is also of no interest.

3. The results differ because the failure effect when this component fails has changed. This category is important, as some of the worst problems in vehicles are introduced by late changes to the vehicle, and items in this category should be studied carefully.

4. The results are new, because the failed component did not exist in the previous version of the schematic. This category also has to be studied, because failures in this category have not yet been checked out by an engineer.

Only categories 3 and 4 are presented to the engineer as the results of an incremental FMEA. In (Price96), two versions of the schematic in figure 1 are given as an example, the first with a single fuse as shown in figure 1, and a second where each set of lamps is fused separately from the ECU. In the latter case, complete loss of lighting is avoided when one of the wires to the lamps shorts to battery. Only a small number of changes between the two designs are shown to the engineer as a result of repeating the FMEA, making incremental FMEA a sustainable and efficient practice.

Automated Incremental Generation of Diagnostics

A good amount of the work of producing diagnostic systems is achieved by the automated generation of potential failures causing each possible symptom. The remaining work is in suitably arranging the candidates for presentation in a manual or for service bay testing, and in adding any potential failures that cannot be modeled electrically.

Repetition of this work can be minimized by the use of software tools that record all operations performed on the output of the automated FMEA. The candidate failures for each symptom (driver-level symptom or DTC, depending on what kind of diagnostic system is being constructed) are presented to the diagnostic system building engineer (DSBE) by the software, and the DSBE can change the order in which the failures are investigated, and can add extra failures. All reorderings and additions are logged by the software.

Where a variant is drawn as an addition to a basic schematic or a change is made to a design, then incremental FMEA can be used to produce the differences in causes for possible symptoms. The information about the way in which the previous version of the diagnostic system was ordered can be used to produce the basis of the diagnostic system for the new version (reordering tests and adding non-electrical failures), and the differences from the previous version can then be added interactively by the DSBE.

This would significantly reduce the amount of effort needed to change the diagnostic system as the design changed or as variants of the design were produced.

Related Issues

Better on-line assistance

While this paper has discussed the production of workshop manuals, these are now seldom produced in paper format for use by professional mechanics - although there is still a market for paper-based manuals for the amateur enthusiast. For the professional, it is much more common for such information to be delivered via computer.

The kind of technology discussed in this paper brings us close to the workshop manual being automatically generated "on the fly". The engineer would enter the vehicle identification number (VIN) of the vehicle. The VIN would be used to access a database containing the variants used in building the vehicle, and the correct diagnostic system for the problem could be constructed as described earlier. More ambitiously, it would be possible to take into account any modifications made during after-service if they were properly recorded in a database. Such tracking of a changing design might be too much effort to expect for a car, but would be much more appropriate for a plane with a 30 year lifespan and several refits during its lifetime.

Another advantage of such technology is that it is based on simulation. It would be possible to provide engineers with interactive versions of the schematic, where they can choose symptoms, be shown all possible faults that could cause the symptoms, select a fault, and see the detailed effects of that fault in simulation.

Wider application of these techniques

Our own work in using model-based simulation to produce diagnostics has, for the most part, been limited to electrical systems, but there has been a good deal of work in other domains, for example (Sachenbacher and Struss) in hydraulic systems, and (Cascio et al.) in a variety of automotive domains. These efforts are not as commercially advanced as work in the electrical domain, but as the efficiency of modeling in these other domains improves, one would expect similar benefits to those being experienced in the electrical domain.

Conclusions

Electrical systems have proved to be a successful domain for the application of model-based reasoning. They are simple to model, but complex enough that it can be difficult to understand the consequences of component failures. The commercial advantages of such technology for design analysis are clear.

The use of design analysis results (specifically, the results from FMEA) for the production of diagnostics has a number of significant advantages:

- The diagnostics are based on information provided by design engineers, and the effects of component failures will have been validated by design engineers. This provides a much closer link between design and diagnosis than is often the case in large corporations.
- Much of the effort of producing the diagnostics is automated. Generation of a fault population and much of the work of ordering the population can is done by software.
- Incremental FMEA techniques help produce different versions of diagnostics. Techniques for dealing with design changes efficiently can be applied to the production of diagnostics and greatly reduce the effort of producing diagnostics for different variants, and correct diagnostics as systems evolve through different versions.

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References

Cascio, F; Console, L et al. 1999. Generating on-board diagnostics of dynamic automotive systems based on qualitative models, in Proceedings of the 13th International workshop on Qualitative Reasoning, pp265-283, Loch Awe, Scotland.

McManus, A.G.; Price, C. J. ; Snooke, N.; and Joseph, R. 1999. Design Verification of Automotive Electrical Circuits, in Proceedings 13th International Workshop on Qualitative Reasoning, QR'99, Loch Awe.

Price, C. J. 1996. Effortless Incremental FMEA, in Proceedings of Annual Reliability and Maintainability Symposium, pp43-47, Las Vegas, Nevada.

Price, C. J. 2000. AutoSteve: Automated Electrical Design Analysis, in Proceedings ECAI-2000, pp721-725, Berlin, August 2000.

Price, C. J. and Hughes, N. 2002. Effective Automated Sneak Circuit Analysis, in Proceedings Annual Reliability and Maintainability Symposium, Seattle, January 2002. Forthcoming.

Price, C. J. and Taylor, N. S. 1997. Multiple Fault Diagnosis Using FMEA, in Proceedings AAAI97/IAAI97 Conference, pp 1052-1057, Providence, Rhode Island.

Sachenbacher, M. and Struss, P. 1997. Fault isolation in the hydraulic circuit of an ABS: a real-world reference problem for diagnosis, Working notes of the 8th International Workshop on the Principles of Diagnosis, (DX-97), pp113-119, Mont-St-Michel, France.

Snooke, N. 1999. Simulating Electrical Devices with Complex Behavior. AI Communications 12 (1,2), p45-59.