INTELLIGENT KNOWLEDGE-BASED SYSTEM FOR ELECTRICAL FAULT DIAGNOSIS IN A VEHICLE

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Abstract

An intelligent knowledge-based system (IKBS) for fault diagnosis and supply restoration in a vehicle is introduced. The system is based on techniques used successfully in the electrical power supply industry. The IKBS communicates with a simulator-store that remembers past faults. Scenarios are described to illustrate fault diagnosis and supply restoration. Manufacturers are replacing mechanical links between the driver and the road wheels in vehicles with electrical wires. This may apply to the primary systems such as brakes, steering and throttle. These networks (generically termed X-by-Wire) will tend to be routed through an on-board computer, allowing control systems to manipulate driver inputs. This has implications for safety and this paper describes a system for electrical fault diagnosis and automatic correction in a vehicle.

Keywords: vehicle, electrical, fault, diagnosis, knowledge.

Introduction

Technology has tended to increase safety and future car systems should continue this trend but in-vehicle electrical systems are becoming increasingly complex.

Through computer control, cars may become less likely to crash as onboard systems assist drivers. For example, it has been estimated that 30-40% of accidents happen because of drowsiness or lapses of concentration and that state could be detected and warnings sounded and driving assistance given if needed.

Steering, acceleration and braking have conventionally been inextricably linked with the driver's commands. With new technology, electronic actuators could play an ever-increasing role.

A concern is that as vehicle electrical systems become more complex, so the danger from failure in part of the systems becomes more catastrophic. This paper describes a potential new and novel system for electrical fault diagnosis and automatic correction in a vehicle.

Knowledge based systems (KBS) have demonstrated practicality in the area of power-system diagnosis and restoration [Sakaguchi & Matsumoto(1983); Hotta *et al* (1990); Ma *et al* (1992)].

A simple PC-based KBS was built during this work to demonstrate the potential for electrical power system diagnosis and restoration in a vehicle electrical network.

The KBS communicates with another PC-based vehicle electrical-system simulator (VEHSIM). VEHSIM represents the real electrical power-system in a "fly-by-wire" vehicle that constantly supplies analog and digital information to the KBS.

The VEHSIM-KBS system realistically mimics the corresponding state of a vehicle electrical network. During testing of the system, scenarios such as cable faults, component malfunctions and loss of battery or alternator sources were set in VEHSIM. The system attempted to diagnose and restore the system using the built-in generic diagnostic rules and restoration algorithmic tools in the KBS.

Capabilities were provided for the KBS to build its knowledge base through machine learning, and to retrieve the knowledge later if the same network conditions occurred again.

X-By-Wire

At the time of writing, cars tend to have bundles of individual wires (often 250 or more), forming wiring looms. The intention is to replace these by an automotive 'bus' analogous to that of a computer.
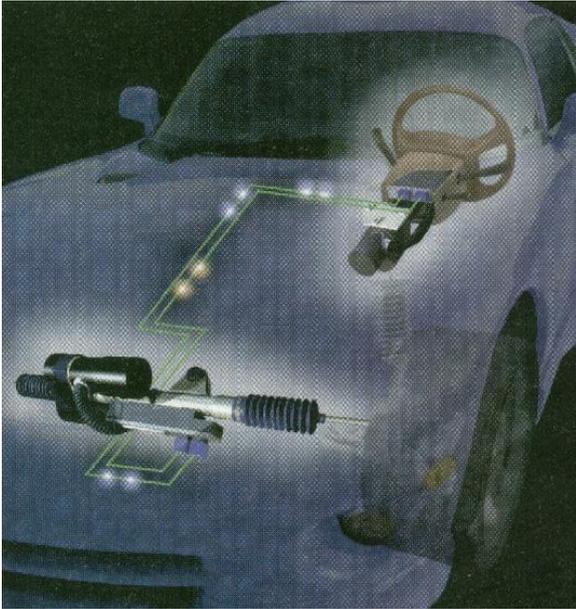
Figure 1: Steer-by-wire
[From Professional Engineering (2001)]

Like a computer, the 'standard' computer on the car can then be programmed as to what type of car it is, allowing future upgrades, for example updating of brake control software.

Optical fibres are being considered for the interlinking parts of the network as EMC (immunity to electrical interference) is an increasing issue, especially with the advent of the mobile phone and global communications.

A X-by-Wire braking system would follow this basic sequence: when the brake pedal is depressed then a sensor sends a signal to a computer. In response a signal is sent to the brakes, which in turn tighten, and additionally the brake lights would be instructed to turn on. Since the car could have the transmission controlled in a similar manner, advanced functions such as automatic downshift may be included.

The power supplies to each of the components will also be transferred by a bus system. This paper concentrates on control through adjustment to the power bus.

The sub-systems used as examples in the work described in this paper were:

- Steer-by-wire
- Brake by wire
- Drive-by-wire

These sub-systems are introduced before describing the structure and working of the knowledge-based systems
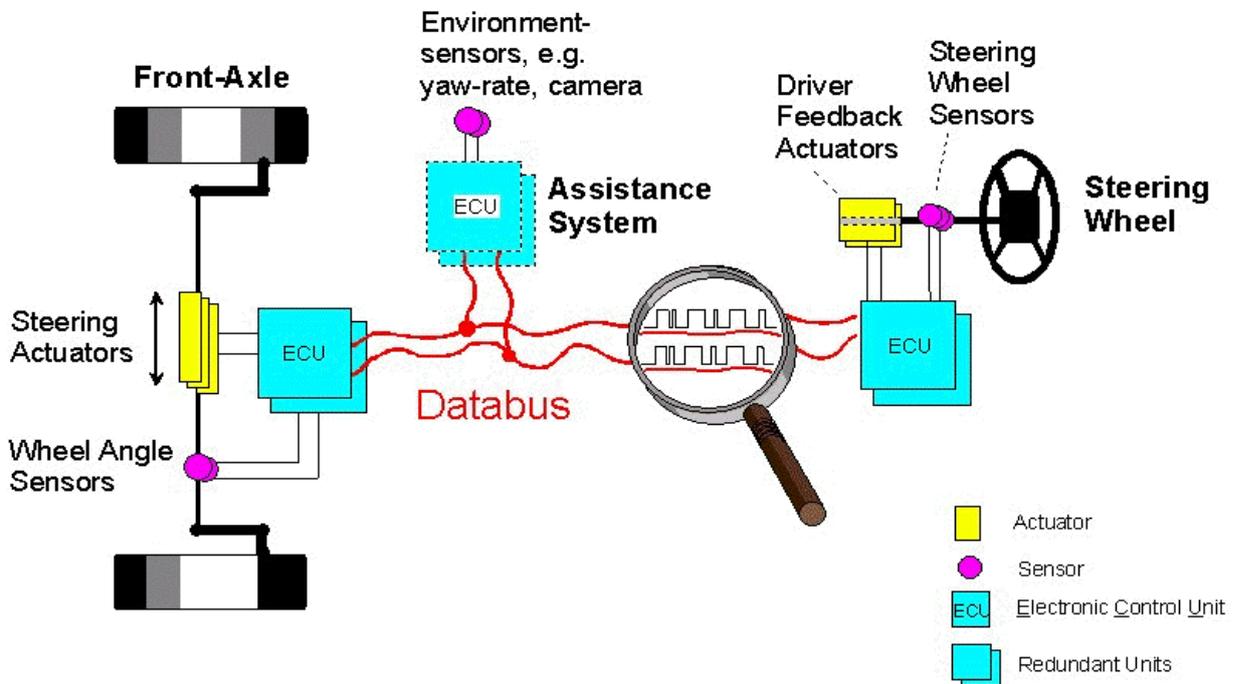

Figure 2: Steering system
[From vmars xbywire project (2004)]

and some simple case studies to demonstrate their operation.

Sub-systems used as examples

The following sub-systems were used in simulations.

Steer-by-Wire. Information from a rotary encoder detecting wheel movement was simulated. This could replace the connecting shaft between rack and steering wheel. These signals could be passed through wires to steering actuators. To complete some form of feedback loop for the driver, a further actuator could be added to the shaft of the steering wheel. Feedback to the driver is necessary to avoid dangerous over-control inputs. The systems also have potential for precision, especially in evasive action. A steering system is represented in figure2, reproduced from vmars xbywire project (2004)

Brake-by-Wire Conventional braking systems operate using hydraulics. This can be expensive due to servo assistance and regular maintenance, such as replacement of brake fluid. Future braking systems may be electro-mechanical. An electrical calliper is shown in figure 3. This could result in shorter stopping distances, as brakes may be more efficient, since excessive pedal force may not be required in emergency stops; currently the pedal may not be pressed hard enough in emergencies. The electronic braking at each wheel ties in well with the ESP systems, allowing the system to exercise greater control over the car. A full Electro Mechanical Braking system (EMB) is shown in figure 4. A tandem system for redundancy purposes is employed so if one half fails the car will still stop in a straight line. Outputs to the actuator and force feedback signals were simulated.
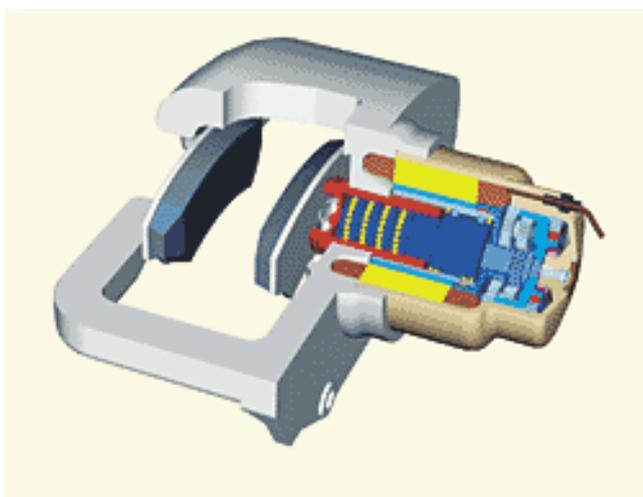

Figure 3: Electro mechanical brake calliper [From daimlerchrysler (2004)]

Drive-by-wire. Toyota's Tundra 4WD employs an electronically connected throttle control; signals generated at the pedal are fed directly into the engine management system, resulting in quicker response, improved fuel efficiency and reduced emissions. Transmission may also be controlled remotely in a similar manner. Modern electronics can amount to 40% of the value of a car [Professional Engineering (2001)]. Due to increased power demands from ancillary equipment approaching the practical maximum of today's cars, a dual standard is evolving. Higher power is demanded from new components such as electronic steering and braking systems. To get the equivalent power at 12 V means an impractical increase in current – and hence the thickness of cabling and cost. Running at 42 V addresses this. A transitional-period where cars run dual voltages using DC-to-DC converters is likely as shown in figure 5. Some of the costs of 42 V can be mitigated by starter-generator systems; Bosch's system has efficiency levels of 80% across the entire speed range, and outputs 8 kW at 36 V. Conventional 12 V alternators output 1.5 kW, with maximum efficiencies of 70%, reducing to 30% at high speeds [Marsh(2000)].

Structure of the knowledge based systems

Two simple IKBS were implemented: a diagnostic knowledge-based system (DKBS) and a restoration knowledge-based system (RKBS). This was similar to the structure used in Teo and Gooi (1997). Both systems were written in Microsoft Visual Basic on a desktop computer. VEHSIM was a separate program running on a separate computer that provided simulated telemetry data from vehicle sensors and actuators and responded to control actions from the IKBSs. VEHSIM provided an environment for the development and verification of the IKBSs.

A serial line connected the two computers. After communication had been established, control characters, defined according to Teo *et al (*1990) were sent and VEHSIM responded accordingly.

Simulation. In the VEHSIM computer, the vehicle electrical system simulator integrated the sensor and actuator states and the modeling of the overall system state. This was similar to the modeling of power over-current relays and breaker operation described by Teo(1992).

Different vehicle electrical configurations were used to test the systems. Once a particular vehicle electrical network had been loaded then a simple system state calculation was initiated and sensor and actuator operation was modeled. After a simulated fault had been applied to a power supply for an actuator or sensor then the simulator calculated the fault distribution. This calculation was repeated whenever any fault was detected.
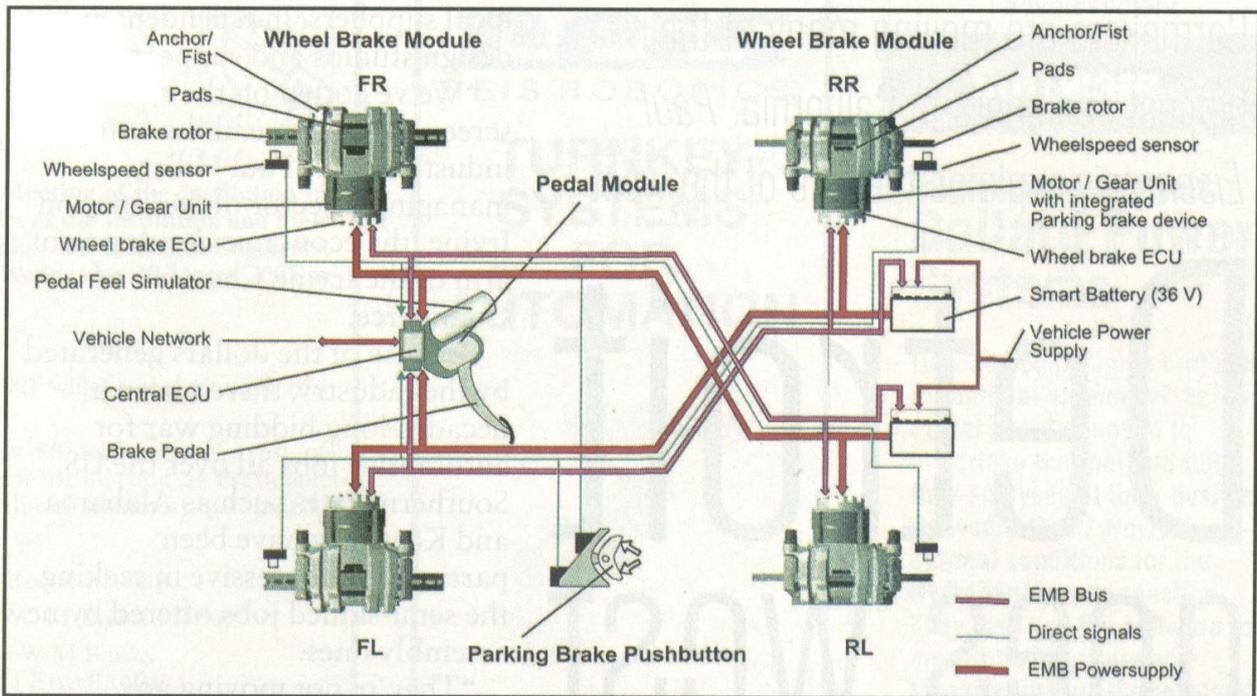
Figure 4: Electromechanical braking system
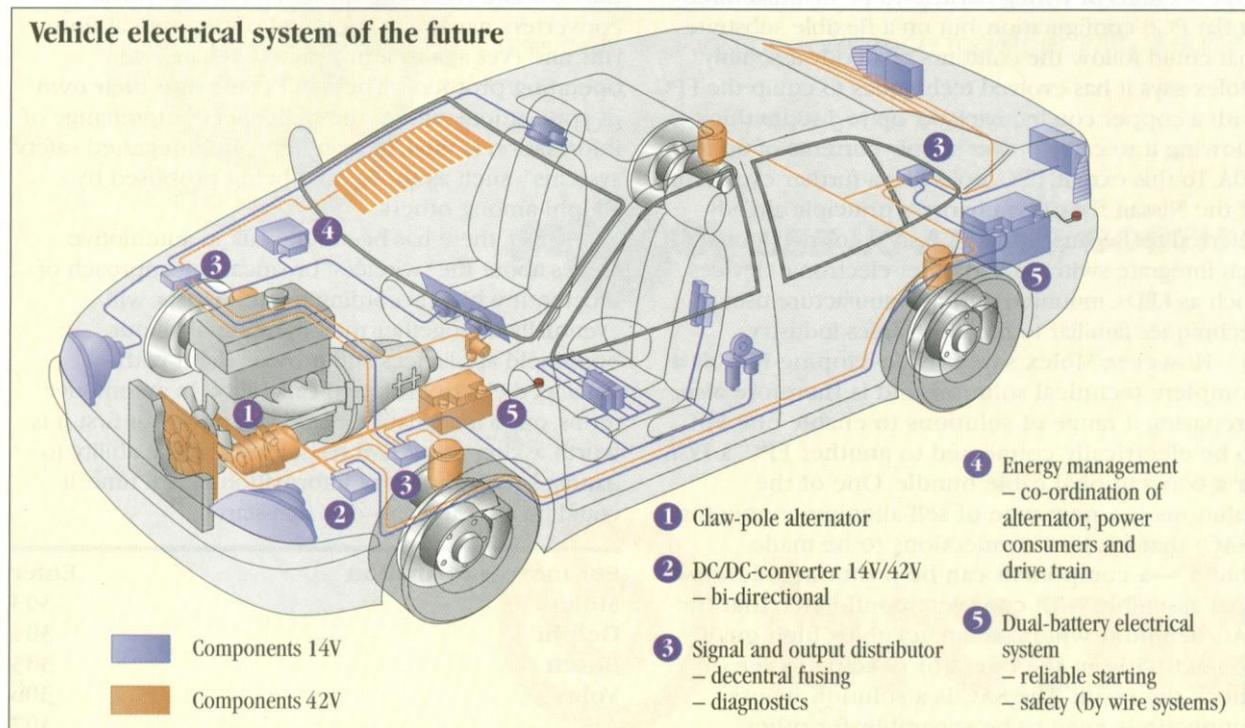*[From Professional Engineering (2001)]*

Figure 5: Vehicle electrical system of the future
[Baldwin(2001)]

Breakers were assumed to protect the power bus from overloads.

The process terminated when the fault was isolated. Time-to-detect was recorded and compared to the predicted time for that sensor or actuator to cause an accident at the speed of the vehicle. That information was stored in a simple look-up table.

Faults were detected by simulating a change in the load flow on the power supply bus without an associated signal to say that a device had been switched on or off. Load flow was calculated automatically whenever a fault was isolated or after control actions such as the operation of a breaker or the changing of the load in a bus.

Data communication. The IKBS computer asked the simulator to send the network state (to show the car and configuration of the vehicle electrical system), sensor and actuator status and electrical bus loading. If an overload or a fault current occurred that resulted in the tripping of breakers then the simulator sent the list of tripped breakers to the KBS computer.

In the KBS computer, after the fault has been diagnosed correctly, and upon receiving the fault identification and the topology of the post-fault vehicle electrical network from the IKBS, the IKBS sent commands to the simulator to lock out the faulty element.

The IKBS then generated a restoration plan and sent restoration operations one at a time to the simulator. After the execution of each command, the simulator sent the complete circuit status and all the bus loading information back to the IKBS.

The diagnostic knowledge base

The diagnostic process utilized a set of generic rules, record matching and stored memory of past diagnosis of faults, based on a pre-specified record structure. Each IKBS record was automatically constructed during the diagnostic process. This is similar to the system described by Teo and Gooi (1997).

A set of rules based on breaker and corresponding bus status was adequate for fault diagnosis. Rules were generated to determine fault location based on the status of the vehicle electrical circuit and the breaker status. These rules are referred to as hard-wired rules since they remained unchanged in the program code.

A hypothesis was generated once a rule had been matched and the simulator was prompted to confirm the fault location as hypothesized. In a case where more than one breaker had tripped, the fault was hypothesized in the region of the first breaker to trip. If the simulator did not agree with the hypothesis, the fault was then hypothesized in the region of the second tripped breaker and so on.

The hard-wired rules were implemented through standard if-then-else statements. In most cases, this rule-based approach worked well and detected faults correctly in the vehicle electrical system. It failed under certain circumstances such as changes in network topology but that is unlikely to occur in practice in the foreseeable future.

Record matching and learning. Each IKBS record contained information to identify one particular post-fault network status. The data included the electrical network name, the vehicle type, the list of tripped breakers, the live sources (alternator or battery), the live and dead electrical power supply buses, bus identification, a fault identification number (known as the VEHSIM ID_NUM), a description of the faulty element (sensor or actuator or wire) and a common end of record marker.

A virtual record that had the same data structure as in the IKBS record represented the current post-fault network state. This virtual record was constructed through a network state-capture mechanism that conducted a recursive trace on the network to obtain the post-fault network topology. During the inference process, the record-matching mechanism searched for a record that matched the virtual record. If all the necessary items were the same, the faulty element in the matched record was retrieved for fault identification. If the virtual record did not match with any record then the system prompted the simulator to provide a guess at the faulty element. The information contained in the virtual record was then copied as a new record.

The new record contained the faulty element and the new VEHSIM ID_NUM, an integer generated by the system to identify a new fault. This process was defined as machine learning [Ypsilantis & Yee(1991)]. More records could be added by activating various different possible faults, one at a time, in the vehicle electrical circuit. The IKBS became more intelligent as the diagnostic knowledge base expanded through machine learning.

Restoration knowledge base

Once the simulated fault had been correctly diagnosed by the IKBS, the restoration knowledge base sent the relevant commands to lock out the power to the faulty element and prompted the simulator to select one of the following:

- warn the driver to brake safely and stop,

- automatically brake and stop,
- restore the fault through human intervention,
- automatically restore power by rerouting.

Through load-flow calculation and modeling of the vehicle electrical system, a restoration algorithm searched for a solution. If no overload tripping was detected and the breakers at both ends of a link were not marked as locked then the IKBS recommended that the full electrical link in the power circuit be closed.

After the full link had been closed and rerouting the electrical circuit had restored the entire circuit, then the IKBS updated the network status and searched for an alternative link. The process was repeated until no more full links could be found. The IKBS attempted to restore any remaining partial links until there were no more restorable loads.

The first part of each IKBS record contained the post-fault network VEHSIM ID_NUM, the restoration method used, the locked breaker information and the system status. The second part of the record contained the recommended restoration codes for a particular vehicle electrical network.

Once the post-fault network was confirmed and represented by a particular VEHSIM ID_NUM, the restoration system searched the file for the first part of each record that matched all parameters. When a matching IKBS record was found then the restoration operation was extracted from the recommended restoration codes stored in that particular IKBS record. If no matching IKBS record was found then the simulator called for human intervention to restore the supply manually or generated an alarm to alert the driver to stop the vehicle. Upon successful completion, each restoration step was combined with the post-fault network state to form a new IKBS record.

Case studies

Two model networks, Alpha and Beta were implemented in the system. The Alpha network was based on a vehicle fitted with steer-by-wire and brake-by-wire and the Beta system the Beta network was based on a top of the range vehicle fitted with steer-by-wire, brake-by-wire and drive-by-wire systems. The following faults were tested:

Cable fault. A cable fault caused the tripping of breakers. The possible fault locations diagnosed by the IKBS using generic rules were at the supply or in the electrical power bus. Since a breaker would trip to isolate a fault, the fault was diagnosed as a cable fault between two bus nodes and according to a generic rule. Once the fault location had been confirmed, the IKBS sent a command to lock out the fault by opening the

breaker and (based on the IKBS restoration algorithm) the supply to the buses was restored after re-routing.

A cable fault could be introduced with a breaker opened prior to fault. This fault was activated at the same location in a cable as for the case in the previous paragraph but with a breaker opened prior to the fault. In this network configuration, only some breakers tripped to isolate the fault while the breaker closest to the fault remained closed. This was because prior to the fault the breaker was opened and it prevented the bus from feeding current to the fault. As a result, the generic rules sometimes mistakenly interpreted the fault at the wrong bus. As the simulator would not agree with the diagnosed result in this case then the IKBS prompted the simulator to suggest the faulty element and a new IKBS record was constructed. Opening a breaker locked out the faulty cable. Based on the recommendation by the IKBS algorithm the supply to the buses was restored by closing the relevant breaker. Subsequently, the simulator activated the same fault on the same vehicle network configuration. This time the fault was correctly diagnosed since the IKBS had been trained.

Malfunction of an actuator or sensor. A malfunction of an actuator or sensor on the vehicle network bus caused the simulator to request human intervention to restore the fault manually without the IKBSs. The simulator observed the effect on the system state and learned what had happened as the human taught the system what action was necessary. Multiple faults were too complicated for the IKBSs and a human being needed to restore the system manually although the simulator sometimes then recognized similar disturbances. The system always automatically selected the alarm to ask for manual restoration of power.

Loss of one incoming source. A failure in an incoming source (battery or alternator) caused overload tripping and the IKBS was unable to diagnose correctly using either IKBS records or generic rules. Breakers were initially opened prior to the fault. Since it was an overload tripping, the simulator recorded the faulty element as an overload and a new IKBS record was added to the IKBS. Successful manual restoration was checked and stored in the knowledge base by inserting a new IKBS record.

If the loss of one incoming source occurred after learning then the simulator restored the loss of a source in a vehicle network. Since the IKBSs had learned this specific disturbance, it was demonstrated that the fault could be identified correctly as an overload and the supply could be restored automatically.

Conclusion

The new vehicle systems being developed may lead to improved safety. Cars may be programmed not to crash and may have increasing margins of safety. Cars may perform better due to increased road holding. Unfortunately, the amount the driver actually *drives* the car may be reduced, together with loss of *real* feedback. Loss of this involvement may be to the detriment of driver satisfaction.

Cost benefits and life saving potential of advanced systems can be demonstrated by better reactions and stability; however, the most important criterion will be the reliability of the 'X' systems. Regulations require steering to be mechanically linked and drive-by-wire systems are not yet roadworthy [Automotive Engineering international (2000)]. In addition, motor manufacturers are still trying to agree on the protocol for the new systems so that the systems used in the research work described in this paper are fictitious and not actually available yet in Ford or BMW cars or any other cars.

Commercial systems may still be 10 years away.

Concerns are expected to filter down from luxury saloons and purchasers of these expensive vehicles. The systems described in this paper can diagnose faults in sensors, actuators or in the power lines that make up the vehicle electrical bus network and either warn the driver, stop the vehicle or restore power within the vehicle electrical system.

Some simple training scenarios were tested and the IKBS record for overload tripping and faults were investigated. Levels of complexity were set up through VEHSIM, while the IKBSs were used as tools to test the programmed logic and reasoning for fault diagnosis and supply restoration. Generic rules for fault diagnosis, restoration algorithms, knowledge acquisition and an inference mechanism were incorporated in the IKBSs.

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