Research on Electrical/Electronic Architecture for Connected vehicles

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Abstract

A vast increase in automotive Electrical/Electronic systems, coupled with related demands on connection, has created an array of new engineering challenges. Strong coupling and correlative relationship between electric/electronic devices are more and more complicated, and the malfunctions and failures are more difficult even no access to detect and locate, which seriously threatens the vehicle safety. In addition, motorists' insatiable demand for comfort and convenience features is posing challenges to manufacturers in terms designing reliable vehicle's Electrical/Electronic Architecture.
Based on the concept of “body and brain”, a brand new Electrical/Electronic Architecture is introduced, which is a three-layered architecture. Sense & execution layer is composed of intelligent network nodes, which obtain both in-vehicle electric/electronic devices’ states and the data from V2X, achieve real-time online diagnosis, and implement the control command to them; Network & Transmission Layer for information transmission between sense & execution layer and Decision Layer; in Decision Layer, central coordination management mechanism is set to analyse all the correlative relationship between the whole vehicle’s devices, achieving coordinated control and all-around supervisory of the whole vehicle.
This proposed Electrical/Electronic Architecture is demonstrated on a luxury vehicle model that in volume production, and experiments on test bench and sample vehicle are carried out to verify this structure.

1 Introduction

With the rapid development of vehicle Electrical/Electronic technologies, the surging number of electrical/electronic devices (EEDs, as is shown in Figure 1) has been applied in the vehicles [1][2], which results in system complexity and increasing failure risks [3][4]. Meanwhile, higher degree of intelligence and automation makes the correlative relationship between ECUs more and more complicated, and the malfunctions and failures are more difficult even no access to detect and locate for their strong coupling relationship. Therefore, a brand new structure is urgently needed, to realize extensive monitoring of all the EEDs and achieve overall fault diagnosis and detection, to ensure the vehicle’s safety and stability.
In this paper, the in-vehicle network based on the concept of “ body and brain ” is proposed, which is a three-layered network frame. Sense & execution layer is composed of intelligent network nodes (INNs), which enable all the EEDs digitalizing and intelligent communication. INNs obtain all-around state information and self-diagnosis information of all EEDs, and implement the coordinated control command from Decision Layer to them. Network & Transmission Layer is responsible for information transmission between sense & execution layer and Decision Layer. In Decision Layer, central coordination management mechanism is established, which analysis all the correlative relationship between all EEDs, achieving coordinated control and all-around supervisory of the whole vehicle, convenient for detecting failures, especially coherent faults.

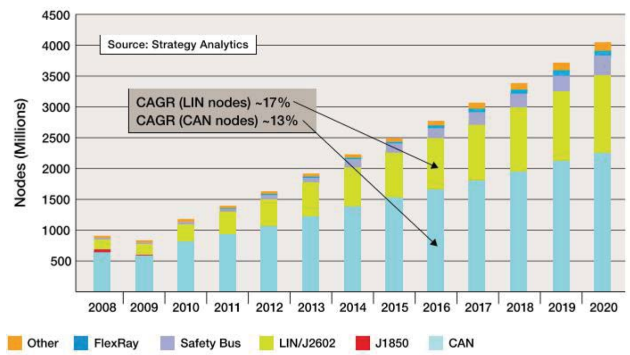


Figure 1 The growth of CAN, Lin and other nodes in vehicles

Compared with the traditional vehicle electrical/electronic structure, the proposed in-vehicle network architecture can realize fully monitoring of all EEDs in real time, and extensive fault detection of the whole vehicle, especially coherent fault detection and fault-tolerant processing.

2 Proposed Electrical/Electronic Architecture

In-vehicle network architecture is an intelligent vehicular network, unifying and linking all the EEDs, acquiring their states and self-diagnosis messages in real time, and facilitating information sharing with appointed protocol, in order to achieve all-around monitoring, extensive fault detection and warning, and central coordination, in system level of the whole vehicle.

Different from traditional In-vehicle network architecture, the proposed one is a three-layered network frame, which is composed of sense & execution layer ("body"), Network & Transmission Layer ("nervous system"), and Decision Layer ("brain"), as is shown in Figure 2.

The sense & execution layer ("body") is consists of intelligent network nodes (INNs). As is shown in Figure 2, there are different types of EEDs with various functions, which are all linked to the network with INNs for communication. Different from the concept of 'perception layer' or 'data acquisition layer' in the IoT world, [19] the sense & execution layer not only acquires real-time information (including fault diagnosis information) from EEDs, but also is responsible for implementation of coordinated control commands to EEDs. With its own ID for each INN, INNs are information sources and instruction executants in the in-vehicle network, which are important foundation of in-vehicle network architecture.

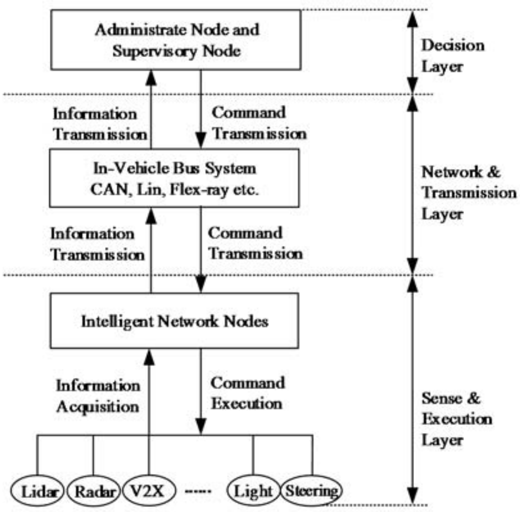


Figure 2 Network architecture of in-vehicle network

Network & Transmission Layer ("nervous system") is responsible for message transmission, including EEDs' state information (bottom-to-top) and control commands (top-to-bottom). With modern bus technology, Network & Transmission Layer packs data with appointed protocol, realizing communication between all EEDs and subnet.

Decision Layer ("brain") is composed of administrate node and supervisory node. Administrate node, the brain of in-vehicle network, makes fusion processing to holographic data, and generates control commands to all EEDs, by analyzing the correlative relationship between EEDs, in order to realize orderly management and extensive fault detection of the vehicle.

As the interactive interface of human-computer, supervisory node on not only receives the driver's operating instructions to control EEDs, but also displays the status and fault messages of the EEDs, sometimes even the warning alert. Besides, establishing communication with remote monitoring center, it has potential to develop remote monitoring and remote fault diagnosis.

3 Sense & executive layer design of in-vehicle network architecture

3.1 Classification of intelligent network nodes

In the proposed in-vehicle network, numerous EEDs are connected to the network through INNs, which can be classified into five types according to their different functions. Resistor-type INN: they only have two working states, open and closed, for example, almost all lamp-type EEDs. They are the most common and simple actuators in vehicles; Motor-type INN: they usually require larger power to drive comparing with resistor-type INNs. Generally, they have three working states, turn clockwise, turn counter-clockwise, and stop; Switch-type INN: buttons are basic form, as well as knob, pneumatic switch, electromagnetic switch, etc. Different kinds of switches, with different working principles, export different types of signals, to send control commands to particular EEDs; Sensor-type INN: there are several kinds of sensors, according to working principles, classified into rheostatic sensors, transformer sensors, and transducer sensors. They send simulative signals to relevant system and instrument; Assembled INN: they implement more complicated functions and have already been developed to separate electronic control unit, such as EMS, anti-lock braking system (ABS), etc.

3.2 Modularization design of intelligent network nodes

INNs are information sources and instruction executants in the in-vehicle network, which perform state acquisition, driving control, and fault diagnosis. As shown in Figure 3, state acquisition module and fault diagnosis module obtain EEDs' status messages and fault messages, sometimes maybe needs data fusion stage, and then sent to Network & Transmission Layer by message sending module; on the other side, INNs receive commands with message receiving module, and then drive EEDs with execution control module.

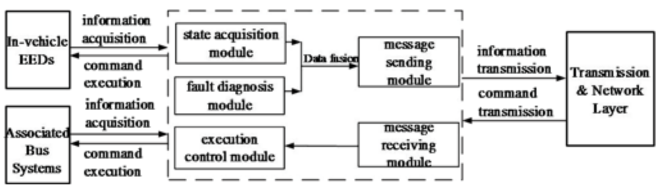


Figure 3 Deconstruction the intelligent network node's functionality

(1) State acquisition

INNs achieving state acquisition are switch-type INNs or sensor-type INNs. Switch-type INNs obtain switches' states through something like input & Output (I/O) digital port; sensor-type INNs obtain states of rheostatic sensors and transformer sensors through analog port A/D; and transducer sensors through frequency calculation.

(2) Execution control

INNs possessing execution control module are resistor-type INNs and motor-type INNs. Most of resistor-type INNs achieve controlling through I/O; motor-type INNs through analog port A/D; some exceptions of resistor-type INNs and motor-type INNs need an analogy voltage through D/A to realize driving control, such as, adjustable background light, adjusting motor of front headlamp optical axis, etc.

(3) Fault diagnosis

For resistor-type INNs and motor-type INNs, load feedback method is used to detect over-current or open circuit failure. If the real load current is much larger than normal, the over-current failure occurs, and the critical threshold value is designed as 1.5 times of the rated current; if the real load current is close to 0, then it is determined as open circuit failure.

Sensor-type INNs implement failure detection with threshold value method, expressed as equation 1. If the tested value of sensor exceeds the threshold, the sensor lapses.

$$S_{min} \leqslant S \leqslant S_{max} \qquad (1)$$

Where s is tested value of sensor, S_{min} is defined as lower limit of the sensor, S_{max} is defined as upper limit of the sensor. If the test result meets equation 1, the sensor is fault-free; on the contrary, it breaks down.

Switch-type INNs complete fault diagnosis with help of the human-computer interactive interface, that is, the supervisory node. The supervisory node displays the switch's status, if the displayed state match driver's operation, the switch is fault-free; on the contrary, malfunction occurs.

4 Network & Transmission Layer design of in-vehicle network architecture

Network & Transmission Layer, linking sense & execution layer with Decision Layer, is the data transmission channel of the in-vehicle network. Packaging data with appointed protocol, Network & Transmission Layer sends information of EEDs from sense & execution layer to Decision Layer, and assigns commands from Decision Layer to each INN. Based on the representative structure of in-vehicle network shown in Figure 3, working mode of Network & Transmission Layer is designed shown as Figure 4.

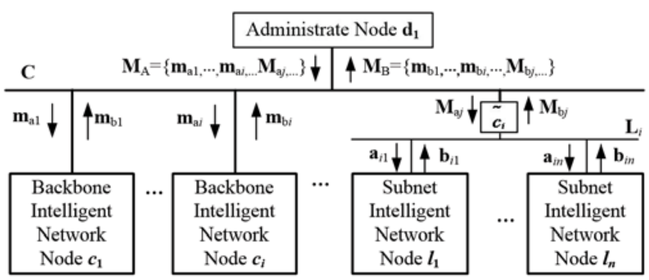


Figure 4 Schematic diagram of data transmission

There are two kinds of data, EEDs' information, including working state messages and fault diagnosis messages, and control commands. Backbone INN c_i sends information data m_{bi} to the backbone network C; subnet INN l_n sends its information bin to subordinate network, the gateway $\tilde{c}_i$ packages all the information data of this subordinate network L_i, and generates information packet M_{bj} to send to C. Then all the information of INNs in C is packaged as one information packet MB, sent to Decision Layer. With fusion processing and comprehensive coordination, command packet MA is generated and sent to C. Backbone INN c_i only obtains its own command m_{ai}, the gateway gets command packet M_{aj} of the subordinate network L_i and assigns these commands to the specific INNs.

Therefore, each INN only communicates with administrate node, achieving decoupling between INNs, convenient for orderly management and coordination of the network. Furthermore, each INN's functional logic is greatly simplified, facilitating their design and development rapidly and efficiently, and the impact of one INN's failure is greatly reduced.

5 Decision Layer design of in-vehicle network architecture

5.1 Central coordination management mechanism

Central coordination management mechanism is to achieve comprehensive diagnosis of coherent faults and central coordination control of the whole vehicle, by analyzing the logical correlative relationship between EEDs, and establishing associated subsystems, functions of state combination, and state machines.

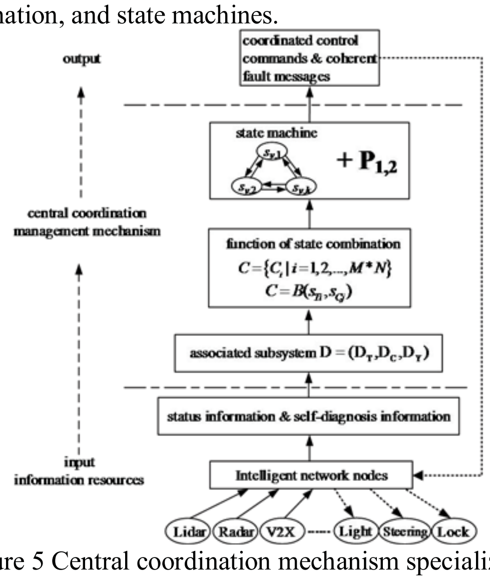


Figure 5 Central coordination mechanism specialized for connected vehicles

As shown in Figure 5, EEDs' status information and self-diagnosis information are input and information resources of central coordination management mechanism. Administrate node, which performs the central coordination management mechanism, establishes the target EEDs' associated subsystem, function of state combination, and state machine, and finally generates coordinated control commands of target EEDs, and the subsystem's coherent fault messages as output.

5.2 Design of central coordination management mechanism

5.2.1 Associated subsystem

Usually, EEDs are mutually restrictive in logic, cooperative or exclusive in working states, or, similar or opposite in functions. These complex correlative relationships between EEDs are expressed with associated subsystem, as shown in Figure 6.

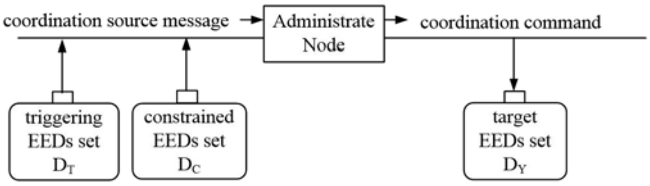


Figure 6 Correlative subsystem

An associated subsystem consists of triggering EEDs, constrained EEDs, and target EEDs, expressed as follows:

$$D=\left(D_T, D_C, D_Y\right) \tag{2}$$

Where D is associated subsystem, D_T stands for triggering EEDs set, which trigger target EEDs' actions, such as switch-type EEDs, sensor-type EEDs, and operation screen of human-computer interactive interface; D_C stands for constrained EEDs set, which restrict target EEDs' actions; and DY stands for target EEDs set, which are controlled targets of this correlative subsystem, usually are actuators, such as resistor-type EEDs, motor-type EEDs. As shown in figure 6, administrate node obtains status information and self-diagnosis information of D_T and D_C, and generates coordination commands for D_Y. Triggering EEDs and constrained EEDs are all called as correlative EEDs of target EEDs.

5.2.2 Function of state combination

In an associated subsystem, state sets of D_T, D_C, and D_Y are S_T, S_C, S_Y, respectively, expressed as equations (3) ~ (5).

$$S_T=\left(s_{Ti} \mid i=1,2,\ldots,M\right) \tag{3}$$

$$S_C=\left(s_{Cj} \mid j=1,2,\ldots,N\right) \tag{4}$$

$$S_Y=\left(s_{Yk} \mid k=1,2,\ldots,K\right) \tag{5}$$

Where s_{Ti} is one state combination of all triggering EEDs; s_{Cj} is one state combination of all constrained EEDs; and s_{Yk} is one state combination of all target EEDs. According to equation (3) and equation (4), state combination of D_T and D_C are shown as table 1.

Table1 State combination of D_T and D_C

EEDs' states	$s_{C,1}$	$s_{C,2}$	……	$s_{C,N}$
$s_{T,1}$	C_1	C_2	……	C_N
$s_{T,2}$	C_{N+1}	C_{N+2}	……	C_{2*N}
……	……	……	……	……
$s_{T,M}$	$C_{(M*N-N+1)}$	$C_{(M*N-N+2)}$	……	C_{M*N}

In table 1, C_i (i = 1, 2,…, $M*N$) is Boolean expression of states of all triggering EEDs and constrained EEDs, which is defined as equation (6).

$$C=B(s_{Ti}, s_{Cj}) \tag{6}$$

$$\text{Where, } C=\{C_i \mid i=1,2,\ldots,M\times N\} \tag{7}$$

5.2.3 State machine

The state combinations C_i is state transfer conditions of target EEDs D_Y, as shown in Figure 7. If C_i changes, D_Y will transfer to different state or keep its current state, according to the logic correlative relationship.

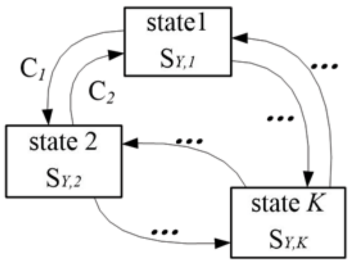


Figure 7 State machine of D_Y

According to Figure 7, state machine of D_Y is defined as equation (8).

$$s_{Yk} \in S_Y = f(C_i)\left(k=1,2,\ldots,K\right) \tag{8}$$

Where, the function f is set according to the correlative logic relationship between EEDs of the correlative subsystem.

5.2.4 Cyber security considerations

For connected vehicles (CVs), Connectivity have different types like 3rd party/OEM connected services, built-in connectivity, GNSS antenna beamed-in connectivity, etc. As we know, open means value, but also introduce risks to traditionally closed vehicular system, which ought to be protected, making vehicles a more accessible and more attractive target to adversaries (especially introduce of wireless communication attack surfaces). We introduced a parameter $P_{1,2}$ here to reduce the risk to an acceptable level, which can be defined as follows:

$$P_{1,2}=\begin{cases} 1 & X_{e1} \neq 0 \text{ and } X_{e2}=0; X_{e1} \neq 0, X_{e2} \neq 0; \\ 0 & X_{e1}=0 \text{ and } X_{e2} \neq 0; \end{cases} \quad (9)$$

Where, X_{e1} is the commands based on Central coordination mechanism, and X_{e2} is the command that generated from the connectivity methods. Obviously, when the two commands conflicts, the vehicle will executive command from in-vehicle network for the higher trust degree, that is the reason why we introduced the parameter $P_{1,2}$。

6 Vehicle and bench tests

6.1 The topology of proposed in-vehicle network architecture for CVs

The proposed in-vehicle network architecture has been applied to a three-compartment luxury passenger car. The topology and harness scheme of the in-vehicle network architecture is shown in Figure 8.

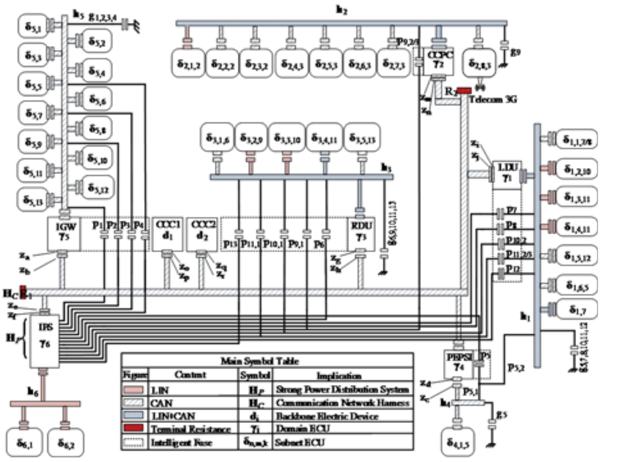
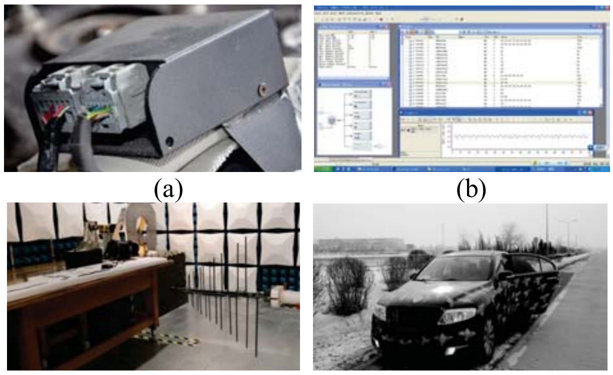


Figure 8 Topology and Harness scheme of in-vehicle network architecture of the experimental vehicle

Remote diagnosis was succeed in execution through a 3G communication model, which is shown on the top right corner, named $\boldsymbol{\delta}_{2,8,3}$. All functions were tested on the experimental vehicle and a test bench.

6.2 The product and road test

In order to meet the test conditions of the product. We write test plans, test cases and track results, which were executed in hardware-in-the-loop test bench and vehicle function test bench and the field test (static experiments). One of the test INNs was shown in Figure 9 (a). Network reliability and load rate were tested on different test benches. All the INNs were connected to the network, and CANoE was used to monitor and analyse the data transmission of the network. The monitoring interface was shown as Figure 9 (b), the maximum load rate (include all tested subnets) was less than 10% . one of the EMC test (part of product testing content) environment was shown in Figure 9(c). The experiment vehicle, one of the vehicle road test (different from static experiment, all the test cases were executed in different driving conditions) scenarios was shown in Figure 9(d), has experienced various test environments and runs for 5000km, during which the new structure worked stably and reliably.

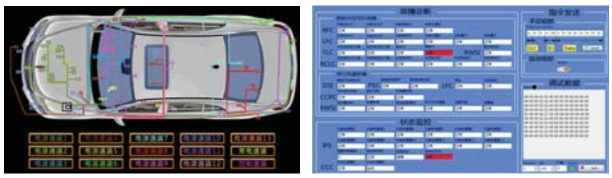


(a) (b) (c) (d)

Figure 9 Road, Function and Hardware-in-the-loop test (a) Hardware-in-the-loop test bench (b) Monitoring interface of CANoE (c) Product test environment (EMC) (d) The road test of vehicles

6.3 The local and remote diagnosis of CVs

The test vehicles experienced different sets of network, function and fault-tolerant test, the results of which can severed as evidences to verified the proposed architecture.



(a) (b)

Figure 10 The diagnosis interface of in-vehicle network

We achieved the proposed goals (mentioned in paragraph one, realize fully monitoring of all EEDs in real time, and extensive fault detection of the whole vehicle) and the diagnosis interface of vehicle power supply systems is chosen as the selected examples, as is shown Figure 10(a). Based on the connectivity features of CVs, the remote diagnosis application system was developed. we realized the remote diagnosis, condition monitoring, and even remote emergency control of the vehicle mounted electric system, the remote monitoring and control interface is shown in Figure 10(b).

7 Conclusion

The proposed Electrical/Electronic Architecture brings totally new sense of information age that appeared in-vehicle network, for the digitalization and intelligence of EEDs, which severed as intelligent in-vehicle network nodes that obtaining the real-time states and diagnosis information and achieving online monitoring extensively and widely. The proposed central coordination management mechanism can achieve coordinated control, coherent fault detection and fault-tolerated processing.

The proposed in-vehicle network architecture has been applied and demonstrated in a sample luxury vehicle, which has no less than 183 EEDs. All the bench , field and road tests done in the project have proved that the in-vehicle network architecture can realize all-around monitoring and comprehensive fault detection of the whole vehicle in real time both locally and remotely. It is believed that the new structure is of great potential in enhancing vehicle's maintainability, reliability and security. The B sample vehicles (specifically responsible for road tests) has experienced 5000kms in various conditions such as rain, snow and fog weather after a series rigorous testing content applied in A sample vehicles (specifically responsible for function tests), the excellent test results ultimately proves the feasibility and reliability of the new structure and contributes to the witness of the small batch production of vehicles.

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