Networking Optimization for Holo-distributed Automotive Body Electrical System

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***Abstract*—In this paper, an ordered-specimen cluster analysis based network optimization is proposed. The holo-distributed automotive electrical system features that all electrical devices are the network nodes and connected with two separate networks, namely the digital signal network and the power supply network. The digital signal network features a set of hierarchy local subnets. The proposed optimization method for networking the widely scattered and utterly disordered body electrical devices, aims to a connection with the simplest harness. Through electrical device reduced-dimension ordering, the optimization problem is converted to an ordered-specimen with limited-group-capacity partition problem with the restrain of network schedulable condition. Problem's solver algorithm is also proposed based on global search in shrank space. Finally, the method is used during the development of distributed body electrical system on prototype urban bus, and proved to be feasible.**

***Index Terms*—Holo-distributed control system; automotive body electrical system; ordered-specimen cluster analysis; networking optimization; global search**

I. Introduction

With the rapid development of electronic and electric technologies, in vehicle electrical & electronic devices (EEDs) have become much more complicated than ever before[1][2]. Micro-control unit came into application in vehicle electrical system in the later 1980s, and swiftly became an important part of vehicle electrical system. Discrete and stand-alone control modules, in which devices are controlled by their corresponding controllers or switches, made the system more intelligent and versatile; however, they still cannot fulfill the requirement imposed by the booming of the in-vehicle EEDs anymore. The information sharing, synergy, harness simplification and cooperation among various EEDs become the key factor for the automotive electric/electronic system architecture.

In the early 1990s, many kinds of digital communication technology, namely the multiplexing technology, were developed, who have their own technical specifications and standards [3]. For example, UART by GM, CCD bus by Chrysler, BEAN by Toyota, ACP, J1850 and UBP by Ford, VAN by Renault, CAN by Bosch, and so on. Application of multiplexing technology has a great effort on automobile harness simplification, as well as electrical/electronic architecture innovation. Distributed system based on multiplexing was widely adopted and embedded control with network connections becomes a trend [4]. Many types of distributed system are collected and compared. The degrees of distribution are shown in Fig. 1. Freescale, NXP and Volvo proposed automotive body electrical system architectures with semi-centralized layout for passenger cars, composed of a CAN bus for body control module, and several Local Interconnect Networks (LIN) for side power windows, climate control network, etc.[5,6,7] Freescale even introduced a Media Oriented Systems Transport (MOST) for navigation and rear view system. Scania suggested a system architecture for commercial vehicles, which consists of three CAN networks for power train, diagnose and other devices[8]. Continental Automotive recommended system architecture with four CAN buses for instrument, diagnostic, power train and multiplex respectively. Volvo even goes deeper in the distributed body electrical system trend, who introduced a Bus Electronic Architecture in its B9 and B12 coach series which links chassis and body electrical systems[13].

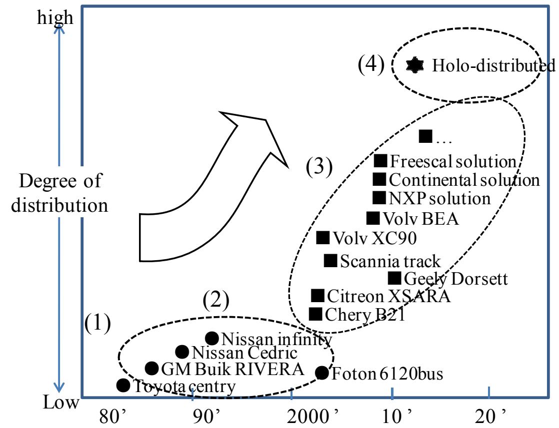

Figure 1. Degree of system distribution.

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Automotive body electrical system architecture now still on its evolution way from point-point system(Fig. 1(1)), central controlled system(Fig. 1(2)), discrete control module system(Fig. 1(3)) to holo-distributed system(Fig. 1(4)). A kind of body electrical system architecture by Gu et al.[8] features that all the body EEDs operates under central coordination. Besides in-vehicle network optimization is also necessary. Muller et al.[9] used genetic approach to plan the electrical control unit's location, while Thilo et al.[10] proposed a multi-objective optimization method for network topology. Kim et al.[11] proposed a joint optimization for harness and time response. In holo-distributed system, sub-netwok grouping is a problem.

This paper proposed a network optimization method for holo-distributed electrical/electronic system. Based on ordered-specimen cluster and sub-network grouping, automotive harness is simplified and system architecture is optimized. Optimization model and its solving algorithm are also proposed. Prototype was carried out on a bus and the method was proved to be feasible.

II. Holo-distributed Automotive Body Electrical System

A. System Architecture and EEDs Grouping

The holo-distributed system consists of two separate components, namely the Digital Signal Network (DSN)[8], to which all in-vehicle EEDs, from a single light to the complex engine control unit, are connected directly, and the Power Supply Network (PSN), from which all EEDs obtain status-monitored power supply. DSN can be is composed of back-bone signal network (BDSN) and sub-digital signal network (SDSN). The basic concept is sketched in Fig. 2.

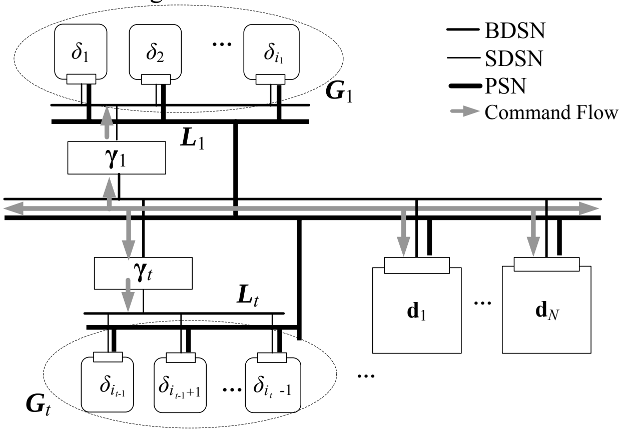

Figure 2. Layout of holo-distributed system[8].

As is shown in Fig. 2, all the EEDs presented in the vehicle are digitalized with a network communication interface. The DSN that features a hierarchy structure connects all the digitalized EEDs. The EEDs in SDSN (δ_i in Fig. 2) exchange data with EEDs in BDSN (d_i in Fig. 2) through the gateways (γ_t in Fig. 2) The hierarchy structure releases the load of the backbone network, simplifies the topology and harness route design. A dedicated power supply network (PSN in Fig. 2) is introduced in the system, which is responsible for the power supply for all the EEDs.

Comparing to conventional automotive electrical system architecture, the holo-distributed system has the following features: (1) in such system, the EEDs are treated equally despite their various function, because of the uniformed interface and self-organized operation; (2) The holo-distributed system is to simplify and clarify the harness. It facilitates a unified connection over all the EEDs, which minimizes the types of the plugs and cables, simplifying the assembly process as well as reducing the cost of harness. In such system, network planning becomes an EED grouping problem. The EED group $\boldsymbol{G}_t$ in sub-network $\boldsymbol{L}_t$ may contain any possible EEDs, however the group should be optimized.

B. SDSN Networking and Physical Connection

In vehicle body electrical/electronic system, The EEDs have the following features should be assigned to BDSN: (1) Real-time requirement of the information exchange; (2) Large amount of information from the EED; (3) Relative high criticality in the conventional system.

The BDSN usually can be a CAN network with the number of EEDs up to around 30. All other EEDs are assigned to the distributed subnets. There are multiple SDSNs and the SDSN set **L** can be expressed as:

$$\mathbf{L} = \{ \boldsymbol{L}_t \mid t = 1, 2, \ldots M \} \tag{1}$$

Where $\boldsymbol{L}_t$:

$$\boldsymbol{L}_t = (b_t, \boldsymbol{G}_t)$$

$$\boldsymbol{G}_t = \{ \delta_k | k \in [i_{t-1}, i_t - 1] \}$$

Where b_t – Subnet bus harness; $\boldsymbol{G}_t$ – tth Subnet EEDs set; In such system, there are only three types of wiring schemes necessary, corresponding to BDSN, SDSN and PSN respectively. The definition of SDSN harness is illustrated in Fig. 3.

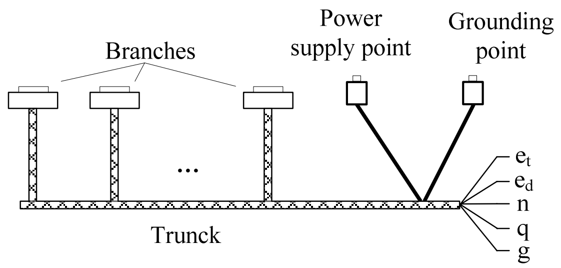

Figure 3. SDSN harness and its wiring set.

The SDSN wiring system consists of three different components for easy mounting: Trunk, branches and the high voltage supply points, namely the power supply point and grounding point. SDSN define the connector's physical characteristics and the unique wire configuration as well, With single-wire communication line and two power lines of low voltage (e_t, e_d in Fig.3, usually 5V) and two of high voltage (q, g in Fig.3, usually 12V).

For the widely scattered and utterly disordered body EEDs, the SDSN harness accounted for the largest proportion. EEDs that assigned to a dedicated SDSN are

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mainly depends on their physical location. Unfortunately, the physical location of EEDs is decided by their function defined in the system. So classification or grouping of EEDs within SDSNs based on physical location is feasible but not the best solution. At most of the time, it is much significant to optimize subnet EEDs sets $\boldsymbol{G}_t$, (t=1,2,…) to get a much simplified harness.

III. Sub-nework Optimization

A. SDSN Harness Length Calculation

The layout of automobile harness is restrained by the mechanical structure of the body. In general, there is always one backbone harness that goes throughout the whole body, with the help of the wire way and alignment hole which were previously prepared. Typical layout of backbone harness is sketched in Fig. 4.

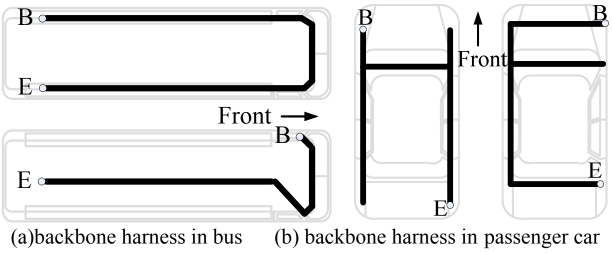

Figure 4. Typical layout of backbone harness in bus and passenger car.

As is shown in Figure 4, the most common backbone layout in bus can be depicted as "U" form and "L" form in bus, while "H" and "E" in passenger car, because they look like the corresponding letter from the top view. The "U" and "H" form layout features one horizontal wire way cross over the dashboard together with two longitudinal wire way on both sides of the framework, while the "L" and "E" form takes one wire way and another wire way cross the dashboard. The backbone harness is for BDSN wiring. If we straighten the backbone harness from one end to another, the backbone harness becomes a trunk-branch structure with branches orthogonal to the trunk, as in Fig. 5.

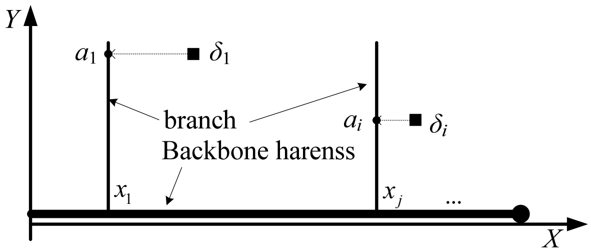

Figure 5. Straightened backbone harness.

As Fig. 5 shows, Cartesian coordinate system is defined: the origin point on the end of backbone harness and X axis superposed on the trunk. As Fig. 5 shows, the branches which are derived from the backbone trunk at (x_j, 0) may possibly be the SDSN harness trunks. Projecting the subnet EEDs to either trunk or branches of backbone harness, the subpoint which has the shorter projecting distance will be its substitute. The subnet EEDs δ_i is uniquely mapped to the point a_i, and thus 3-D physical location is degraded into 2-D location.

The EEDs in SDSN can be arranged according to their 2-D coordinates, the arrangement rule is: in ascendant order by X coordinates, or in ascendant order by Y coordinates when two EEDs meet the same X coordinates. So we have the ordered series $\boldsymbol{\Delta}$:

$$\Delta = \{\delta_1, \delta_2, ..., \delta_n\} \tag{2}$$

For any δ_i, $\delta_j \in \boldsymbol{\Delta}$, we have

$$i < j : x_i \le x_j, y_i \le y_j \tag{3}$$

And harness distance between δ_i and δ_j can be defined as:

$$d(i,j) = \begin{cases} |x_i - x_j| + |y_i + y_j|, x_i \ne x_j \\ |y_i - y_j|, x_i = x_j \end{cases} \tag{4}$$

In (4), (x_i, y_i) and (x_j, y_j) are the coordinates of δ_i and δ_j. $d(i,j)$ has the clear physical meaning: it is the practical length of wire between δ_i and δ_j.

For tth group $\boldsymbol{G}_t$, t=1,2,…k, the diameter of $\boldsymbol{G}_t$, is defined as:

$$D_t = \max(d(i,j)) \tag{5}$$

Where $d(i,j)$ is define in (4) with $\delta_i, \delta_j \in G_t$. D_t also has the clear physical meaning: it is the practical length of SDSN trunk harness.

B. Networking Schedulable Constraint

The network schedulable condition should be satisfied which make the network communication feasible. According to the proposed architecture, for each SDSN within EEDs in collection $\boldsymbol{G}_t$, signals on communication bus including the command from central coordinator and status from EEDs. The command signals from central coordinator are shared by all the SDSN EEDs and its attributes (for example, coding, period and so on.) are uniquely the same, while the status signals from each EED differ. The status signals can be sensor signals or diagnostic signals, which depend on types of EEDs.

Different signals take different length (in bit) and period. A catalog of typical signals of body EEDs in a prototype vehicle based on a modern urban bus is given in table 1.

In table 1, D stands for diagnostic signals while S for sensor signals. The actual EEDs consist of one or multiple units and the length should be the sum of the individual ones. In general, sensor signals are periodic while diagnostic signals are usually of event. To simplify bus load calculation, we treat all the status signals as periodic ones. For body EEDs, the period varies from 100 to 2000ms.

According to the specification of LIN, signals have to package into frames before transportation on the LIN bus, and the coding rule is defined usually on the application layer[14]. Signals from the same EED can be

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TABLE I.
SIGNAL LENGTH REQUIREMENT OF TYPICAL BODY EEDS

No.	Device	Type	Signal length
1	Resistive load	D	2 bit
2	Motor	D	2 bit
3	Switch	S	2 bit
4	Resistive sensor	S	8 bit
5	Voltage output	S	8 bit
6	Frequency output	S	8 bit
7	Frequency output	S	8 bit
8	Power-enable input	D	2 bit
9	Earth-enable input	D	2 bit
10	Analog input	D	2 bit
11	Serial bus communication	D	2 bit

packaged into one frame while signals from different EEDs should be in separate frames.

The length of frame in bytes depends on the total length of signals from one EED, at the same time, LIN specification recommends that the length of frame should be even and no more than 8. So the length of frame N_i from EED δ_i can be calculated as:

$$N_i = 2 \cdot \lceil (\lceil l_i / 8 \rceil) / 2 \rceil \quad (6)$$

l_i is the total length of signals from δ_i and N_i is the length in bytes. For all the body EEDs in the prototype vehicle, no one frame exceeds 8 bytes. Otherwise, the signals should be packaged into two separated frames.

The LIN frame transportation time consists of three parts: header transport time, response transport time and interval time between header and response. So time used to transport a frame with N bytes is:

$$t(N) = 1.4 \times [34 \cdot \tau_{bit} + 10 \cdot (N+1) \cdot \tau_{bit}] \quad (7)$$

In (7), τ_{bit} is the bit time under certain baud rate. In table 2 we calculated transfer time for each frame with different bytes under different baud rates in milliseconds.

TABLE II.
TRANSFER TIME FOR FRAMES WITH DIFFERENT BYTES UNDER DIFFERENT BAUD RATE (MS)

Baud rate(bps)	2Byte	4Byte	6Byte	8Byte
19200	4.7	6.1	7.6	9.0
9600	9.3	12.3	15.2	18.1
4800	18.2	24.6	30.4	36.2

For a LIN bus, schedulable condition means bus load should not exceed 100%, which is equal to:

$$S(G_t) = [\frac{t(N_c)}{T_c} + \sum_{\delta_i \in G_t} \frac{t(N_i)}{T_i}] \le 1 \quad (8)$$

Where N_c, T_c are the frame length and period of command from CCCU, and N_i, T_i are the frame length and period from δ_i.

C. Ordered-specimen with Limited Group Capacity

With the ordered series $\mathbf{\Delta}$ and SDSN harness definition, networking optimization problem can be converted to an ordered-specimen cluster analysis problem under restrained condition. According to the cluster analysis theory, we define the lost function L as:

$$L(b(n,k)) = \sum_{t=1}^{k} D_t \quad (9)$$

Where, $b(n, k)$ is the solution that n EEDs are divided into k groups. D_t is defined in (5). So the lost function L is the total length of the SDSN harnesses. So the SDSN networking optimization problem is to find the segmentation $b(n,k)$ on ordered series $\mathbf{\Delta}$ with the minimized lost function L. The SDSN networking optimization model is

$$\begin{cases} \min L(b(n,k)) = \sum_{t=1}^{k} D_t \\ \text{s.t. } S(G_t) \le 1, t = 1,2,...,k \end{cases} \quad (10)$$

Where $S(\boldsymbol{G}_t)\le 1, t=1,2,\dots,k$ is network schedulable condition defined in function (8), which keeps the SDSN communication feasible.

D. Solving Algorithm

The optimization model defined in (10) with restraint condition, which means the limited capacity clusters in the solution. So the ordinary solving algorithms, e.g. fisher algorithm, are not suitable for this problem. In this situation, problem's scale is limited, because EEDs' number in automobile is always limited, usually no more than one hundred. According to LIN specification, number in one network should not exceed 16, while system's economy becomes worse when the number goes down below 4. So global searching algorithm is adopted. We assign i_t to index of the last subnet EED in tth group $\boldsymbol{G}_t$, and network total number is m. So the possible solution can be noted as the division point vector $\boldsymbol{i} = [i_1, i_2, ..., i_m]$, forming the searching space $\mathbf{B} \in \mathbf{Z}^m$, which can be described as:

$$\mathbf{B} = \begin{cases} 4 < i_1 < 16 \\ i_1 + 4 < i_2 < i_1 + 16 \\ \dots \\ i_{t-1} + 4 < i_t < \min[(i_{t-1} + 16), N - 4] \\ \dots \\ i_m = n \end{cases} \quad (11)$$

With n: number of subnet EEDs. With the ideal condition of subnet EEDs individual busload uniform distribution in OES, we have the network number m as:

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$$m = \max(\lceil n/15 \rceil, \left\lceil \sum_{i=1}^{n} \frac{t(N_i)}{T_i} / (1 - \frac{t(N_c)}{T_c}) \right\rceil) \quad (12)$$

In fact, the ideal condition is usually unsatisfied and the actual number of networks is more than that calculated from (13). For every segment point, 12 times of calculation is required, so the complexity of the global search algorithm can be O(1.18^n). Number of subnet EEDs is limited and searching space shrank, which means numerical calculation is acceptable. The optimal solver process is as Fig. 6 shows.

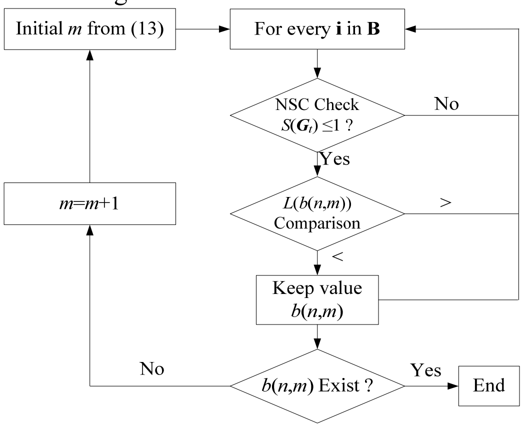

Figure 6. Solver algorithm process.

The solver process can be described as 4 steps:

- Step 1: calculate the initial network number m from function (13), and start the solver;
- Step 2: iterate i in space B. for every i, check the NSC (as function (8) described) and calculate the lost function. The initial lost function value can be the d(1,n). If the vector i passes the NSC check and its lost function value is smaller than the former one, keep i and the new lost function value;
- Step 3: If b(n,m) exists, we find the optimal solution;
- Step 4: If b(n,m) does not exist, increase network number m and repeat step 2~3 till the optimal solution is found;

III. Experiment and Application

The proposed system architecture and SDSN networking optimization method have been applied to two types of prototype vehicle, i.e. a mid-size concept car and a twelve-meter long urban bus. In the urban bus prototype, by digitalization of all the 85 EEDs, from the simple light to the complex air conditioning subsystem, and creating a DSN with 14 dedicated backbone EEDs and 71 subnet EEDs. Distribution of body EEDs in the prototype is sketch in Fig. 7.

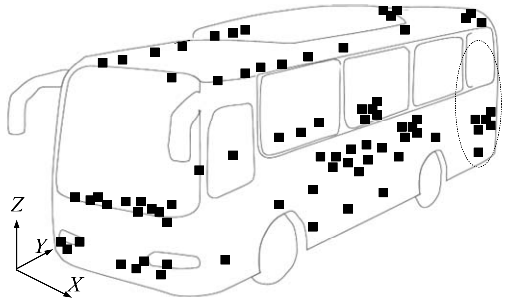

Figure 7. EEDs that scattered in the prototype bus

The SDSN EEDs scattered in top, front, button, back, inner and outer areas without any regularity. The Boundary of each area seems blurred with each SDSN carrying different amount of signals. So the proposed SDSN networking optimization method is implemented. According to the urban bus body structure, with dimensions 1198 by 250 by 375 in centimeter, the layout of backbone harness is done, with the length of 30 meters and 5 branches (see Fig. 8). SDSN EEDs' 2D coordinates are measured, based on which, the ordered series **Δ** is achieved. Base on the networking optimization method, modeling and calculation is done. The initial network number *m* is 5, the result with *m*=6 and 7 are as table 3~4 show.

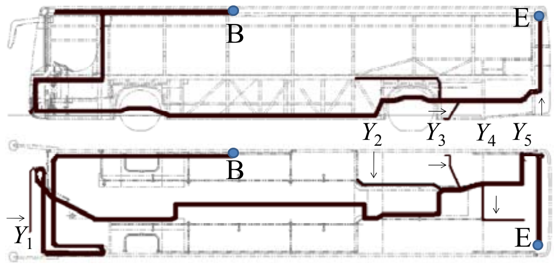

Figure 8. Backbone harness layout.

The prototype vehicle is based on an urban bus platform, with the consideration of system configurability and extendibility, the solution with 7 subnets is adopted. For every subnet, the SDSN harnesses are rerouted with its trunk superposed on the backbone harness. The SDSN subnet with EEDs in $\boldsymbol{G}_6$ are laid in battery chamber, and the harness is short and simple.

TABLE III.
Optimization Result with 6 Subnets

EEDs Group	G_1	G_2	G_3	G_4	G_5	G_6
Division Point	11	26	40	49	56	71
Num. of EEDs	11	15	14	9	7	15
Harness Length	5.7	4.7	6.0	0.4	1.4	6.1
Bus load (%)	42.6	44.9	96.7	69.	92.	62.

TABLE Iv.
Optimization Result with 7 Subnets

EEDs Group	G_1	G_2	G_3	G_4	G_5	G_6	G_7
Division Point	11	22	35	40	49	56	71
Num. of EEDs	11	11	13	5	9	7	15
Harness	5.7	3.4	3.8	0.7	0.4	1.4	6.1
Bus load (%)	42.6	42.6	43.7	91.5	69.4	92.6	62.5

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The substitution of the original conventional point to point electrical system with the proposed holo-distributed one significantly reduces the weight of the electrical system harness from 145kg to 70kg, the types of wires from 217 to 21, the types of interconnectors from 28 to 7, the number of cut-leads from 803 to 536, and the total amount of the interconnectors from 223 to 118, showing apparent advantage in harness cost and simplicity.

IV. Conclusions and Discussion

Architecture of holo-distributed system is the trend of next generation of automotive body electrical/electronic system. The system consists of digital signal network and power supply network, with requirement of digitalized electrical devices. Harness simplification can effectively done through sub digital signal network optimization.

3-D location can be degraded to 2-D location by projection to backbone's trunk or branches. Ordered specimen with limited group capacity partition method is suitable for optimization.

The holo-distributed automotive body electrical system requires the digitalization of the entire vehicle electrical system, which concerns not only the vehicle assembly factory but also the numerous supportive EED manufacturers. The compatibility of the digitalized EEDs from diverse manufacturers and standardization of the EED communication protocol are the key factors for the successful and effective application. Wiring harness is the least automated product among all the automobile electrical products. With the increasing cost of labor and copper material, harness simplification and standardization for automatic production will become more and more meaningful.

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