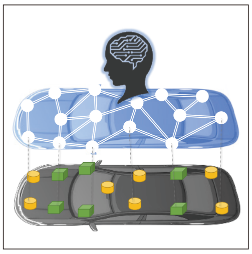

Architecture Verification Using Digital Engineering

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The automotive industry is becoming increasingly intellectualized through CASE (Connected, Autonomous, Shared, and Electric) innovations. While development times for in-vehicle systems are lengthening, products must be brought to the market quickly to remain competitive. We are making efforts to utilize digital engineering for design verification of in-vehicle systems in order to derive optimal architectures in a short period. We have applied mathematical optimization to the verification flow of the system architectures with the number of zone ECUs and the number of variations as parameters. This paper presents our efforts to shorten the verification time by combining the derived results with the response surface method, which predicts optimal conditions for the design parameters.

Keywords: CASE, architecture, mathematical optimization, response surface method

1. Introduction

In the automotive industry, technological innovation is accelerating in the area known as *connected, autonomous, shared, and electric* (CASE). In this context, there is a demand for further advanced in-vehicle systems, and the scale of in-vehicle system development is increasing each year. Meanwhile, it is necessary to shorten the development time and quickly bring superior products to market for enhanced corporate competitiveness. Therefore, active use of digital engineering including model-based development is promoted in automotive research and development to improve development efficiency and create innovations.(1)

To respond to diverse future needs, AutoNetworks Technologies, Ltd. utilizes digital engineering in assessing architectures and delivers proposals for auto manufacturers. This paper describes a type of architecture verification that uses mathematical methods in assessing architectures.

2. Study of Architectures

2-1 Overview of architectures

The term architecture means a design concept on which in-vehicle systems connecting electronic control units (ECUs), sensors, actuators, and other devices are based. To build an increasingly complex in-vehicle system comprising increasing ECUs, sensors, and actuators due to CASE, the importance of architecture in determining the configuration of these elements is increasing. Currently, most vehicles incorporate a dispersed architecture configuring ECUs for each function. However, it is expected in the future that the architecture will evolve into central-and-zone architecture (C&Z architecture) which consists of a central ECU concentrating control functions across multiple domains and zone ECUs*1 placed in each area of the vehicle.(2),(3)

2-2 Matters of C&Z architecture

In C&Z architecture, the control and application functions previously located in each ECU are separate from the input and output functions; C&Z architecture consists of a central ECU concentrating control and application functions, and zone ECUs in which input and output functions are concentrated (hereinafter referred to as "function allocation").

By concentrating functions into a central ECU, it becomes possible to efficiently update the in-vehicle system software over the air (OTA)*2 which has been difficult with conventional architecture. Moreover, for zone ECUs, their hardware will be updated with only a small change as increasing ECUs and sensors are connected in the vehicle on an area-by-area basis.

However, a cost advantage may not be ensured for the entire system unless an appropriate number of zone ECUs are placed in suitable locations according to the integrated functions. For example, an increased number of zone ECUs placed in each vehicle area will reduce the overall wiring harness length; on the other hand, the greater number of zone ECUs may cause the development time to increase and workability during mounting in the vehicle to decrease.

Additionally, zone ECU variations should be considered with the quantity and locations of the mounted zone ECUs. The equipment and input/output functions required in an automobile differ with vehicle model and grade. Accordingly, in general, multiple ECU variations have been developed and ECU variations assigned several part numbers have been designed to accommodate several tens of vehicle models and grades. A reduced number of variations towards design commonality does reduce the development period; however, this results in excessive product specifications with vehicles with fewer functions. Conversely, leaning towards individual optimal designs would produce relatively waste-free product specifications but at the cost of increased development period in proportion to the number of variations.

Assessment of C&Z architectures involves multiple design parameters, such as the number of units mounted and the number of variations, making it necessary to reach the best solution through the verification of a huge number of architecture patterns. Even with two zone ECUs, changes in the locations of zone ECUs will affect the results of wiring harness length verification, as illustrated by the parallel coordinate plots in Fig. 1.

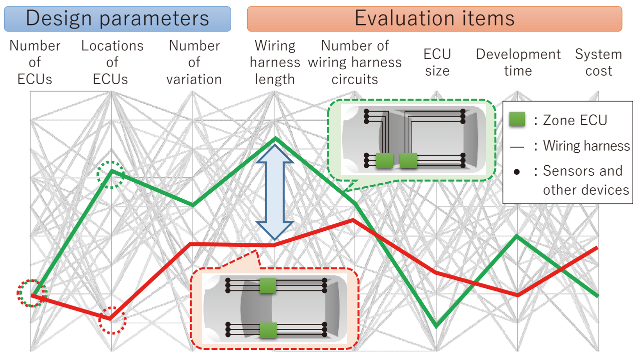

Fig. 1. Parallel coordinate plots of architecture verification results

3. Architecture Verification

3-1 Verification flow overview

For this verification, a flow was formed to derive an optimal architecture using, as inputs, vehicle and parts information such as locations where zone ECUs can be mounted and wiring harness routing, using the number of zone ECUs and the number of variations as design parameters, and establishing combinations of design parameters as verification patterns.

First, vehicle and components information was input to generate an architecture verification pattern. This was followed by deriving, the zone ECU function allocation and mounting locations based on the generated verification pattern. That would minimize the weighted sum of the number of electronic components in zone ECUs, the development scale, and the overall wiring harness length. Next, the required number of pins was calculated based on the number of input and output functions of zone ECUs, and a connector that would minimize the number of unused pins was selected from available connectors. According to the results of this operation, calculations were conducted to determine the overall wiring harness length and other evaluation items. At this point, a configuration was developed to enable the optimal architecture to be derived for each verification pattern by applying mathematical optimization to the derivation of function allocation and mounting locations and to the selection of connectors.

Although the verification flow could reach an optimal solution through mathematical optimization, it had a drawback in that it required a tremendous amount of time because there were repeated optimization calculations with an increasing number of verification patterns for the derivation of function allocation and mounting locations and the selection of connectors. Our solution to this challenge is to reduce the calculation time required for the overall verification flow using the response surface method (RSM) to reduce verification patterns. We added new processes to the validation flow. After evaluating all generated patterns, we generated approximate models, verified the accuracy of the approximate models, and added additional verification patterns if the accuracy was insufficient. These steps are effective for drafting an optimal architecture through a small number of attempts (Fig. 2).

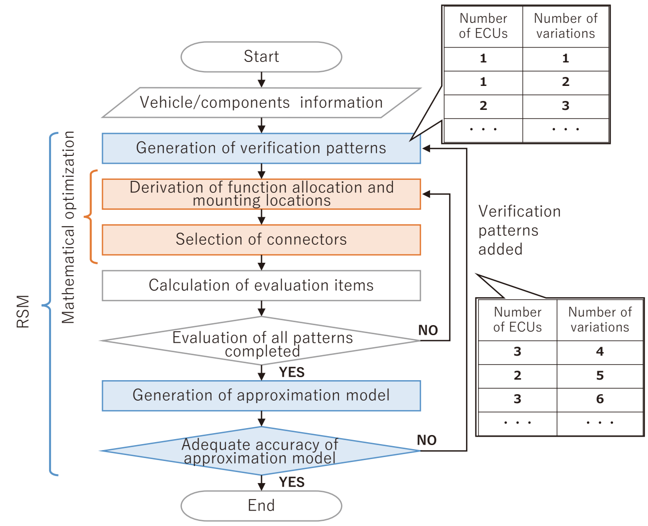

Fig. 2. Verification flow

3-2 Application of mathematical optimization

To optimize the derivation of function allocation and mounting locations as well as the selection of connectors for zone ECUs, the formulation is carried out as an integer programming. Table 1 shows the sets used for the derivation of capability allocation and mounting locations, Table 2 shows the decision variables, and Table 3 shows the constants. Using these elements will enable formulation, as illustrated below.

Table 1. Sets

Subscript	Description
G	Set of vehicle model/grade
E	Set of zone ECU
V	Set of variation of zone ECU
P	Set of electronic components
C	Set of functions
L	Set of mounting location of zone ECU
A	Set of location of in-vehicle equipment
D	Set of route of wiring harness

Table 2. Decision Variables

Decision variable	Description
$x^{i}_{g,e,p} \in \mathbb{Z}_{\geq 0}$	Number (nonnegative integer) of electronic components $p \in P$ mounted in zone ECU $e \in E$ of vehicle model/grade $g \in G$
$y_{g,c,e} \in \{0,1\}$	1 where function $c \in C$ of vehicle model/grade $g \in G$ is placed in zone ECU $e \in E$; 0 for other cases
$y_{g,c,e,l} \in \{0,1\}$	1 where function $c \in C$ of vehicle model/grade $g \in G$ is placed in zone ECU $e \in E$ in mounting location $l \in L$; 0 for other cases
$y_v \in \{0,1\}$	1 where variation $v \in V$ is valid; 0 for other cases
$y_{g,e,l} \in \{0,1\}$	1 where zone ECU $e \in E$ of vehicle model/grade $g \in G$ is placed in mounting location $l \in L$; 0 for other cases

Table 3. Constants

Constant	Description
w	Weighting factor of objective function $w = \{w_1, w_2, w_3\}$
c^d	Development scale per part number
$b_{g,p,c}$	Value determined according to vehicle model/grade $g∈G$, electronic components $p∈P$, and function $c∈C$
$b_{g,c,a}$	Value determined according to vehicle model/grade $g∈G$, function $c∈C$ and location of in-vehicle equipment $a∈A$
$b_{l,a,d}$	Value determined according to the location of in-vehicle equipment $a∈A$, mounting location of zone ECU $l∈L$, and route $d∈D$
$d_{l,a}$	Route length between the location of in-vehicle equipment $a∈A$ and mounting location of zone ECU $l∈L$
$s_{g,c}$	Cross-sectional area of wiring harnesses connecting in-vehicle equipment and input/output circuits linked to function $c∈C$ of vehicle model/grade $g∈G$
$s_{g,d}^{max}$	Maximum cross-sectional area of wiring harness on route $d∈D$ of vehicle model/grade $g∈G$
$r_{g,d}$	Filling rate of wiring harness on route $d∈D$ of vehicle model/grade $g∈G$
T^{min}, T^{max}	Minimum and maximum numbers of electronic components that can be mounted in a zone ECU

Objective functions:

$$\min\ w_1 f_1 + w_2 f_2 + w_3 f_3 \quad (1)$$

$$f_1 = \sum_{g∈G}\sum_{e∈E}\sum_{p∈P}\left(x_{g,e,p}^i - \sum_{c∈C}\left(b_{g,p,c}\cdot y_{g,c,e}\right)\right) \quad (2)$$

$$f_2 = \sum_{g∈G}\sum_{c∈C}\sum_{l∈L}\sum_{a∈A}\left(d_{l,a}\cdot b_{g,c,a}\cdot y_{g,c,e,l}\right) \quad (3)$$

$$f_3 = \sum_{v∈V} c^d \cdot y_v \quad (4)$$

Constraints:

$$\sum_{l∈L} y_{g,e,l} = 1 \quad (5)$$

$$\sum_{e∈E} y_{g,e,l} \le 1 \quad (6)$$

$$y_{g,c,e,l} \le y_{g,e,l} \quad (7)$$

$$\sum_{c∈C} y_{g,c,e} \ge 1 \quad (8)$$

$$\sum_{e∈E} y_{g,c,e} = 1 \quad (9)$$

$$\sum_{e∈E}\sum_{c∈C} y_{g,c,e,l} = 1 \quad (10)$$

$$\sum_{c∈C}\left(b_{g,p,c}\cdot y_{g,c,e}\right) \le x_{g,e,p}^i \quad (11)$$

$$\sum_{c∈C}\left(s_{g,c}\cdot \sum_{l∈L}\sum_{a∈A}\left(b_{g,c,a}\cdot b_{l,a,d}\sum_{e∈E} y_{g,c,e,l}\right)\right) \le r_{g,d}\cdot s_{g,d}^{max} \quad (12)$$

$$T^{min} \le \sum_{p∈P} x_{g,e,p}^i \le T^{max} \quad (13)$$

Equation (1) is the objective function and represents the weighted sum of Eqs. (2) to (4). Equation (2) represents the excess number of electronic components for the intended vehicle model/grade; Eq. (3), the overall length of wiring harnesses; Eq. (4), the development scale proportional to the number of variations. By multiplying these equations by weighting factors w_1 to w_3, an objective functions used to conduct quantitative evaluation of system configurations consisting of zone ECUs and wiring harnesses were prepared. Equation (5) represents a constraint intended to restrict the mounting of each zone ECU to a single location; Ineq. (6), a constraint intended to limit the number of zone ECUs that can be mounted in each mounting location to not more than one; Ineq. (7), a constraint intended for a condition of matching between variables; Ineq. (8), a constraint intended to allocate one or more functions to each zone ECU; Eqs. (9) and (10), constraints to ensure that each capability will be allocated to any one of the zone ECUs; Ineq. (11), a constraint under which the number of electronic components mounted in a zone ECU is more than the number of electronic components; Ineq. (12), a constraint related to compatible diameters of wiring harnesses on routes; Ineq. (13), a constraint on the number of electronic circuits with the ease of mounting zone ECUs taken into account. To conduct formulation for the selection of connectors, similar steps were followed as integer programming, although details are omitted due to paper length limitations.

3-3 Application of RSM

The use of RSM is intended to derive the optimal architecture with the fewest possible number of attempts. RSM is the approach to finding the most suitable conditions by generating an approximation model from experimental data. To generate an accurate approximation model, a large number of samples are required. For this reason, Latin hypercube sampling*3 is used to make sampling efficient. As shown with the verification flow, the minimum number of samples S required to generate a highly nonlinear approximation model can be estimated by the following inequality using the number of design variables N.[4]

$$S \ge (N+1)(N+2)/2 \quad (14)$$

Additionally, radial basis function network*4 was employed as a regression model for RSM because it is capable of accurately approximating nonlinear phenomena.

4. Verification Results

The results of architecture verification conducted using the verification flow and the verification time reduction effect of RSM are reported below.

The preconditions for the verification were: the sum of input and output functions of zone ECUs, 573; the number of vehicle models, six; the maximum number of zone ECUs mounted in each vehicle model, three; the maximum number of zone ECU variation part numbers, six. For input and output functions, standard functions provided in all six vehicle models and optional functions provided in some vehicle models were devised, assuming the number of functions differing with vehicle models. According to Ineq. (14), the number of samples was set to increase in increments of 20 from the initial number of 40. In these steps, we used Gurobi Optimizer, which is an optimization solver, to carry out mathematical optimization calculations, and modeFRONTIER, which is optimization software, to couple individual processes in the verification flow and to generate an approximation model.

The verification results revealed that under the current preconditions, the optimal solution is to use six part numbers as a total number of variations, placing one zone ECU at the left end of the dashboard*5 for three vehicle models with fewer features, and two zone ECUs—one each at either end of the dashboard—for three vehicle models with more features. The use of mathematical optimization was effective in deriving parts configurations that would enable the excess number of electronic components in zone ECUs to be reduced by approximately 17% compared to manual designing.

To verify the accuracy of the approximation model, first, the optimal solution was worked out in advance through verification using all verification patterns. Then, we compared the error between the optimal solution and the evaluation value calculated using the design parameters obtained from the approximate model. Table 4 shows the comparison results and the approximation model accuracy evaluation results produced using a coefficient of determination and a mean absolute percentage error. Using 100 samples, it was possible to verify that the rating of the approximation model agreed with the optimal solution, only requiring an amount of verification time approximately 80% shorter than using mathematical optimization alone.

Table 4. Model Accuracy Verification Results

	Number of samples				
	40	60	80	100	120
Difference from optimal solution [%]	4.52	3.39	3.39	0	0
Coefficient of determination	0.721	0.796	0.857	0.874	0.906
Mean absolute percentage error [%]	3.68	2.9	2.33	1.91	1.48

The generated approximation model is shown in Fig. 3, in which the number of zone ECU variations is plotted on the x-axis, and the number of zone ECUs mounted in the vehicle model with the most features is plotted on the y-axis. The chart reveals that the lowest cost is obtained when the number of variations, or part numbers, is six and the number of units installed is two.

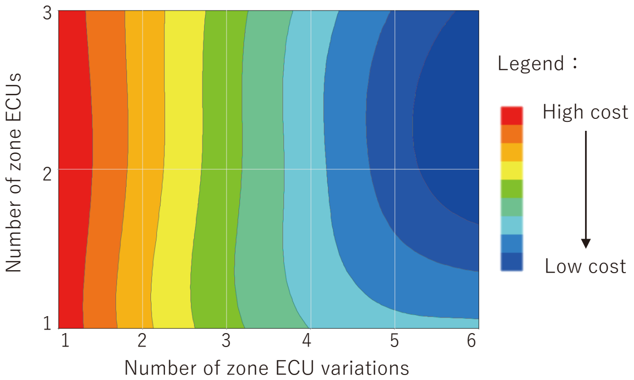

Fig. 3. Approximation model using 100 samples

5. Conclusion

This paper presented architecture verifications using mathematical optimization and RSM and the derivation of better architecture configurations in a short period of time.

Going forward, we will continue to develop and utilize digital engineering to complete the large-scale verifications required in architecture studies within a short period of time.

• Gurobi Optimizer is a trademark of Gurobi Optimization, LLC.
• modeFRONTIER is a trademark or registered trademark of ESTECO SpA.

Technical Terms

*1 Zone ECU: An electronic control unit placed in each vehicle area, such as front, rear, right, and left. Major functions of zone ECUs include power supply, power output to loads, and signal inputting.

*2 OTA: Data transmission/reception via wireless communication.

*3 Latin hypercube sampling: The technique of sampling experimental points in an input parameter space for achieving a frequency of occurrence comparable to a given probability density distribution.

*4 Radial basis function network: A type of neural network designed to express nonlinear functions using the weighted sum of radial basis functions.

*5 Dashboard: The vehicle interior feature located below the windshield and in front of the driver's and passenger's seats.

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