

Design Information Management of an On-Line Electric Vehicle Using Axiomatic Design

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ABSTRACT

Axiomatic design is utilized to identify the design characteristics of an On-Line Electric Vehicle and to manage the design information. The On-Line Electric Vehicle, which is being developed at the Korea Advanced Institute of Science and Technology, is a different concept of an electric vehicle from conventional electric vehicles which use the electric power of a charged battery(s). It is operated by an electric power supplied by the contactless power transmission technique between the roadway side and the vehicle. In other words, the power is transmitted based on the principle of an electric transformer. The On-Line Electric Vehicle can overcome the limitations of conventional electric vehicles such as the weight of the battery and driving distance problems. Because designers have little experience and knowledge about the On-Line Electric Vehicle in the developmental stage, an appropriate design guide is needed. The axiomatic approach is employed for the design process. Functional requirements (FRs) and design parameters (DPs) are identified, and the design matrices are defined. The entire design process is decomposed into a hierarchy and the FRs and DPs are defined based on the rule that is recommended in the axiomatic approach when using the Independence Axiom. An appropriate design guide for the On-Line Electric Vehicle is proposed based on the design information and the design guide makes the designers manage the design process of the vehicle more efficiently and systematically.

INTRODUCTION

Increasing concerns on the impact of global warming and decreasing fossil fuel stocks have led to increased interest in eco-friendly vehicles to replace the internal-combustion engine vehicle [1, 2]. There are many types of eco-friendly vehicles including clean-diesel, hybrid, battery electric and hydrogen engine vehicle [3]. Among these vehicles, a battery

electric vehicle is one of the leading candidates to replace the internal-combustion engine vehicle. The conventional electric vehicle was developed at the end of the 19th century before the internal-combustion engine vehicle but disappeared at the start of the 20th century. This was due to some limitations including driving distance on a single charge and the heavy weight and the high cost of the battery [4]. Recently the battery electric vehicle has been reconsidered as an alternative for the internal-combustion engine vehicle because of its zero-emission characteristics. However, the current type still has the same problems as those of the old type although the problems have been considerably improved.

To overcome the limitations of the conventional electric vehicle, the On-Line Electric Vehicle (OLEV), an electric vehicle which has a different concept from the conventional electric vehicle, is being developed at the Korea Advanced Institute of Science and Technology (KAIST). The On-Line Electric Vehicle adopts a contactless power transmission technique, which is based on the Faraday's law of electromagnetic induction, to obtain electric power to operate the vehicle component such as a driving motor, power steering motor and other electric/electronic devices. Electric power is transmitted from the roadway devices, which are buried under the road, to the vehicle by the contactless power transmission technique and the transmitted electric power is used to operate the On-Line Electric Vehicle. The On-Line Electric Vehicle can overcome the limitations of conventional electric vehicles including driving distance, weight and cost with the power transmission technique.

Although there are many researches on the technologies of the current vehicle, research on the design characteristics and process is insufficient to design the On-Line Electric Vehicle. Without research for the design, the vehicle would be designed in a heuristic process with the designer's intuitions

and experiences. Although intuitions and experiences are helpful to design products, the heuristic design process has some difficulties. It is difficult to identify causes when product performance has some defects and many feedback processes can be required, which make the process inefficient and time-consuming [5, 6]. To overcome these difficulties, research for the design should be performed to identify the design characteristics and define the design sequence of the On-Line Electric Vehicle.

In this paper, the Independence Axiom of the axiomatic design theory is utilized to identify the design characteristics of the On-Line Electric Vehicle. Axiomatic design is a design theory proposed by N. P. Suh [6,7,8] and provides designers with a theoretical background to generate conceptual design and to determine detailed design of products. Axiomatic design also provides good design analysis tools based on the relationships between the functional requirements and the design parameters [9-10]. The functional requirements and the design parameters are established and the relationships between them are investigated to identify the design characteristics of the On-Line Electric Vehicle. Detailed design analysis of a roadway system of the On-Line Electric Vehicle is performed and the results are discussed.

AXIOMATIC DESIGN [5,6,7,8,9,10,11]

Axiomatic design is a design methodology that was proposed by N. P. Suh [6,7,8,9,10]. It gives a theoretical background to design products in an objective and rational way. Design is defined as a continual interplay between ‘what we want to achieve’ and ‘how we want to achieve it.’ ‘What we want to achieve’ is called functional requirements (FRs). To satisfy the functional requirements in a functional domain, the design parameters (DPs) must be selected in a physical domain. Design is defined as the mapping process between the functional requirements and the design parameters. There can be multiple design solutions because the mapping process may depend on a designer's individual experience and/or creativity.

The domains and mapping processes are illustrated in Fig. 1. Based on the customer needs, design engineers define the functional requirements in the functional domain and the constraints. And then, the design parameters are determined in the physical domain to satisfy the corresponding functional requirements. The functional requirements and the design parameters are decomposed into a hierarchy until the designers achieve a complete detailed design or until the design is completed. Hierarchy is generated by the zigzagging process. The functional requirements of the sub-level are determined by the characteristics of the design parameter in the upper-level and the design parameters of the sub-level are selected to satisfy the corresponding functional requirements at the same level in the zigzagging process.

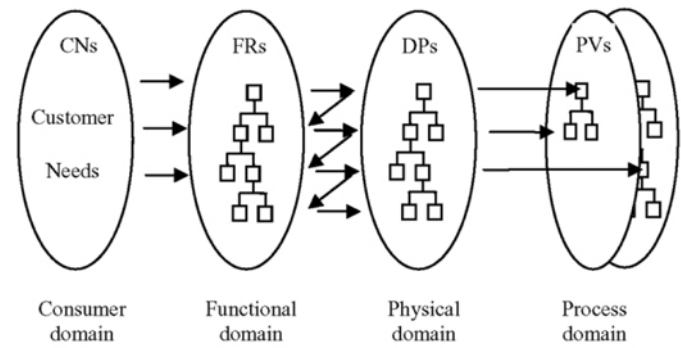


Fig. 1. Concept of design, mapping and spaces

In axiomatic design, there are two design axioms. One is the Independence Axiom and the other is the Information Axiom, but only the Independence Axiom is utilized in this research. The Independence Axiom deals with the relationship between the functional requirements and the design parameters. As mentioned earlier, design is defined as the mapping process between the functional requirements and the design parameters. This relationship can be characterized as follows:

$$\{\text{FR}\} = [A]\{\text{DP}\} \quad (1)$$

The characteristics of a design are represented by a set of independent functional requirements and these may be expressed by a vector $\{\text{FR}\}$ with m components. The design parameters also constitute a vector $\{\text{DP}\}$ with n components. $[A]$ is the design matrix which relates the components of the functional requirement vector to the components of the design parameter vector. The design matrix $[A]$ can be written as

$$[A] = \begin{bmatrix} A_{11} & A_{12} & \cdots & A_{1n} \\ A_{21} & A_{22} & \cdots & A_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ A_{m1} & A_{m2} & \cdots & A_{mn} \end{bmatrix} \quad (2)$$

Table 1 shows three cases of the design according to the characteristics of the design matrix. When the design matrix $[A]$ is diagonal, each of the functional requirements can be satisfied independently by a corresponding design parameter. Such a design is called an uncoupled design. When the design matrix is triangular, the independence of the functional requirements is guaranteed if and only if the design parameters are determined in a proper sequence and such a

design is called a decoupled design. For all other matrix types, it is called a coupled design.

Based on the difference in the numbers of functional requirements and design parameters, there are three cases of design such as the ideal, redundant and insufficient designs as shown in Table 2. When the number of functional requirements is equal to the number of design parameters, the design is an ideal design, provided that the Independence Axiom is satisfied. A design is redundant if the number of design parameters is larger than the functional requirements and the design is a insufficient design if the number of design parameters is smaller than the functional requirements. A redundant design may or may not violate the Independence Axiom. The Independence Axiom encourages an ideal design rather than the redundant or insufficient design. Designers should develop designs to create a diagonal or a triangular design matrix when there are multiple FRs to be satisfied.

ON-LINE ELECTRIC VEHICLE

The On-Line Electric Vehicle is a type of vehicle which uses electric power. There are two types of electric vehicles; the conventional electric vehicle and the light-rail vehicle. The conventional electric vehicle, which uses charged batteries, does not need a special road and/or highway but has some limitations such as driving distance on a single charge, the heavy weight and the high costs of batteries [12]. A light-rail vehicle, which uses electric power supplied by contact between electric wires and pantographs, does not have the limitations of the conventional electric vehicle. However, it requires special rail road and infrastructures for driving which causes visual pollution [13]. Visual pollution means unattractive and man-made visual elements that a person does not feel comfortable to look at [14]. The On-Line Electric Vehicle overcomes the problems of the conventional electric vehicle and the light-rail vehicle by using contactless power transmission technique which uses a buried roadway system and pickup devices on the vehicle.

Table 1. Relationship between FRs and DPs

	Uncoupled	Decoupled	Coupled
	design	design	design
Design	$\begin{bmatrix} A_{11} & 0 \\ 0 & A_{22} \end{bmatrix}$	$\begin{bmatrix} A_{11} & 0 \\ A_{21} & A_{22} \end{bmatrix}$	$\begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix}$
Matrix			

Table 2. Ideal, redundant and coupled (insufficient) design

	Design Equation
Ideal design	$\begin{Bmatrix} FR_1 \\ FR_2 \end{Bmatrix} = \begin{bmatrix} A_{11} & 0 \\ 0 & A_{22} \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \end{Bmatrix}$
Redundant design	$\{FR_1\} = [A_{11} \quad A_{12}] \begin{Bmatrix} DP_1 \\ DP_2 \end{Bmatrix}$
Insufficient design	$\begin{Bmatrix} FR_1 \\ FR_2 \end{Bmatrix} = \begin{bmatrix} A_{11} \\ A_{21} \end{bmatrix} \{DP_1\}$

Some researches have been performed to use the contactless power transmission technique for vehicles. One approach is the Roadway Powered Electric Vehicle (RPEV), a vehicle developed in the Program for Advance Transit and Highways (PATH) project from 1989 to 1996 by California University, USA [15]. However, it was not commercialized because of some problems such as power transmission efficiency and economical efficiency. The other approach focuses on the contactless power transmission technique in Auckland University, New Zealand [16] but the results are applied to a small remote control (RC) car. There are some other researches that used the contactless power transmission technique [17,18,19] but they could not commercialize the vehicle until now. The On-Line Electric Vehicle also uses the contactless power transmission technique but has higher power transmission efficiency and economical efficiency compared to other approaches.

The On-Line Electric Vehicle system is composed of a roadway system and an electric vehicle which has on-board pickup devices as illustrated in Fig. 2. The roadway system consists of electric wires and ferrite cores, and generates a strong magnetic field using electric current from the inverter which converts the general 60 Hz three phase alternating current (AC) to a single phase high frequency alternating current. Pickup devices also consist of electric wires and ferrite cores, and induced current are generated in it by the Faraday's law of electromagnetic induction when the vehicle is moving and when it is stationary. The induced current is used to operate the driving motor and other electric/electronic devices, and to charge backup batteries. Although batteries are not required in the On-Line Electric Vehicle theoretically, the backup batteries, 20 percent capacity batteries compared to the conventional electric vehicle, only exist for an emergency when it is impossible to supply electric power from the roadway system.