Design-in of Reliability through Axiomatic Design

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KEYWORDS

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ABSTRACT

To completely meet the requirements of reliability design in the product designing, an axiom-based Design-in Reliability approach is proposed. In light of the axiomatic design principles, products are designed preliminarily to establish their functional requirements. According to these, functions preserving requirements are augmented, which constitute a Functional Requirement Preserving domain included in functional domain, and derives the parameterized solution for reliability design systematically. Subsequently, the design parameters are augmented and optimized to achieve the functions preserving requirements. Mapping model of the augmented functional domain and the physical domain is established. And a solutions evaluation approach based on Independence Axiom is proposed. Ultimately, via identifying the potential failure modes from the perspective of the disappearance or reduction of functions preserving capability, a control process is elaborated to mitigate the failure modes on the basis of independence axiom and logic decision in order for the reliability requirements to be implemented. Being exemplified by the design of a temperature sensor, the present study demonstrates that all approaches are feasible, efficient, and could be applied in real engineering scenarios.

Introduction

As an optimum approach for product design, reliability design is to minimize the products' flaws (Huang and Zhang, 2009; Wang *et al.*, 2010; Xiao *et al.*, 2012). Its core idea is to progressively understand the loads and stresses of each component, gradually recognize the failure modes and mechanism, actively eliminate the exposed failure modes or reduce the occurrence probabilities, and narrow the uncertainties and satisfy the reliability requirements (GEIA-STD-0009, 2009). The traditional technology of reliability design, being more dependent on "experience", often make it difficult for the results to be evaluated directly as they are relatively implicit (Michael , 2009; Yan, *et al*., 2011; Zhao, *et al*., 2012). Thus, it is difficult or even impossible to compensate for or evade the shortcomings of a poor design concept developed in the early stages of the design process (Diyar, *et al*., 2011). Currently, reliability test is the main method for evaluation, but it could be carried out until the prototypes are manufactured, which is time-consuming and is prone to redesigning (Yao, *et al*., 2012). Although a new approach through simulation has been proposed recently, it is not applicable to system-level products for its complexity. All the deficiencies in those methods restrain the application and development of reliability technology in engineering practices (Gong , *et al*., 2012; Li, *et al*., 2011).

Orienting to product development processes, professor Nam Pyo Suh developed Axiomatic Design (AD) principles (Pyo, 1990), which laid a scientific foundation for designers, especially in the design processes of large system design (Suh, 1995; Suh, 2001), software design (Suh, *et al.*, 2000; Suh, 2001), manufacturing system design (Suh, 2001; Kulak, *et al.*, 2005), human–machine systems (Helander, 2007), materials and materials-processing (Nakao, *et al.*, 2007; Kulak, *et al.*, 2010), product design (Kulak, *et al.*, 2010; Tang, *et al.*, 2007), decision making (Kulak , *et al.*, 2010; Celik, *et al.*, 2009), safety-critical system (Ahmed , *et al.*, 2007), and supply chain management (Kulak , *et al.*, 2010; Schnetzler, *et al.*, 2007). These principles are widely used to solve various design problems and provide better design solutions in the shortest term as they offer a systematic research process in a design space which becomes complicated with customer needs. Also, the fact that they can be generalized to different design areas renders them even more effective and powerful.

However, how to apply the principles to achieve the object of "Design-in of reliability" still needs further studies. The present research thus proposes an approach in which engineers could determine explicit reliability requirements of the products simultaneously with the applications of AD principles for product design, analyze failures that cause difficulties for the realization of reliability thoroughly, and take measures to mitigate them.

Product Design through Axiomatic Design Principles

(1) Design Decomposition

A design description usually consists of multiple abstraction levels with the higher levels being more abstract and the lower levels more detailed. At each level, there is a set of functional requirements (FRs). To decompose this set of FRs, the designer needs to identify the set of design parameters (DPs) at this level. Such decomposition process, which alternates between design domains, is referred to as the 'zigzagging process' (see figure 1). In this process, the lower-level FRs are consistent with the DPs chosen and its parent FR (Suh, 2001). The mapping between all the upper-level FRs and DPs has to be realized before these FRs and DPs can be decomposed to the lower-level FRs and DPs. This progressive process could be optimized hierarchically.

In figure 1, the mapping between all the same-level FRs and DPs can be mathematically expressed as

$$\begin{bmatrix} \mathbf{FR}_1 \\ \mathbf{FR}_2 \\ \vdots \\ \mathbf{FR}_n \end{bmatrix} = [\mathbf{A}]_{n\times d} \begin{bmatrix} \mathbf{DP}_1 \\ \mathbf{DP}_2 \\ \vdots \\ \mathbf{DP}_d \end{bmatrix} \quad (1)$$

where $[\mathbf{FR}_1 \ \ \mathbf{FR}_2 \ \ \cdots \ \ \mathbf{FR}_n]^{\mathrm{T}}$ is the second level functional requirement vector; $[\mathbf{A}]_{n\times d}$ is the design matrix that characterizes the design. Each entry a_{ij} of $[\mathbf{A}]_{n\times d}$ relates the ith FR to the jth DP, denoted by $a_{ij}=\partial \mathrm{FR}_i/\partial \mathrm{DP}_j$. n does not have to be equal to d, namely during the decomposition process, the design matrix developed may not be square; and $[\mathbf{DP}_1 \ \ \mathbf{DP}_2 \ \ \cdots \ \ \mathbf{DP}_d]^{\mathrm{T}}$ is the second level design parameter vector.

(2) Design Axioms

There are two design laws in the form of axioms: the Independence Axiom and the Information Axiom.

(A) The Independence Axiom states that the independence of functional requirements (FRs) must always be maintained, where FRs are defined as the minimum set of independent requirements that characterize the design goals (Kulak and Kahraman, 2010). In order to satisfy the Independence Axiom, [A]n×d matrix should have an uncoupled or decoupled design, namely the [A]n×d matrix should be square and must be diagonal or triangular.

(B) The Information Axiom states that, among the design solutions that satisfy the independence axiom, the best solution is the one that has the lowest information content. The paper conforms to the Independence Axiom only.

(3) A Case Study of Temperature Sensor

The main functional requirements of a temperature sensor (TS) are to monitor the temperature of its installation environment in real-time (Anderson, 2012). The aim is to prevent accidents caused by over rising temperatures. Therefore, two lower-level functional requirements could be determined: sensing the temperature (-55~125) of its installation environment in real-time and outputting the temperature information (stimulating and transmitting the electrical signals of temperature). Each one should be mapped to one design parameter at least. We choose a thermistor which could sense the environmental temperature using the functions of resistance and temperature, and an electrical circuit as its stimulating and transmitting unit. figure 2 shows the first-level decomposition of FRs and DPs for TS.

The relationship between FRs and DPs for TS is mathematically expressed as

$$\begin{bmatrix} FR_{R1} \\ FR_{R2} \end{bmatrix} = \begin{bmatrix} X & 0 \\ 0 & X \end{bmatrix} \begin{bmatrix} DP_1 \\ DP_2 \end{bmatrix} \quad ((2)$$

where FR_{R1} is sense the temperature; FR_{R2} denotes stimulate and transmit the electrical signals of temperature; DP_1 is thermistor; DP_2 denotes electrical circuit for stimulating and transmitting the signals.

The decomposition in axiomatic design principles is an ideal process. In practice, there are several reasons why a system may be coupled, for example, implicit FRs and customer needs, complexity of system components, system constraints (Helander, *et al.*, 2007). The AD principles did not give an approach to achieve the functional requirements sufficiently. Although the functional requirements are validated independent through the independence axiom, it is still not a good solution because of its insufficiency. As the previous example exhibits, the solution merely satisfies the fundamental requirements: measuring the temperature. It does not take stability and accuracy into account.

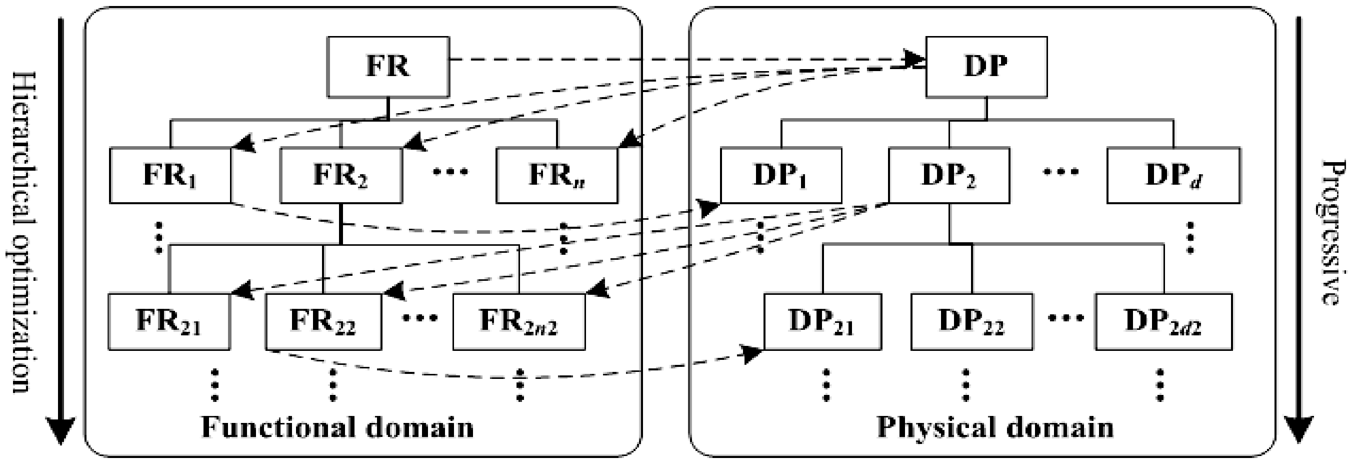

Figure 1: Zigzagging to Decompose FRs and DPs

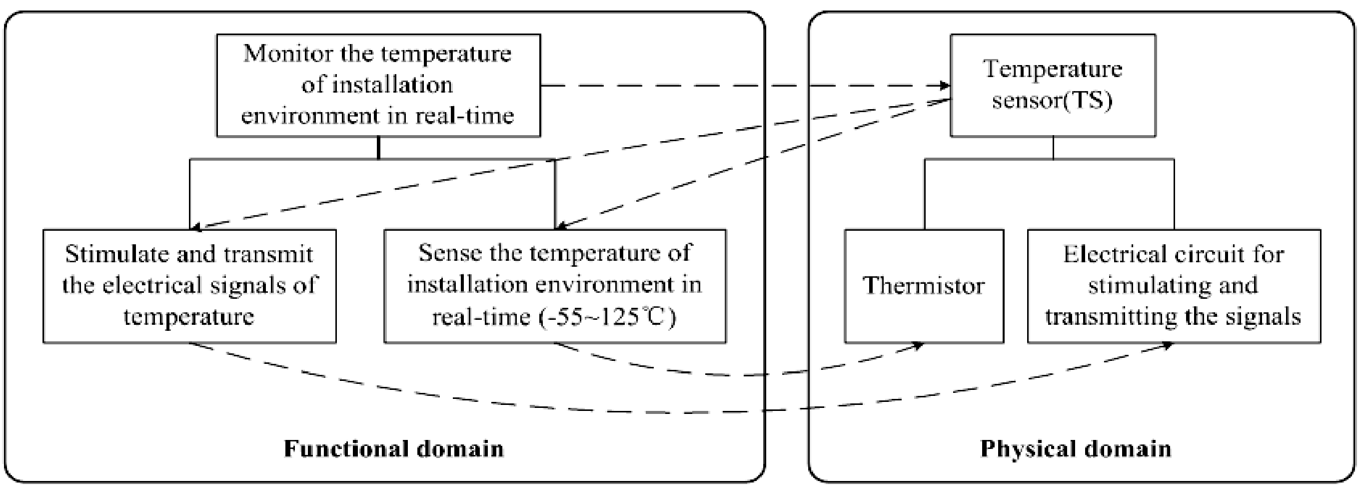

Figure 2: Zigzagging Diagram for TS

Augmentation Process of Functional Domain Considering Reliability Requirements

In the axiomatic design principles, functional domain is a unified concept. To embody the reliability requirements systematically, the functional requirements should be subdivided into functions realization requirements and functions preserving requirements. Then the functional domain should be further divided into Functional Requirement Realization domain (FRRD) and Functional Requirement Preserving domain (FRPD) accordingly.

(I) Functional Requirement Realization domain (FRRD). The functions which embody the conventional requirements only, and are designed to satisfy the demands for customers.

(II) Functional Requirement Preserving domain (FRPD). The requirements are used to preserve all the functions in functional domain under the effects of all uncertain factors (the paper takes functions preserving requirements of the product into consideration only, excluding the functions preserving ability provided by external systems).

A function realization requirement may be mapping to one or more functions preserving requirements. Similarly, a function preserving requirement could be preserving one or more functions realization requirements. The decomposition is shown in Figure 3.

We need to augment some functional requirements for the temperature sensor. It is to make sure that the sensor could sense the environmental temperature accurately, and transmit electrical signals of the temperature precisely. The augmented requirements are as follows.

(I) Preserving the stability of thermistor's temperature characteristics

(II) Preserving the stability of the electrical signals.

According to the installation environment, the augmented requirements could be further decomposed.

(I) Aiming at preserving the stability of thermistor's temperature characteristics, the physical characteristics of thermistor should not be changed firstly. Secondly, the nonlinear effects between resistance and temperature should be eliminated. Therefore, two requirements have to be realized:

(a) Correcting the nonlinear errors between resistance and temperature

(b) Preventing the changes of thermistor's physical characteristics

(2) Aiming at preserving the signals' stability, the effects caused by slight wave propagation of thermal field and external interference signals should be avoided. Therefore, two requirements have to be realized:

(a) Preventing slight wave propagation of thermal field

(b) Shielding external interference signals

From the above, the augmented decomposition of functional domain would be established, which is shown in figure 4.

For each function preserving requirement, engineers should also determine the design parameters. Combined with zigzagging decomposition of FRs and DPs, the relationship between functions preserving requirements and design parameters could be established, shown in figure 5. In this process, the design parameters would be augmented or optimized correspondingly for the achievement of functional preserving requirements, namely, the relationship exists: $\begin{bmatrix}\mathbf{DP}_1 & \mathbf{DP}_2 & \cdots & \mathbf{DP}_d\end{bmatrix}^{\mathrm{T}} \subseteq \begin{bmatrix}\mathbf{DP}_1 & \mathbf{DP}_2 & \cdots & \mathbf{DP}_{d'}\end{bmatrix}^{\mathrm{T}}$.

Being combined with Equation (1), the relationship between the FRs and DPs are mathematically expressed as

$$\begin{bmatrix}\mathbf{FR}_{R1}\\ \mathbf{FR}_{R2}\\ \vdots \\ \mathbf{FR}_{Rn}\\ \mathbf{FR}_{P1}\\ \mathbf{FR}_{P2}\\ \vdots \\ \mathbf{FR}_{Pm}\end{bmatrix} = \begin{bmatrix}\mathbf{A}_{n\times d'}\\ \mathbf{A}_{m\times d'}\end{bmatrix}\begin{bmatrix}\mathbf{DP}_1\\ \mathbf{DP}_2\\ \vdots \\ \mathbf{DP}_d\\ \vdots \\ \mathbf{DP}_{d'}\end{bmatrix} \tag{3}$$

where $\mathbf{A}_{n\times d}$ is the design matrix augmented from $[\mathbf{A}]_{n\times d}$; $\begin{bmatrix}\mathbf{FR}_{R1} & \mathbf{FR}_{R2} & \cdots & \mathbf{FR}_{Rn}\end{bmatrix}^{\mathrm{T}}$ is the second level functional requirement realization vector; $\begin{bmatrix}\mathbf{FR}_{P1} & \mathbf{FR}_{P2} & \cdots & \mathbf{FR}_{Pm}\end{bmatrix}^{\mathrm{T}}$ is the second level functional requirement preserving vector; and $\mathbf{A}_{m\times d'}$ is the preservation matrix that characterizes the relationship between functional requirement preserving domain and physical domain.

Functions preserving requirements are also functional requirements. According to the independence axiom, if the augmented matrix $\begin{bmatrix} \mathbf{A}_{n\times d'} \\ \mathbf{A}_{m\times d'} \end{bmatrix}$ is diagonal or triangular, then the design is uncoupled or decoupled. However, to determine design parameters for functions preserving requirements directly is a problem.

The paper presents an approach to solve it from the perspective of failure. Engineers could analyze the functional characteristic and its causes on the assumption that a function preserving requirement is not satisfied, and then determine the design parameters to prevent it. Theoretically, the characteristic is known as failure or failure modes (failure mode is the manner by which a failure is observed, such as no-output, output error. It is generally described as the way the failure occurs and its impact on product operation.). Engineers should consider functions preserving requirements and their implementations as early as possible. In so doing, engineers would take initiation to eliminate the failure modes or reduce the occurrence probabilities to prevent the disappearance or reduction of function preserving ability, and thus achieve satisfying products with less iteration.

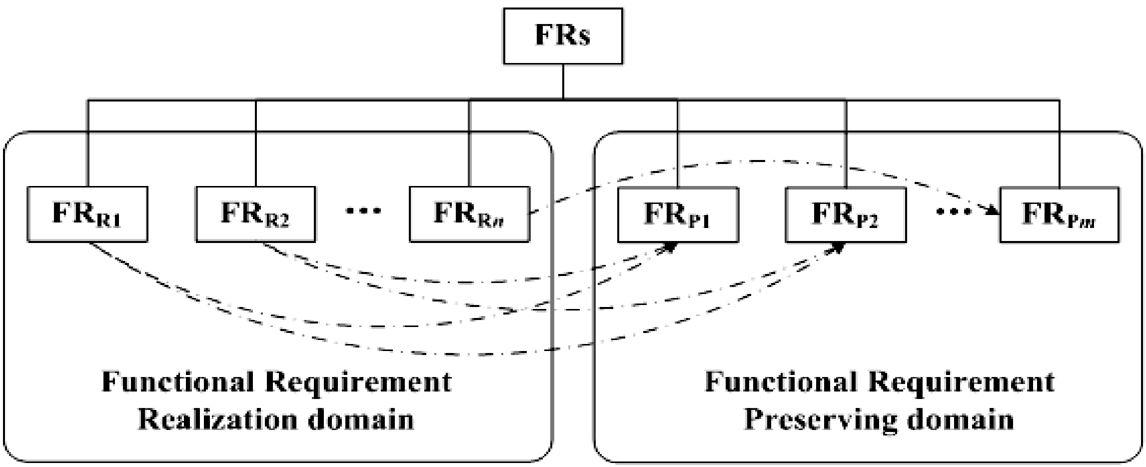

Figure 3: New Decomposition of FRs

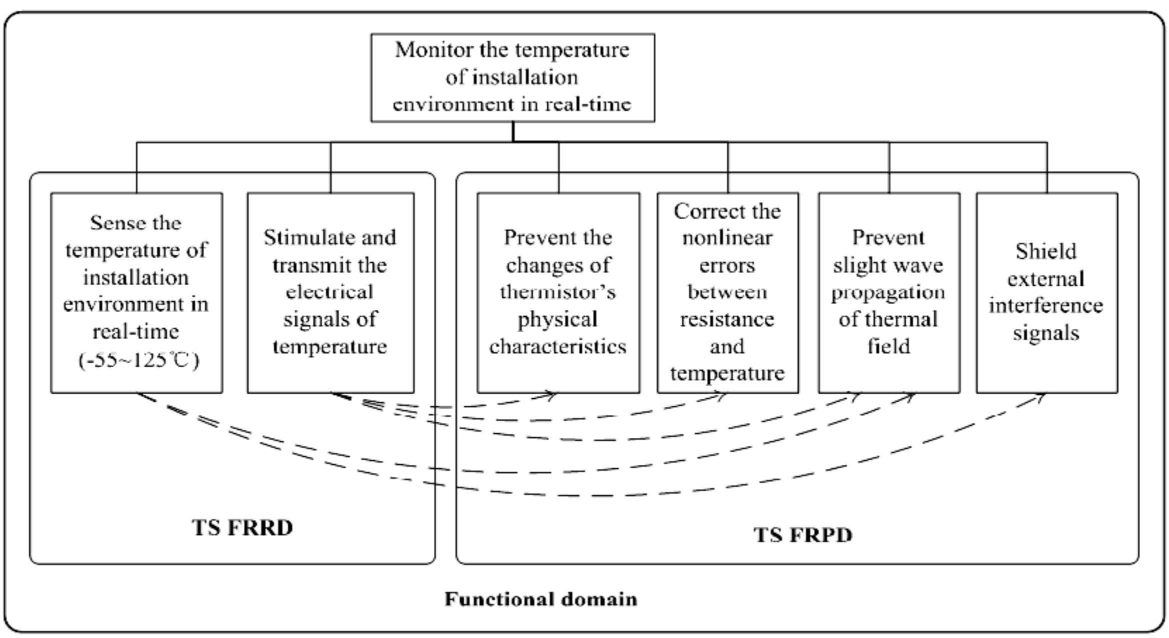

Figure 4: The Augmentation of TS's Functional Domain

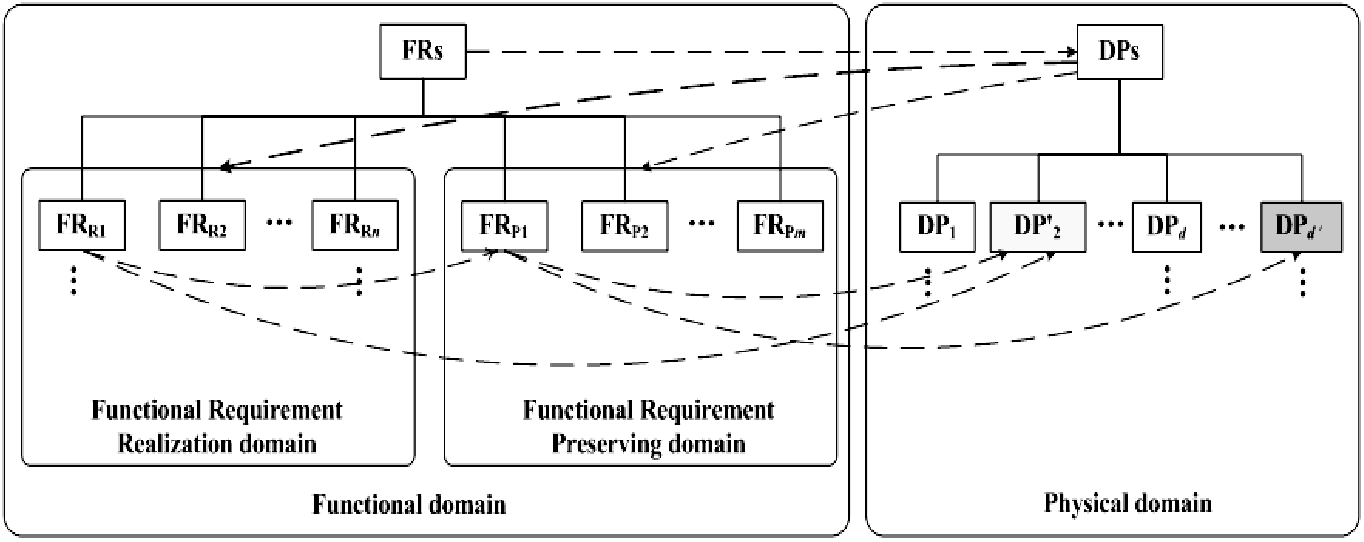

Figure 5: Corresponding Decomposition of FRs and DPs

Determination of Reliability Design Parameters Through failure modes mitigation

(1) Failure Modes Mitigation

Although the concept "mitigation" is explored numerously in engineering, its definition is still not clarified. Since failure modes mitigation aims to improve the reliability, the definition is proposed firstly based on the notions of reliability growth in standards, the core idea of failure modes mitigation in GEIA-STD-0009 and the comprehension in engineering practices.

Definition 1: Failure modes mitigation should be a hybrid process, in which the improving measures, operational compensatory provisions, diagnosis means are employed to eliminate the failure modes or reduce the occurrence probabilities according to the causes and severity of failure modes. It is denoted by FM2.

FM2 process is a closed-loop one, shown in Figure 6 (GEIA-STD-0009, 2009). It begins with the analysis of failure modes introduced in the early stage of design, maybe after the first decomposition of FRs and DPs, and does not end until the procedures of mitigating the failure modes have been validated to be efficient.

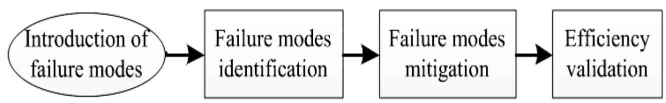

Figure 6: The Closed-loop Process of FM2

Combined with the closed-loop process of FM2 and the independence axiom, engineers could identify the failure modes leading to the disappearance or reduction of function preserving ability in function preserving domain through failure modes and effects analysis (FMEA), and then mitigated them, especially the ones with high severity or occurrence probability. The functional FM2 process based on independence axiom and logic decision is shown in figure 7.

(A) Identify the failure modes leading to the disappearance or reduction of function preserving ability in function preserving domain through FMEA: FMEA is a procedure by which each potential failure mode in a system is analyzed to determine the results or effects exerted on the system, and to classify each potential failure mode according to its severity. In application, engineers could refer to worksheet shown in the example formats in table 1. certainly, it can be tailored.

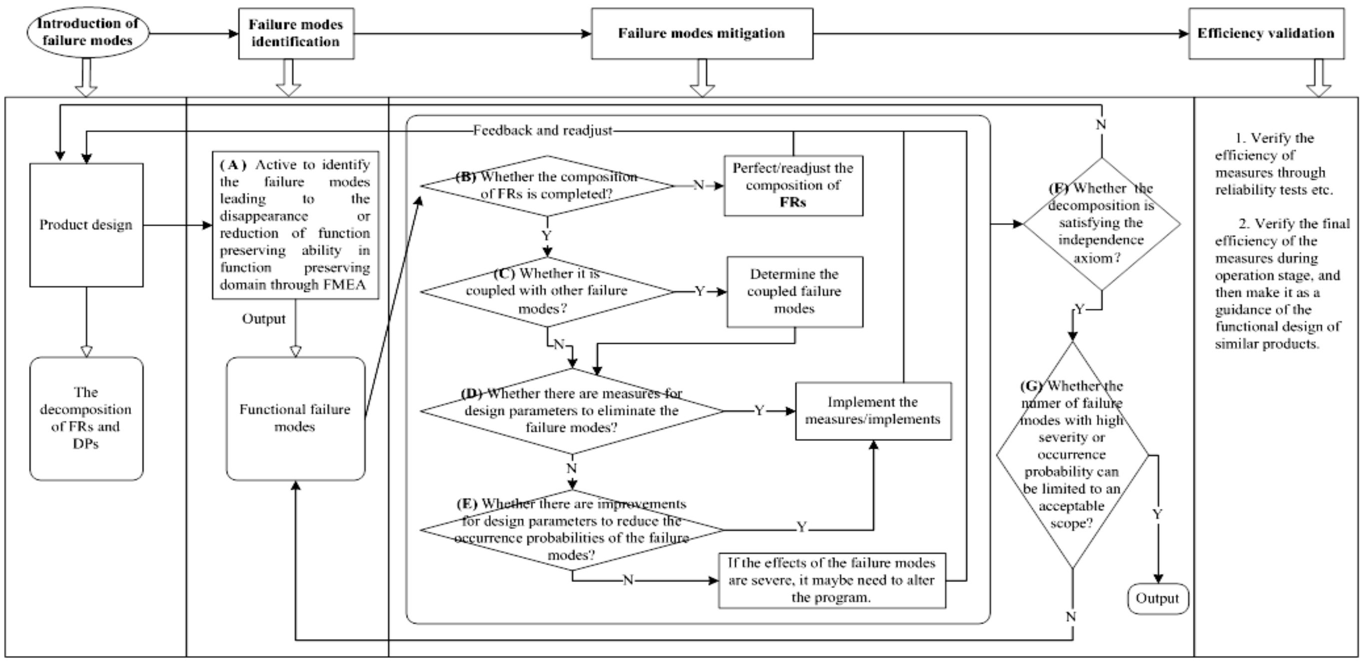

Figure 7: The Functional FM2 Process Based on Independence Axiom and Logic Decision

Table I: Example of FMEA worksheet format

no.	function preserving requirement	failure mode	failure cause	failure effects			severity class	occurrence probability
				local effects	next higher effects	end effects		
	(I)	(II)	(III)	(IV)	(IV)	(IV)	(V)	(VI)

Table II: The FMEA worksheet of temperature sensor

no.	function preserving requirement	failure mode	failure cause	failure effect
1	correcting the nonlinear errors between resistance and temperature	FM11：be higher than actual temperature	the nonlinear errors between resistance and temperature is uncorrected	the result is higher than the real situation
		FM12：be lower than actual temperature	the nonlinear errors between resistance and temperature is uncorrected	the result is lower than the real situation
2	preventing the changes of thermistor's physical characteristics	FM21：non-output signals	thermistor is damaged because of collision	TS is damaged
		FM22：be higher than actual temperature	remainders affect the thermistor, and change its physical characteristics.	the result is higher than the real situation
		FM23：be lower than actual temperature	remainders affect the thermistor, and change its physical characteristics.	the result is lower than the real situation
3	preventing slight wave propagation of thermal field	FM31：be higher than actual temperature	there are some deviations for interference.	the result is higher than the real situation
		FM32：be lower than actual temperature	there are some deviations for interference.	the result is lower than the real situation
4	shielding external interference signals	FM41：be higher than actual temperature	there are some deviations for interference.	the result is higher than the real situation
		FM42：be lower than actual temperature	there are some deviations for interference.	the result is lower than the real situation

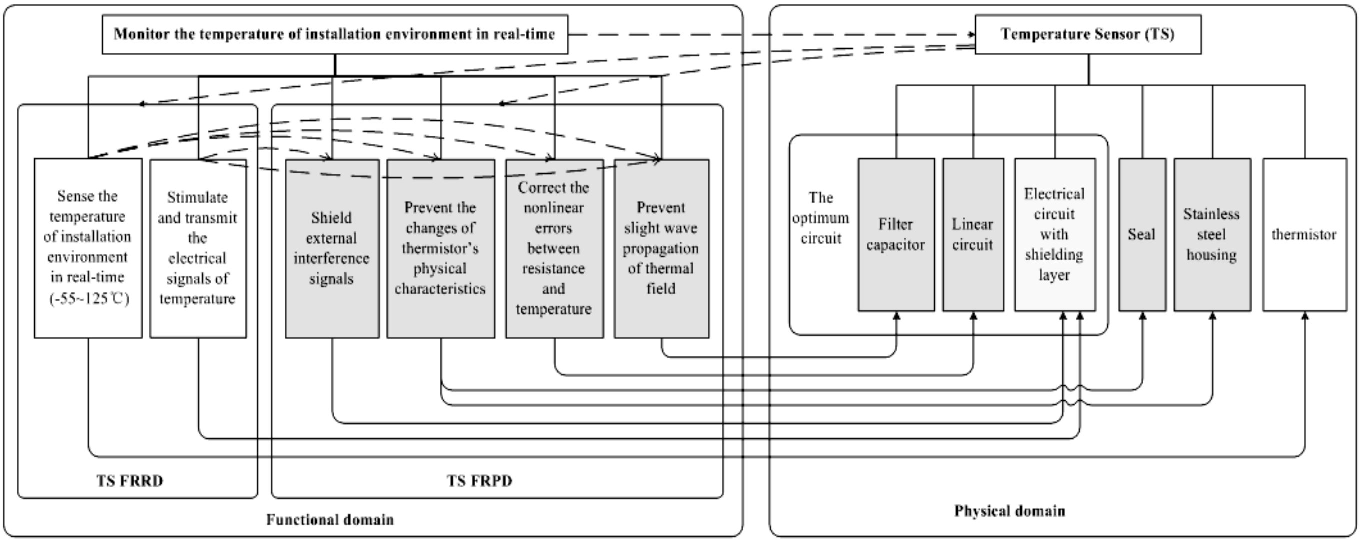

Figure 8: An Decomposition Example of FRs and DPs—TS

(I) Function preserving requirement. Engineers should analyze the function preserving requirement item by item.

(II) Failure mode. The failure modes lead to the disappearance or reduction of function preserving ability in function preserving domain. One function preserving requirement may correspond to more than one failure modes.

(III) Failure cause. The physical or chemical processes, design defects, quality defects, part misapplication, or other processes which are the basic reason for failure or which initiate the physical process by which deterioration proceeds to failure. One failure mode may correspond to more than one failure causes.

(IV) Failure effects. The consequence(s) a failure mode has on the function. Failure effects are classified as local effect, next higher effect, and end effect. Local effect is the consequence(s) a failure mode has on the function of the specific function preserving requirement analyzed. Next higher effect is the consequence(s) a failure mode has on the function of the items in the next higher indenture level above the indenture level under consideration. End effect is the consequence(s) a failure mode has on the function of the highest indenture level.

(V) Severity class. Severity classifications are assigned to provide a qualitative measure of the worst potential consequences resulting from a failure mode. It is divided into four categories: I (Catastrophic), II (Critical), III (Marginal) and IV (Minor).

(VI) Occurrence probability. The possibility a failure mode occurs in the operational process. After the analysis, engineers could mitigate the failure modes according to severity class and occurrence probability.

(B) Whether the composition of FRs is completed?
If the answer is "Yes", the second question is followed up as "whether the failure mode is coupled with other failure modes?"; if the answer is "No", then perfect the decomposition of FRs, feedback it to the first phase and readjust the decomposition.

(C) Whether the failure mode is coupled with other failure modes?
If the answer is "Yes", then determine the coupled failure modes set, and continue to answer the third question "whether there are measures for design parameters to eliminate the failure modes?"; if the answer is "No", continue to answer the third question directly.

(D) Whether there are measures for design parameters to eliminate the failure modes?
If the answer is "Yes", then implement the measures for design parameters, feedback it to the first phase and readjust the decomposition; if the answer is "No", continue to answer the forth question "whether there are improvements for design parameters to reduce the occurrence probabilities of the failure modes?"

(E) Whether there are improvements for design parameters to reduce the occurrence probabilities of the failure modes?
If the answer is "Yes", then implement the measures for design parameters, feedback it to the first phase and readjust the decomposition; if the answer is "No", and if the effects of the failure modes are severe, the program needs to be altered.

(F) If the failure modes have been mitigated, then answer the question: whether the decomposition is satisfying the independence axiom?
If the answer is "Yes", continue to answer the sixth question; if the answer is "No", feedback it to the first phase and readjust the decomposition.

(G) Whether the number of failure modes with high severity or occurrence probability can be limited to an acceptable scope?
If the answer is "Yes", output; if the answer is "No", feedback it to the second phase and continue to mitigate the failure modes.

In fact, it is necessary to make sure the measures taken to eliminate the failure modes or reduce the occurrence probabilities are efficient through reliability tests etc. However, in early stages of the development, designers do not get the physical entities. They could not conduct the tests. For the time being, designers could verify the efficiency preliminarily combined with the independence axiom.

(2) Failure Modes Mitigation for Temperature Sensor

The FMEA worksheet of temperature sensor is shown in Table 2 without considering severity class and occurrence probability of failure modes. Hypothesize all the failure modes analyzed should be mitigated.

Combined with the failure modes mitigation process shown in Figure 7, we determine improvement measures for each failure modes.

(I) FM11 and FM12. A linear circuit is adopted to correct the nonlinear errors between thermistor's temperature and resistance.

(II) FM21, FM22 and FM23. Housing and seal are adopted to prevent the remainders. The housing could also be used to prevent collision deformation. However, the ability to sense temperature outside in real-time should be ensured, and the self-heating effects be avoided. Therefore, stainless steel is adopted as the materiel of housing.

(III) FM31 and FM32. A filter capacitor is augmented to filter noise waves.

(IV) FM41 and FM42. A shield is adopted to prevent external interference signals.

From the above, the decomposition of temperature sensor is shown in Figure 8. The mathematical express is as follows:

$$\begin{bmatrix} FR_{R1} \\ FR_{R2} \\ FR_{P1} \\ FR_{P2} \\ FR_{P3} \\ FR_{P4} \end{bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 & 0 & 0 \\ 0 & X & 0 & 0 & 0 & 0 \\ 0 & X & 0 & 0 & 0 & 0 \\ 0 & 0 & X & X & 0 & 0 \\ 0 & 0 & 0 & 0 & X & 0 \\ 0 & 0 & 0 & 0 & 0 & X \end{bmatrix} \begin{bmatrix} DP_1 \\ DP_2 \\ DP_3 \\ DP_4 \\ DP_5 \\ DP_6 \end{bmatrix} \quad (4)$$

where FR_{R1} = sense the temperature; FR_{R2} = stimulate and transmit the electrical signals of temperature; FR_{P1} = shield external interference signals; FR_{p2} = prevent the changes of thermistor's physical characteristics; FR_{P3} = prevent slight wave propagation of thermal field; FR_{P4} = correct the nonlinear errors between resistance and temperature; DP_1 = thermistor; DP_2 = electrical circuit for stimulating and transmitting the signals. DP_3 = stainless steel housing; DP_4 = seal; DP_5 = linear circuit; DP_6 = filter capacitor;

From Equation (4), we can conclude that the requirements of temperature sensor are independent according to the independence axiom. And the failure modes analyzed have been eliminated while the improvements have been implemented. Certainly, the augmented design parameters will also have impacts on the design. It could be further analyzed in the lower-level functional design with the approach the paper proposed.

Conclusions

We can draw the conclusions as follows:

(1) Aiming at solving the problem about designing-in of reliability requirements to products systematically, the paper presents an approach to design reliability requirements explicitly during the design process through axiomatic design. Then the reliability solution could be determined.

(2) The application efficiency of axiomatic design principles is quite dependent on the sufficiency of functional requirements analysis. However, the AD principles did not give an approach to achieve all functional requirements. Aiming at solving the problem, a new concept is proposed: functional requirements preserving domain. From the perspective of preserving the functions realization requirements, engineers could specify the implicit requirements, and then augment and perfect the functional domain.

(3) With the view of disappearance and reduction of function preserving ability, the paper offers a new approach to identify failure modes. It assures that the failure modes and failure causes identified are complete. Taking the closed-loop process of FM2 as the main line, we establish a control process of failure modes mitigation based on the independence axiom and logic decision.

(4) All the approaches proposed in the paper are demonstrated feasible and efficient through a case study: the design of a temperature sensor. However, there still remain some other problems which need to be studied further in the future.

(5) If there is more than one solution satisfying the independence axiom, then engineers should evaluate them through the information axiom. The Augmented functions preserving requirements are mainly qualitative, so the quantity evaluation approach needs further work.

(6) The application of the approaches proposed above in the decomposition of physical domain and process domain also needs further studies. Besides, we can see that more than one failure mode have been mitigated through the same improvement from the case, which shows that there are interconnections among failure modes. Although it is mentioned in the mitigation process, we did not present those details due to the limitation.

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