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TOWARD DESIGN FOR SAFETY PART 2: FUNCTIONAL RE-ENGINEERING USING AXIOMATIC DESIGN AND FMEA

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ABSTRACT

The design process of product development is the earliest opportunity to integrate safety into the product. The term 'design for safety' captures this effort to integrate the safety knowledge in the design process. In this context, this research suggests to do 'design for safety' through two sequential methods in two parts. In the first part a method for functional reverse engineering (FRE) driven by Axiomatic Design (AD) was proposed. The second part, discussed in this paper, proposes a functional re-engineering (FR2E) using AD and failure mode and effect analysis (FMEA) to define a system with high mechanical safety as well as reliability and robustness. This method is validated through a case study that examines a power take-off (PTO) system.

Keywords: design for safety, functional re-engineering, robust design, Axiomatic Design, FMEA.

1 INTRODUCTION

The term 'design for safety' captures the effort to integrate the knowledge on safety in the design process. For successful safety integration in design, design experiences to answer what-how and then know-how play a crucial role. In this context, the first part of this research work proposed a FRE based on design experiences analysis to extract safety and design information. To this aim, the AD proposed by Suh [1990; 2001] is used as a basis. The aim of the present paper is to make use of the extracted information in Part 1 in the design process.

Ghemraoui et al [2009a; 2009b; 2011] attempted to define and integrate safety requirements early in the product design process by proposing the innovative risk assessment design (IRAD) method. This method defines the safety requirements and offers a mechanism for the integration of these safety requirements in the design synthesis (Figure 1). Design synthesis based on technical and safety requirements allows the consideration of safety as an integral part of the entire

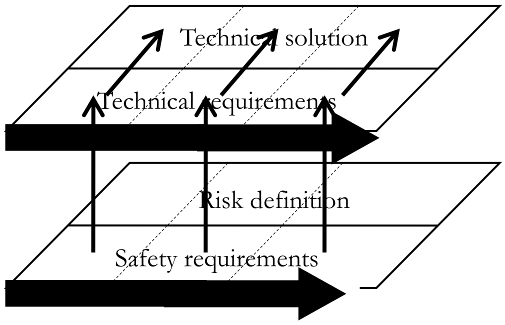

Figure 1. Safety requirements integration in design synthesis.

design solution. This paper aims to complete this mechanism of IRAD.

Sadeghi *et al.* [2013] focused on the extension of reverse engineering to FRE. This paper extends re-engineering as FR2E. AD is used as a basis to propose a method for FR2E. As a starting point, we must ask: does the probability of satisfying the FRi depend on the reliability of the DPj? On the other hand: "if DPj failes (is missing, broken, damaged, etc.) will FRi be satisfied?". FMEA, which is a reliability engineering method, is used to identify potential failure modes, determine their effect on the operation of the product, and identify actions to mitigate the failures.

The remainder of this paper is organized as follows. Section 2 explains the research background concerning robust design methods and FMEA as a reliability engineering method. This section also describes the motivation of using AD and FMEA as a basis for proposing one method for FRE. Section 3 explains the proposed method for FR2E. In Section 4, a PTO system is used as a case study to illustrate and examine the different steps of the proposed method. Section 5 includes the main results and a brief discussion and presents the general conclusion concerning two parts of this research study.

2 RESEARCH BACKGROUND

2.1 RELIABILITY, ROBUSTNESS, PERFORMANCE, ACCIDENTS, SAFETY

This section attempts to answer the question: why is reliability and robustness analysis needed in research toward design for safety? Safety is defined as the absence of unwanted events while risk is defined as the probability that something unwanted may happen. Unwanted occurrences can lead to accidents [Ghemraoui, 2009]. Accidents can occur due to human errors, machine (system) faults, environmental anomalies or a combination of them.

System faults are due to a system or component that does not perform as expected under erroneous, stressful, or unexpected inputs or conditions (in perturbations). This refers to two concepts: 'reliability' and 'robustness'. In engineering, 'reliability' is associated with the confidence that a system will perform its intended function during a specified period of time under the stated conditions, as well as under unexpected circumstances [Barber and A Salido, 2011]. Reliability is defined as the ability of a machine or its components to perform a required function under specified conditions and for a given period of time without failing [NF EN ISO 12100]. In a general way, 'robustness' can be defined as the ability of a system to withstand stress, pressure, perturbations, unpredictable changes or variations in its operating environment without loss of functionality [Barber and A Salido, 2011]. In engineering, robustness can be defined as reducing the variation in FRs of a system and having them on target as defined by the customer [Taguchi and Wu, 1980].

In some cases, safety problems are related to system reliability and its robustness. That means the safety aspect is considered during the design process of system and there are no accident and safety problems for new systems but it does not consider more time. Therefore, in the design for safety method, the system must be both robust and reliable in order to fulfill safety goals and this must be considered early in the design process

2.2 ROBUST DESIGN METHODS

Park *et al.* [2006] classified robust design in three methods: 1. the Taguchi method, 2. robust optimization, and 3. robust design with AD. In this section, the first and third methods are briefly reviewed.

2.2.1 TAGUCHI METHOD

Two types of variables or factors are defined by Taguchi in robust design: easy-to-control variables (control factors) and hard-to-control variables (noise factors). Noise factors may come from several sources; noise external, noise internal, and noise unit-to-unit. The objective of robust design is to determine the setting of the control factor to achieve the best product or process performance that is insensitive to the variability of noise factors. To achieve this, Taguchi recommends performing experiments in which control and noise factors setting are determined using orthogonal arrays [Taguchi, 1987]. Table 1 presents the three major phases of the design process emphasized by Taguchi: concept design, parameter design, and tolerance design. For each phase, some design activities are listed that have a major impact on robustness.

Table 1. Phases in the design process and design activities related to robustness.

Phase	Design activities related to robustness
Concept design	Generate concepts to create the desired function Generate concepts to make a function more robust Evaluate concepts Select from a set of concepts that one is to pursue
Parameter design	Plan a search through the design space Conduct experiments Analyze data
Tolerance design	Estimate the economic losses due to variations Allocate variations among components Optimize trade-offs between cost and quality

The advantage of the Taguchi method is that it provides a simple and systematic framework for identifying critical characteristics in systems to achieve best quality characteristics while minimizing the variation and cost.

2.2.2 ROBUST DESIGN WITH AD

The Information Axiom of AD Theory deals with information content, the probability of satisfying the FRs, and complexity. Information content is defined in terms of probability of success and is the additional information required to satisfy the FR. The process to apply these two axioms has been illustrated by Gebala and Suh [1992] and Suh [2001]. These axioms provide a framework to indicate the adequacy of the design. They are used for considering, evaluating, and comparing different alternatives to satisfy the needs or requirements of a system.

The natures of the Independence and the Information Axioms improve the robustness of artifacts created using AD. By designing a system with minimal interaction between components (satisfying Axiom 1); if noise is introduced into one component of the system, it will not propagate into other components, and therefore robustness will be improved. The second axiom instructs the designer to select the design with the least information content. The information content of a design is determined by the probability of satisfying the design objectives (what the design is trying to achieve). Therefore robustness will be enhanced by satisfying the second axiom of AD.

Computing the information content in a design is facilitated by the notation of the design range and the system range. The design range is specified for each FR by the designer, whereas the system range is the resulting actual performance of the design embodiment [Suh, 2001]. To achieve a robust design, Suh proposed to eliminate the bias and reduce of the variance of the system (Figure 2). The term bias is defined as the difference between the mean of an FR in the system range distribution and the target value T defined by the customer, as depicted in Figure 2. In this figure the overlap between design range and system range is called the common range.

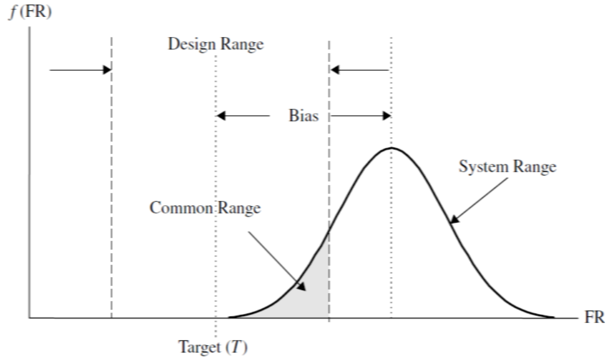

Figure 2. Suh's definition of probability of success [2001].

To eliminate or reduce of bias, in a one-FR design, Suh [2001] suggested changing the DP with a more appropriate one. When there is more than one FR to be satisfied, to eliminate bias, the design must satisfy the Independence Axiom first. To reduce the variance, Suh proposed different ways to determine if the design satisfied the Independence Axiom:

a. Through reduction of stiffness;
b. Through design of a system that is immune to variation;
c. Through minimizing the random variation of DPs and PVs (process variables);
d. By compensation; and
e. By increasing the design range.

Information content is defined in terms of the probability of satisfying a given FRi. In some cases, the probability of satisfying the FRi depends on the reliability of the DPj. On the other hand, if DPj fails, then FRj will not be satisfied. This is why this research requires reliability analysis.

2.3 RELIABILITY ENGINEERING

Reliability engineering methods like failure mode and effect analysis or fault tree analysis (FTA) can be helpful for the analysis of present the failure(s) in the system [Heo *et al.*, 2007]. FTA is frequently used to improve system reliability and safety by identifying the cause(s) of the failure. FMEA is used to identify potential failure modes, determine their effect on the operation of the product, and identify actions to mitigate the failures. The main difference between these two methods is: FTA is used when effect is known and cause is unknown, while FMEA is used for the conditions where cause is known and effect is unknown.

Arcidiacono *et al.* [2004] proposed an approach to reliability improvement of a sliding car door using an AD and FMEA. This paper selected FMEA to define the opportunities to enhance the reliability and robustness of a component. Therefore, a brief description of this method is presented here. FMEA is a method for analyzing potential reliability. This method is used to identify potential failure modes, determine their effect on the operation of the system, and identify actions to mitigate the failures. A crucial step is anticipating what might go wrong with a system. Therefore, it is designed to help the engineer improve the quality and reliability of a design.

2.4 FUNCTIONAL RE-ENGINEERING

Sadeghi *et al.* [2013] extended reverse engineering as FRE. The present paper extends re-engineering as FR2E. According to research background presented in this section, the next section aims to propose a method for FR2E using AD, principles of the Taguchi method and FMEA.

3 PROPOSED METHOD

The purpose of FR2E in this research is to define a system with high mechanical safety, which is reliable and robust with few possible human errors. The proposed method for FR2E integrates AD representation (the design matrix), the two axioms of AD, principles of Taguchi method, and FMEA to propose safe solution(s).

3.1 SYSTEM RELIABILITY ANALYSIS

3.1.1 IDENTIFY UNRELIABLE COMPONENT(S) AND RELATED DP(S) AND FR(S)

The FRE method [Sadeghi *et al.,* 2013] can determine the components, physical structure and functional structure of an existing system and define the hazard related to each component, DP and FR. The question that must be answered is: does the probability of satisfying FRi depend on the reliability of DPj? On the other hand: "if DPj fails (is missing, broken, damaged, etc.) will FRi be satisfied?" If the response of the above question is 'no', we deduce that design is un-robust and unreliable. Therefore, the component that is identified by DPj and FRi has to be redesigned. In the context of FR2E, this question can be answered based on experience feedback analysis (the results of FRE), and this is the advantage of FR2E. The objective is to identify unreliable component(s), and its (their) related DP(s) and FR(s) and try to improve the robustness of the DP(s) and FR(s) to increase the reliability of related component.

3.1.2 Define THE SYSTEM RANGE

This section aims to identify the actual performance of the design embodiment (system range) for the functional failure identified in the previous section. Normally the system range depends on time, meaning that, during the specified period of time, under the stated conditions, as well as unexpected circumstances, the component is reliable.

3.2 SYSTEM NOISE FACTORS IDENTIFICATION

This section aims to identify noise factors. Noise factors may come from several sources. Taguchi defines three types of noise, which include; external, noise internal, and noise unit-to-unit [Taguchi, 1986]. Knowing the categorization of a noise can help the designer to predict which noise may play a factor in the system under consideration. This is an area in which experience feedback on the system will be important.

The information from experience feedback may also be used to predict which noise factors are likely to contribute to the behavior of the system and enhance its performance. The strategy proposed to achieve this purpose is based on use of the FMEA method. The first step is to identify major sources of noise (failure mode and its causes and effects), and then specifically target them to identify the opportunities for improving performance and in consequence robustness and reliability.

An accident can occur due to human error, machine (system) faults, environmental anomalies or a combination. Human error and environmental anomalies can be reduced by supplying guidelines for use (e.g. warning devices, operating procedures and employee training programs) to enhance safety of the system. However, people do not always respect operator guidelines; hence this research investigates a way to enhance the safety of the system through identifying machine faults

3.2.1 Identify Failure Mode, Causes and Effects

The FMEA method is used to identify potential failure modes, determine their effect on the operation of the system, and identify actions to mitigate the failures. A crucial step of this method is anticipating what might go wrong with a system. To effectively identify a failure mode and its causes and effects, the experiences feedback analysis (accident reports and other resources analysis) must be used. This is the advantage of FRE over forward engineering (FE). In FE, the designer defines a potential failure mode and its potential causes and effects, but in FR2E based on experiences feedback analysis the designer can define the real failure mode and its causes and effects.

3.2.2 Identify Opportunities for Improving Performance

The second step in identifying system noise factors using FMEA is to identify opportunity(s) for improving the performance of a component that is not robust, hence enhancing its reliability and robustness. To achieve this purpose, the suggestions proposed by Suh [2001] to eliminate or reduce bias and variance should be applied.

3.3 Robust Safe Design

3.3.1 Creation of Robustness FR(s)

For each defined noise factor in the previous step, this section aims to create FR(s) to minimize the system response or susceptibility to the noise factor. The general form of the FR, in concurrence with standard AD practice, should express the requirement as a verb. The robustness FRs for a PTO system guard will be given in Section 4.

3.3.2 Mapping to Robustness DP(s)

After creating robustness FR(s), the next step will be mapping it (their) to DP(s) by applying AD. One possibility may be to select some parameters of the existing component and use them as the DPs to control system response to a noise factor. If this is not possible, a new element may be added as the DP to the component to provide a parameter to control response to the noise factor. The new robust DP(s) may reduce sensitivity or shield the system from the noise.

3.4 Synthesis

In the framework of ongoing research in 'design for safety', a FR2E method using AD and FMEA is proposed. Table 2 lists the objective, input and output of each step of the proposed FR2E method.

Table 2. FR2E method steps.

Step	Summary
1: System reliability and analysis	**Objective 1:** identify unreliable component(s) and related DP(s) and FR(s) **Input**: AD matrix **Output**: unreliable component(s), and its (their) related DP(s) and FR(s) **Objective 2:** define system range **Input:** unreliable component(s) and its (their) related DP(s) and FR(s) **Output:** system range
2: System noise factor definition	**Objective 1:** identify failure mode, its cause and effects **Input:** unreliable component(s) and its (their) related DP(s) and FR(s) and system range **Output:** failure mode, its causes and effect(s) failure based on experiences feedbacks analysis **Objective 2:** identify opportunities for improving performance **Input:** unreliable component(s) and its (their) related DP(s) and FR(s), system range, failure mode, its cause and effects **Output:** opportunities for improving performance
3: Robust safe design	**Objective 1:** creation robustness FR(s) **Input:** system noise factors **Output:** new robust FR(s) **Objective 2:** mapping to robustness DP(s) **Input:** new robust FR **Output:** new robust DP(s)

4 CASE STUDY: PTO SYSTEM

This section examines a PTO system to illustrate and investigate the proposed FR2E method. Based on the definition of robustness, the aim is to design a PTO system safeguard to withstand stress, pressure, perturbations, unpredictable changes or variations in the operating environment without loss of function. Furthermore, the PTO system safeguard must be robust: it must not be affected by humidity, vibrations, accelerations, temperature, or other noise factors.

4.1 Identify Unreliable Component(s) and Related DP(s) and FR(s) of PTO System

Entanglement with a PTO system is most common when the system is working with missing, broken, damaged or badly fitting safeguards and the person gets too close in proximity [Sadeghi *et al*, 2013]. The results of this section are shown in Table 3. In this table, column 1 illustrates the number of unreliable and un-robust components, and columns 2, 3, 4 present the unreliable components and their related DPs and FRs for PTO system safeguarding.

4.2 Define PTO Guard System Range

The PTO system guard is damaged or broken after a period of its utilization. The experience feedback analysis illustrates the actual performance of its design embodiment is about 1000 hours (Column 5 of Table 3).

Table 3. Results of PTO system reliability and robustness analysis.

N	Component	FRi	DPj	System range
1	guard cone by side of tractor	FR221: cover universal joint by side of tractor	DP221: conical guard by side of tractor	about maximum 1000 hours utilization
2	restraining member	FR224: prevent rotation	DP224: restraining member	about maximum 1000 hours utilization

4.3 IDENTIFY PTO SYSTEM GUARD FAILURE MODE, CAUSES AND EFFECTS

The first question is 'why do PTO system guards tend to break or damage over time?' A review of relevant literature shows that although several aspects of PTO system guarding have been studied, they have not determined the specific causes for damage found on the PTO system guards.

These PTO system guards (guard cones by the side of the tractor, guard tubes and guard cones by the side of the implement) are designed to protect the operator and equipment. These guards not only reduce the risk of an injury; they also keep dust and other foreign objects from damaging the moving elements of the system. A restraining member shall be provided to prevent the guard rotating with the shaft. The member(s) of the restraining system (e.g. a chain or a wire rope) should be securely attached to the guard and provided with a fitting that will enable it to be attached to a stationary part of the system. This restraining system shall not be used as support of the shaft [NF EN 12965+A2].

In Table 4, columns 2, 3 and 4 show the PTO systems guard failure modes, and the causes and effects present after reviewing different accident reports and other applicable resources. The results show that steel guards were missing more often than plastics ones; however plastics guards were more often damaged. The problem with the steel PTO guard is that when it is dented it cannot freely rotate on the shaft. The problem with the plastic guards is that they are not resistant to degradation of the universal joint. The main problem with safeguards is that they crash, rub and push against each other and other parts such as draw bars and three points hitch linkage arms. In addition, safeguards rust, become obsolete and brittle and perish due to exposure to the elements or environmental conditions (sunlight and heat, cold, etc.).

4.4 IDENTIFY OPPORTUNITIES FOR IMPROVING PERFORMANCE OF PTO GUARDS

The opportunities for improving the performance of PTO guards are presented in column 5 of Table 4. The designer can propose information to enhance the PTO system safety following its design. For example: a system can remain in a garage to reduce exposure to damage, or farmers can be encouraged to maintain accepted levels of safety by replacing damaged guards. However, the operators do not always respect the user guidelines. Therefore, the main objective of this research is to improve the PTO system design to enhance safety. In the PTO system, improving the guard cone and restraining member design can enhance their performance and safety.

Table 4. PTO system noise factor definition.

N	Failure mode (what)	Cause(s) of failure (why)	Effect(s) of failure	Opportunities for improving performance
1	- cut - scuffed - missing - bent - loose	- greasing mode - rubbing on the implement PIC guard - contacting the master shield or PIC guard	no/ loss cover of the universal joint	- proposition information for use - improvement of guard cone design
2	- broken fixed eyes	guard -vibration - friction - arrachement	guard rotate	- proposition information for use - improvement of restraining member design

4.5 CREATION OF ROBUSTNESS FR(S) FOR PTO GUARDS

Based on the results in the previous section, to improve robustness of the first component, 'guard cone by the side of the tractor', we can use the new safe robust FR221 to 'cover universal joint by side of tractor able to resist contact damage'. The new FR224 to improve robustness of the 'restraining member' can be created to 'prevent rotation in a condition of high vibration'. The next section deals with definition of a robust DP for satisfaction of each new robust FR.

4.6 MAPPING TO ROBUSTNESS DP(S) FOR PTO GUARDS

Damage caused by contact of different components is related to the type of material(s) used in PTO system safeguards. Therefore, we propose a new robust DP221, which is to create a "conical guard by the side of the tractor manufactured using resistant material(s)".

To enhance the robustness of the restraining member (to prevent it from breaking) the chain has to be strengthened, but without increasing complexity. Therefore, we suggest the new robust DP224 by 'fitting stronger restraining member'.

4.7 SYNTHESIS

To conclude, the results of applying the proposed FR2E method on the PTO system are summarized in Table 5. The first column illustrates existing un-robust FRs and DPs while the second column presents the robust FRs and DPs to increase the reliability of safeguarding the PTO system.

Table 5. Results of FR2E on the PTO system.

un-robust FRs and DPs	robustness FRs and DPs
FR221: cover universal joint by side of tractor	FR221: cover universal joint by side of tractor in the contact condition
DP221: conical guard by side of tractor	DP221: conical guard by side of tractor manufactured by resistant material(s) (to compression, tension, friction, environmental factors)
FR224: prevent rotation	FR224: prevent rotation in condition of high vibration
DP224: restraining member	DP224: fitting stronger (to compression, tension, friction, environmental factors) restraining member

5 GENERAL CONCLUSION

This paper has attempted to illustrate how AD can be integrated with reliability engineering methods to enhance safety in the design process. The proposed method, FR2E, includes three steps. In the first step, based on the AD matrix and feedback evaluation, the reliability and robustness of the system design are analyzed. Next, the FMEA method is used to identify noise factors. In the third step, robust new FR(s) and DP(s) are proposed. This method is demonstrated with a PTO system.

This paper is the result of ongoing research in 'design for safety' and suggests a design for safety method through two sequential methods in two parts. The first part proposed a FRE approach driven by AD to obtain the design feedback and knowledge of the existing system. The aim of FRE is to obtain the original intrinsic design and safety knowledge which is located in the functional model of existing systems. To identify system components and their interaction the following methods are used: the schema abstraction of system, the product breakdown structure and functional block diagrams. The second part proposed a FR2E using AD and FMEA to define a system with high mechanical safety that is reliable and robust with few possible person errors.

The PTO system is used as a case study to illustrate and examine the proposed method in each part. To aid in design decision making, the knowledge from each part has started to be formalized through knowledge engineering approaches. Furthermore, technology for software support of the proposed method is being developed.

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