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An overall methodology for reliability prediction of mechatronic systems design with industrial application

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ABSTRACT

We propose in this paper an overall ten-step methodology dedicated to the analysis and quantification of reliability during the design phase of a mechatronic system, considered as a complex system. The ten steps of the methodology are detailed according to the downward side of the V-development cycle usually used for the design of complex systems. Two main phases of analysis are complementary and cover the ten steps, qualitative analysis and quantitative analysis. The qualitative phase proposes to analyze the functional and dysfunctional behavior of the system and then determine its different failure modes and degradation states, based on external and internal functional analysis, organic and physical implementation, and dependencies between components, with consideration of customer specifications and mission profile. The quantitative phase is used to calculate the reliability of the system and its components, based on the qualitative behavior patterns, and considering data gathering and processing and reliability targets. Systemic approach is used to calculate the reliability of the system taking into account: the different technologies of a mechatronic system (mechanics, electronics, electrical .), dependencies and interactions between components and external influencing factors. To validate the methodology, the ten steps are applied to an industrial system, the smart actuator of Pack'Aero Company.

1. Introduction

1.1. Mechatronics

The field of mechatronics has evolved as a highly powerful and most cost effective means for product realization. This is due to advances in microchip and developments in powerful computer technology including microprocessors, Application Specific Integrated Circuits (ASICs), computational techniques, that have bridged the gap between traditional electronic, control and mechanical engineering. Indeed, the development of mechatronic systems is a revolution for the industrial area, it affects a wide spectrum of fields such as manufacturing, transportation, energy and domestic devices. The field of transport and in particular the automotive sector is widely affected. The use of these systems is spreading rapidly and now reaches all sectors of the industry. Mechatronics has revolutionized the design and manufacturing of complex systems. In particular, its introduction in the automotive sector has deeply changed the development and manufacturing processes. Thus, a car is no longer conceived as a mechanical device that carries some electronic controls, but as a mechatronic system [4], where the components of different technologies are fully integrated [13].

The term mechatronics was first proposed by an engineer from Yaskawa Electric Co. in Japan, in 1969, to designate the control of electric motors by computer [69]. This term has subsequently evolved and mechatronics gained legitimacy in academic circles with the publication of at least two dozens of definitions or descriptions in the literature. One such description is proposed by the international journal *Mechatronics*, published for the first time in 1991: *"Mechatronics in its fundamental form can be regarded as the fusion of mechanical and electrical disciplines in modern engineering process. It is a relatively new concept to the design of systems, devices and products aimed at achieving an optimal balance between basic mechanical structures and its overall control"* [9]. The international journal *IEEE/ASME Transactions on Mechatronics* [48] created in 1996, proposes the following meaning: *"Mechatronics is the synergetic combination of mechanical engineering with electronics and intelligent computer control in the design and manufacturing of industrial products and processes"*. The official definition of the Industrial Research and Development Advisory Committee of the European Community: *"Mechatronics is the synergistic combination of precision mechanical engineering, electronic control and systems thinking in the design of products and manufacturing processes"* (Comerford, 1994; [20]. This definition is adopted by the technical committee on mechatronics formed by the International

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Federation for the Theory of Machines and Mechanisms, in Prague, Czech Republic [27]. Whichever description is adopted, the general process and great significance of mechatronics are apparent. It establishes the multidisciplinary nature of mechatronics, which combines several sectors of different technologies in the designing and manufacturing of a product. Mechatronics is not inherently a science or technology: it must be regarded as an attitude, a fundamental way of looking at and doing things, and, by its nature, requires a unified approach [38]. Ashley, then Alciatore and Histand also have summarized several definitions for Mechatronics [1,2]. Indeed, it can be said that Mechatronics relates to the design of systems, devices and products aimed at achieving an optimal balance between basic mechanical structure and its overall control. Particular importance must be attached to the aspects of innovation in mechatronics design philosophy which illustrate the benefits obtainable by an a priori integration of functionality with embedded microprocessor control (International Journal of Mechatronics). The synergy induced by mechatronic systems leads to an intelligent combination of technologies which leads to solutions with higher performance that cannot be obtained in separate applications. Then, it is important that the system is designed as a whole [61].

The advent of mechatronic systems in industry has led to new constraints, such as: the incorporation of several technologies, the interactions between different functional entities, taking into account the dynamics of the system, the inability to perform exhaustive tests, etc. Despite these constraints, mechatronics brings undeniable benefits such as: cost reduction, customer satisfaction by the proposed innovative solutions, the positive response to societal demands increasingly important (pollution, consumption, safety) [23,38,20,47,24,25,70].

The most important concepts characterizing mechatronic systems are: *re-configurability*, *dynamics*, *hybridity* and *dependency (interaction)*. A system is reconfigurable if it is intended to perform several functions alternately or perform a function by using its resources in several different ways. Indeed sometimes, a reconfiguration of the control system is carried out without interruption of the mission to ensure safety. It is under these conditions that the reconfiguration is dynamic [34,42]. The dynamics of the system lies in its aptitude to change its state during time. The presence of continuous phenomena and discrete events into the different states of the system characterize the hybrid concept. The dependency or interaction is described here by the effects produced by the action of a component to another component in the system changing its operating performances, in terms of degradation. Then, guarantee and security in terms of dependability and reliability becomes essential in the development of mechatronic systems [13,54,11,59].

1.2. Reliability design

On the other hand, reliability has been increasingly used in firms over the last few years. This exponential use can be explained by the following reasons: safety improvement, failure and product lifetime control, customer satisfaction enhancement, maintenance improvement, product cost reduction, etc. The methods for analysis and evaluation of the reliability of a device are numerous [31]. They are characterized according to three criteria: inductive or deductive, qualitative or quantitative, and tracked objectives. In inductive methods, we start with the causes to deduce the consequences, whereas in deductive methods we start with the consequences to infer the causes. In qualitative methods, the reliability is analyzed from a qualitative point of view to determine the modes of failures and risks, whereas quantitative methods seek to assign quantified value to reliability over time. Otherwise, according to the assigned objectives a reliability assessment method is chosen to make an objective analysis. This classification has a direct influence of the period of the lifecycle (design, manufacture, use) in the choice of the reliability method. Indeed, depending on the period in the lifecycle of the device, the reliability can be predicted, experimental (estimated) or operational (mission).

During the design phase, predicted reliability is mainly calculated using a mathematical model, based on a functional/dysfunctional decomposition of the system into subsystems and/or components and on the specific reliability of each. During the manufacturing phase, experimental reliability is assessed. Its calculation is based on the data processing of industrial testing, and on the finding of theoretical models/distributions (exponential, normal, gamma, Weibull …) of the processing results. During the use phase, operational reliability is calculated. This is based on statistical processing of the data gathered from users (failure times) and on the findings of mathematical distributions. But also methods of reliability assessment can be categorized by technology area: mechanical, electrical, electronics, software, etc. For all these reasons, the evaluation of the reliability of a system, as multi-technological mechatronic system, is complex.

Thus, methods of reliability are numerous. Not limited to, the main methods include: fault trees, reliability block-diagrams, Failure Mode and Effects Analysis (FMEA), event trees, Markov chains, Petri networks, Bayesian networks, … It is not a question here to describe all these methods, but the goal is to offer an overall methodology based on some of these methods. For indeed, it is clear that each of these methods is specific and cannot cover alone the whole field of reliability. Our investigation of the state of the art, concerns methodologies dedicated to complex or mechatronic systems.

Research in this area is still in the phase of development despite the few attempts in this direction [12,22,3,26,35,36,42, 56,59,60,65,72]. These methodologies are based on methods such as Petri nets, FMEA, Markov Chains and fault trees. In a recent article, Zhitao et al. [71], a method on the design and analysis of lithium-ion (Li-ion) battery pack from the reliability perspective is presented. The analysis is based on the degradation of the battery pack, which is related to the cells configuration in the battery pack and the state of health (SoH) of all the Li-ion cells in the pack. Other studies, exist in the bibliography. They relate to methodologies based on Bayesian networks. For example, Martins and Maturana [33] proposed a study on the application of Bayesian networks to the human reliability analysis (HRA) of an oil tanker operation focusing on collision accidents. This study uses a four-phase methodology (familiarization, qualitative analysis, quantitative analysis, incorporation) to accomplish HRA [62] using the integration of fault trees and Bayesian networks [16]. Also, to specify the reliability for new product development, Murthy et al. [44] developed a new model of product life cycle in which the life cycle was divided into eight phases and grouped into three stages (Predevelopment, Development, Post-development). Peng et al. [52] used this model for their study on life cycle reliability assessment of new products.

Among the methods dedicated to reliability, graph theory provides an appropriate tool to describe and graphically exploit the dependency relationships or independencies between variables. Probability theory brings, meanwhile, a formalism to quantify the dependency relationships by associating each variable a conditional probability law. Probabilistic graphical models, specifically Bayesian networks, initiated by Judea Pearl in the 1980s [51] proved to be useful tools for representing uncertain knowledge and reasoning from incomplete information.

The graphical part of the Bayesian network indicates the dependencies (or independencies) between variables and gives a visual tool of knowledge representation, more easily