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# A new index based on mechatronics abilities for the conceptual design evaluation☆

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A R T I C L E I N F O

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A B S T R A C T

In this paper, a new mechatronics index is proposed for the evaluation of the alternatives in the conceptual design phase. The criteria aggregated to the index are acquired mostly by the collective knowledge presented in the Multi Annual Roadmap for robotics in Europe and adapted by considering the recent advancements in mechatronics. The mathematical formulation of this design index is based on the discrete Choquet integral, taking into account the interactions among the criteria. An application of the proposed mechatronics index to the design of an educational firefighting robot is presented as a case study to demonstrate the support to the designers in the conceptual design evaluation process.

## 1. Introduction

The current mechatronics systems acquire very advanced capabilities/ characteristics based on the evolution of the mechatronics enabling technologies and the mechatronics design methodology. In [1], the enhanced intelligence/autonomy of the mechatronic systems as well as the increased complexity are identified, however these changes drive to completely new characteristics and capabilities of mechatronic systems supporting the new generation of production systems, e.g. these devices evolved from the simple monitoring to self-optimising their performance. On top of that, mechatronics enhanced the application domains from manufacturing, automotive, precision agriculture, food processing to biomechatronics and micromechatronics.

The development of mechatronics products and systems requires concurrent, multi-disciplinary and integrated design approaches. A lot of research effort have been conducted to improve and support the design process towards advanced mechatronics products and systems as it was presented in some of the most relevant publications [2–4]. However, this paper deals mainly with the abilities of the mechatronics systems and with the formulation of the mechatronic indices so the presentation of the state-of-the-art is focused to those aspects of the mechatronics design [5–11].

The mechatronic design quotient (MDQ) [5–7,9] was proposed as a multicriteria measure for assisting mechatronics design. In this measure, seven criteria were integrated: Meeting task requirements, reliability, Intelligence, matching, Control Friendliness, Efficiency and Cost. Guidelines for the design evaluation using those criteria in the conceptual design phase were presented [5,7]. These criteria were aggregated using the discrete Choquet integral – a nonlinear fuzzy integral that can be used for assisting decision-making with interacting criteria [12].

The Mechatronic Multicriteria profile (MMP) [10,11] with five key-criteria (machine intelligence quotient, reliability, complexity, flexibility and cost of manufacture and production) was proposed for the mechatronic concepts evaluation. Non-linear fuzzy integrals were used for the aggregation of the criteria and the method was applied to the design of a visual servoing system for a 6-DOF robotic manipulator.

A mechatronic index that includes three criteria namely, intelligence, flexibility and complexity was introduced in [8]. The attributes of every criterion were analysed and formulated: the structure for information processing of mechatronic systems was used to model the intelligence, three elements were used for the estimation of the flexibility of a mechatronic system and finally the complexity was modelled using seven elements. Various models for aggregating the criteria were proposed and compared including T-norms, averaging operators and the discrete Choquet integral [13].

Last years, the essential elements and characteristics of the mechatronics systems have been evolved considerably. The mechatronic systems of the new generation are adaptable and reconfigurable with advance mobility and they could self-optimise their performance like

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the active suspension system for railway vehicles [14] and the metamorphic manipulators and robots [15]. The current mechatronic systems [1,16] are autonomous with perception, learning, decision making, and might have cognitive abilities. They have diagnosability and self-aware capabilities to self-predict their potential troubles such as fault appearance or reduced performance. High level of interaction with operators is another mechatronics ability, which is very important from the point of view of reducing the human effort in communicating, maintenance and repair if needed. Apart from the software evolution, intelligence means very advanced physical action to fulfil the mechatronic tasks that was called "embodied intelligence" [16]. A new metasystem intelligence transition is expected or should be pursuit in the area of changing the main action paradigm from electromechanical to electrochemical by new activated materials to develop actuators with similar characteristics to their biological counterparts [17]. A lot of research is devoted to the articulation and dexterity with high efficiency and low weight and cost. According to Bradley et al. [18] significant changes in mechatronic systems and their configuration and this is one of the motivations for updating or even introducing a new version of the mechatronics index. This paper is inspired by the robot abilities that have been presented to evaluate the performance of robotic systems [19]. Taking into account that a robotic system belongs to mechatronic systems and excluding special abilities that are exclusive to robotics, the revision of existing mechatronic indices is considered.

In this paper, the development of a new index is proposed for use in the conceptual design of mechatronic products and systems; the components of this index are derived by investigating the advances of the mechatronic systems. The mechatronic abilities as well as their scoring are analysed systematically, and the aggregation of the new criteria is based on a non-linear fuzzy integral. The contribution of this paper is twofold: (a) The granulation of mechatronic design criteria for facilitating their influence estimation and the examination of their interaction. (b) The adaptation of the robot abilities to mechatronics criteria to be used in the conceptual design phase for the derived alternatives evaluation. The mechatronic ability levels are considered to support the designer in order to estimate the degree of each ability fulfillment. The conceptual design of a small firefighting robot is presented as a case study for demonstrating the solution evaluation by using the proposed criteria and mechatronic index.

## 2. Concept evaluation in mechatronics design

A systematic design process, have well-defined phases beginning form the product/system definition and ends with the product/system support [20]. In this paper, two phases are under consideration, namely the product/system definition and the conceptual design phase and particularly the methodology for concept evaluation shown in Fig. 1.

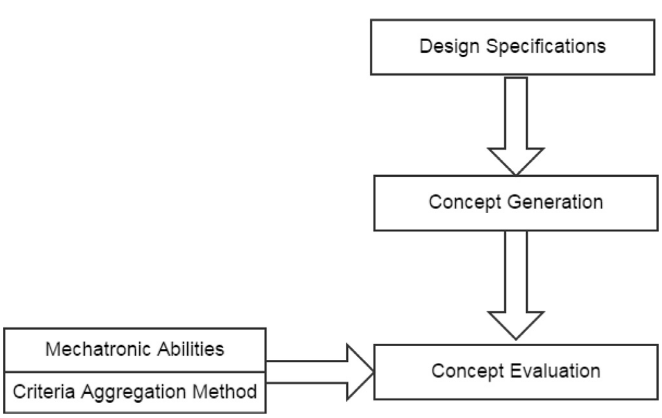


**Fig. 1.** Basic processes in the mechatronics conceptual design.

In the product/system definition, the engineering specifications and the design constraints are derived. In [20], the description of mechatronic system requirements in terms of three types of flows was proposed: Energy flow, Materials flow and Information flow. This description is transformed to functions or subfunctions that the system must accomplish, and this mapping can be represented by an hierarchical model [21].

Concept generation and concept evaluation are critical processes of mechatronics design, where a set of generated solutions are mapped to the set of design specifications that were determined in the previous phase. A design candidate is a synthesis of the derived alternative solutions to implement all the subfunctions. According to Ullman [20], the evaluation and decision making during the conceptual design phase is difficult due to the very limited knowledge and data to be used for the selection of the best concept. The concept evaluation is still subjective and the reliability of the decisions are based mainly on the experience of the designer. However, the mechatronics research community puts effort to develop tools and processes in order to augment the objectivity and reduce the subjectivity of the evaluation. In this direction, this paper proposes a set of mechatronics criteria aggregated by an index that can be used to compare the design alternatives. In addition, successful application of the proposed approach implies that the concepts reached the required level of refinement to be evaluated as mechatronic. In the case that this level is not reached, more time should be spent in the concept generation and refinement of the alternative solutions.

Assuming that for each subfunction $DSF_i$, $i = 1, \ldots n$ a set of concepts $C_{i,j}$, $j = 1, \ldots, m$ are generated. A design alternative $DA_k$ is a set $DA_k = \{C_{1,a}, C_{2,b}, \ldots, C_{n,z}\}$, where $C_{1,\ a}$ is the $a$ concept that satisfies the $DSF_1$ subfunction.

The feasible design alternatives must satisfy two conditions: (a) it meets all the design specifications and (b) it includes all the necessary software and hardware components. If both conditions are satisfied, then the feasible design alternatives should be evaluated using the mechatronics index to select the best one. The proposed new index is a revision of the one presented in [8], and shares some characteristics with the MDQ presented in [7]. Meeting task requirements and matching [7] are considered to be very important and if those two conditions are not satisfied then the design alternatives are discarded. Both conditions are taken into account in concepts generation and the design alternatives not satisfying these conditions are not considered in the evaluation, e.g. a force control law without a force sensor does not meet the matching condition.

The motivation of the present paper originates from the recent advances of the mechatronic systems. The evolution of mechatronic systems and products that includes embeded systems, self-contained smart devices, advances in HMI etc., as it is presented in the next section justifies the reconsideration of the mechatronic index. The introduction of the new criteria makes the design evaluation more detailed, and facilitates the designer's tasks. In the following two sections, the new criteria and their aggregation in the new mechatronics index are presented.

## 3. Mechatronic abilities

The selection of the criteria to evaluate mechatronic systems is based on the collective knowledge presented in the Multi-Annual Roadmap (MAR) for Robotics in Europe [19]. In the following, their mechatronics relevance is justified based on the aforementioned robotic abilities, while the reasons for excluding some of them are explained. These robot abilities are defined in a way that is independent of any particular robot type or application domain. The list of nine abilities was intended to cover all the richness of the current and expected robot characteristics and performance. The abilities found in MAR are the following: