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

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## ABSTRACT

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.

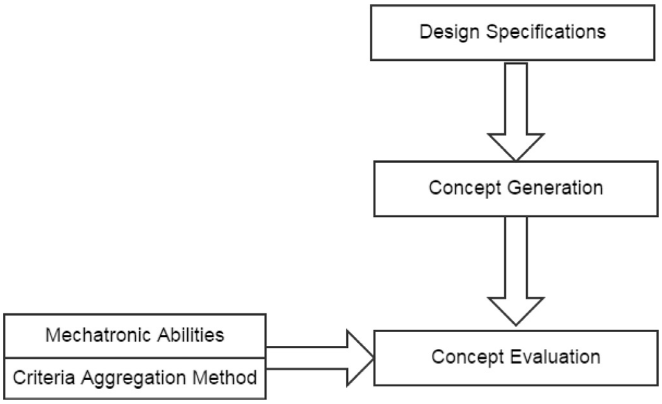

**Fig. 1.** Basic processes in the mechatronics conceptual design.

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 $DSF_i$, $i = 1, \dots n$ a set of concepts $C_{i,j}$, $j = 1, \dots, m$ are generated. A design alternative $DA_k$ is a set $DA_k = \{C_{1,a}, C_{2,b}, \dots, C_{n,z}\}$, 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:

- Adaptability
- Cognitive ability
- Configurability
- Decisional autonomy
- Dependability
- Interaction ability
- Manipulation ability
- Motion ability
- Perception ability

In the present paper, these abilities are thoroughly investigated to identify their suitability to be used in evaluating mechatronic conceptual design solutions. The ability levels appeared in [19] are adapted to the mechatronics criteria scoring. Abilities provide a basis for setting performance satisfaction degree of the metrics and are specified with desired levels for system performance. According to Ref. [19], each robot ability is identified with the current state of the art, and expected research targets that might be reached in the near future.

The selection and conversion of the proper abilities into mechatronics criteria is based on the applicability to any mechatronic system. In the following, each criterion is shortly described along with the levels of its fulfillment or the degree of its satisfaction. For each criterion, the initial number of levels [19] is reduced and a normalized score for each criterion is assigned to be suitable for the formulation of the proposed mechatronics index. There are many scaling types for scoring and evaluation in design, and there is a great dispute concerning the superiority among them [22], as well as, the absence of zero level has been criticized. These scales maps linguistic variables into arithmetic scales that makes the aggregation process easier. In [23], a five point (1–5) linear scale is proposed to be used for concept selection in conceptual design. It is also suggested a finer, nine point linear scale, to be used if the time and the effort are available. In this paper, it is assumed that the progression of the levels advances the characteristics of the system linearly so a linear interpolation is enough to map each level to a score. The number of the levels in every criterion is different so it is decided to scale the criteria in the same universe of discourse. In the highest (lowest) level of each criterion the maximum (lowest) score is assigned which is equal to one(zero). The score of the intermediate levels are assigned linearly between 0 and 1.

The above assumption lowers the burden to find the suitable scale for each criterion independently but it does not take into account the technology advancement from one level to the next. A different judgment scale could be more informative based on the maturity of the technology and this scale should be revised every time the number of levels are changing. However, this work overtakes the contribution of this paper and is left for future work. A suitable mapping of the criteria to scoring methods will provide even more realistic results during the conceptual design phase.

*Configurability*

Considering the structure, more and more of the current mechatronic systems are modular, built with self-contained modules including sensors, actuators, transmission etc., which are interconnected to process, transform and transmit material, energy and information. Reusable software modules are incorporated so operations and functions can be easily configured on-line, which is close to service oriented architecture approach. Reconfigurable systems maintain a high performance level by changing quickly their configuration and with reduced cost compared to the alternative of multiple fixed configuration systems. Modularity and self-optimisation ability enable these configuration changes by replacing the specified modules and updating automatically their interfaces. Last years a lot of papers proposed the design of reconfigurable mechatronic systems apart from robots (Fig. 2), such as race cars [24], manufacturing systems for mass customization [25], surface planetary vehicles [26] and variable stifness joints. The score scaling for the configurability levels is shown in Table 1.

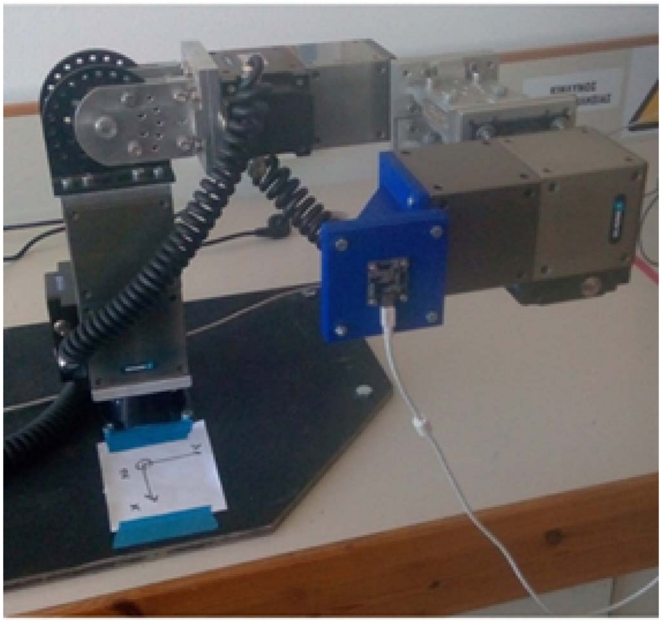

**Fig. 2.** Metamorphic manipulator with two pseudojoints.

**Table 1**
Levels and scaling for configurability.

| Level | Description | Normalised score |
|---|---|---|
| 0 | Single or non-alterable configuration | 0 |
| 1 | User defines the system configuration in the beginning of each cycle of operation | 0.25 |
| 2 | The reconfiguration is made during the cycle of operation | 0.5 |
| 3 | System alter its own configuration autonomously from a pre-determined set of alternative build-in configurations | 0.75 |
| 4 | The system is able to alter its own configuration in response to changing conditions that are not pre-programmed or predetermined | 1 |

*Adaptability*

Adaptability is the ability of a system to adapt in order to deliver intended functionability under varying conditions by changing the values of the design parameters either actively (on-line), or passively (off-line) [27]. The term adaptive is used mostly in the control of mechatronic systems with parametric uncertainty. In the literature, the boundaries between configurability and adaptability are not clear and those terms are used by some authors as alternative definitions of the same concept. In practice, there is an overlapping between the definitions but adaptation is mostly devoted to the parameter change rather than to the structure change. Examples of adaptable mechatronic systems are devices for ultra-precise, adaptronic and high-tech measurement and dimensional control [28], adaptive mechatronic systems for cars, adaptive CNC machines etc. The adaptability scaling scores are shown in Table 2.

*Interaction ability*

Recently, the concept of Human Adaptive Mechatronics (HAM) appeared [29], where the key concept is to design a mechatronic system that includes the human in the control loop and modifies the functions and the structure of man-machine interface to improve the human's operational skills. In Fig. 3, the human and the robot are collaborating in order to complete a task by combining their complementary skills [30]. In Fig. 4, a smart car accelerates/decelerates and changes orientation by keeping safe distances along all directions. Interactivity is considered to most of the modern mechatronic systems either to facilitate the operation and/or the maintenance and repair. Interactive

**Table 2**
Levels and scaling for adaptability.

| Level | Description | Normalised score |
|---|---|---|
| 0 | There is no ability to adapt | 0 |
| 1 | The system behavior is self-evaluated and the need for parameter adaptation is recognized | 0.25 |
| 2 | The need of adaption is recognized and in addition, it can alter individual parameters based on local performance assessment | 0.5 |
| 3 | The adaptation concerns multiple parameter changes | 0.75 |
| 4 | The process of adaption is carried out by multiple agents | 1 |

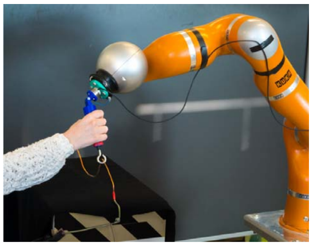

**Fig. 3.** Human and robot are cooperating in order to complete a task.

properties are provided by a versatile haptic interface to an assistive surgical mechatronic system [31,32]. The interaction scores can be evaluated using Table 3.

*Dependability*

Dependability is the ability of the system to ensure the reliability and performance integrity [33]. In this paper, dependability of mechatronic units is defined as the qualitative and quantitative assessment of the degree of performance, reliability and safety taking into consideration all relevant influencing factors [34]. Dependability specifies the level of trust based on the system performance. The dependability levels and the corresponding scores are shown in Table 4.

*Motion ability*

Motion ability is an important characteristic in mechatronic technology [35]. In this paper, the motion ability is considered to categorise the different types of motion control. Open-source 3d printers are systems with level 1 motion ability, while robotic vacuum cleaners are presenting abilities up to level 5. The scores of motion ability levels are shown in Table 5.

*Perception ability*

Current mechatronic systems should be capable to operate in unstructured, dynamic environments, therefore multiple distributed sensors (Fig. 5) and methods for sensor fusion and environment recognition are integrated into them [36]. The ability to detect the ego motion and to be informed and make accurate deductions about the environment based on sensory data is of high importance. The levels and the corresponding scores are shown in Table 6.

*Decisional autonomy*

A feature of many mechatronic systems is the devolution of functional responsibility to the system, freeing the operator or user to pay attention on the higher level functions associated with the deployment and applicability of the system [33]. Mechatronic systems with high decisional autonomy are equipped with logic and deduction tools, heuristics, model-based reasoning, machine learning etc. For example, a smart car (Fig. 4) is able to safely change lanes in order to reach its normal operation; an automatic camera autonomously adjusts it’s parameters in order to achieve more realistic colors etc. The levels and the corresponding scores are shown in Table 7.

**Table 3**
Levels and normalised values for interaction ability.

| Level | Description | Normalised score |
|---|---|---|
| 0 | There is no interaction ability | 0 |
| 1 | The operation of a system can be interrupted at any time by the user | 0.2 |
| 2 | System and user are isolated | 0.4 |
| 3 | System’s work space is divided into safe and unsafe zone according to the user space. | 0.6 |
| 4 | The human–system synergy is considered, while the system checks for dangerous motions/forces | 0.8 |
| 5 | Recognition of the conditions under which the system should have a safe mode behavior when uncertainty is detected | 1 |

**Table 4**
Levels and normalised values for dependability.

| Level | Description | Normalised score |
|---|---|---|
| 0 | There is no ability to predict failures | 0 |
| 1 | Measured only by estimation of the mean time between failures | 0.17 |
| 2 | Diagnose a failure and enters in safe operation mode | 0.33 |
| 3 | Diagnose a number of failures and it can recover from a proportion of them | 0.5 |
| 4 | Diagnose failures and its consequences to its specific or general tasks | 0.67 |
| 5 | Communicates its failures to other systems in order to rearrange the aggregate sequence of tasks and keep system’s mission dependable | 0.83 |
| 6 | Predict a failure and act to prevent it | 1 |

**Table 5**
Levels and scores for motion ability.

| Level | Description | Normalised score |
|---|---|---|
| 0 | No motion | 0 |
| 1 | Predefined motions in a sequence using open-loop control | 0.2 |
| 2 | Predefined movements in a sequence using closed-loop control | 0.4 |
| 3 | Position or force constrained motions | 0.6 |
| 4 | Reactive motion | 0.8 |
| 5 | The system is able to plan its motions by optimizing of a set of parameters | 1 |

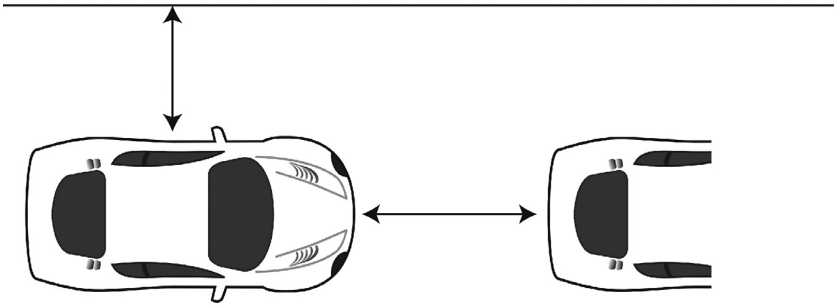

**Fig. 4.** A smart car interacting with the environment and other smart cars.

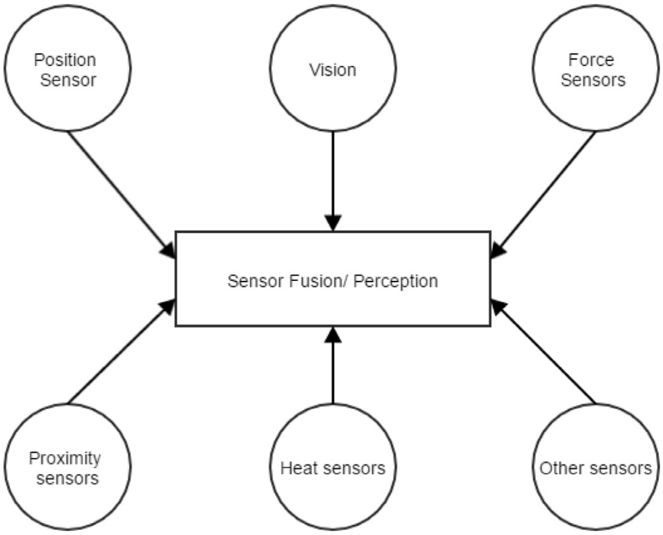

**Fig. 5.** Fused sensors used for perceiving the environment.

**Table 6**
Levels and normalised scores for the perception ability.

| Level | Description | Normalised scores |
|---|---|---|
| 0 | There is no ability to perceive data | 0 |
| 1 | Sensors are used to collect data concerning critical physical quantities, which are used to change directly it's behavior | 0.14 |
| 2 | The sensor information is processed and used to change the system's behavior indirectly | 0.29 |
| 3 | Multiple sensors are used to create a unified model of the environment | 0.43 |
| 4 | The system is able to extract features of the environment by sensing a region of it | 0.57 |
| 5 | Processed features are extracted by the data for better environment interpretation | 0.71 |
| 6 | Objects are identified using an object model | 0.86 |
| 7 | Processed data are used in order to infer about properties of the environment | 1 |

In the following, the abilities and their levels for representative mechatronic systems are considered to illustrate the proposed approach. Typical mechatronic systems that have the aforementioned abilities are modern smart cars, where multiple sensors perceive the environment and their internal functionality (operational conditions) to remain reliable and functional. High efficiency, low energy demands, low noise emissions etc., are some of the adaptation objectives. Autonomous vehicles have high decisional autonomy and motion ability as they can autonomously plan their motions with respect to parameters' optimization and compensating for dynamic events occurring in the environment. While multiple aspects of safety are critical in automotive, only the safe human-machine interaction is considered in this work. Dependability is a major quality factor for modern cars.

**Table 8**
Association of the components with the mechatronics index presented in [8].

| | Flexibility | Intelligence | Complexity |
|---|---|---|---|
| Configurability | X | | X |
| Adaptability | X | | X |
| Motion ability | X | | X |
| Decisional autonomy | | X | X |
| Human–machine safety | | X | X |
| Dependability | | X | X |
| Perception ability | | X | X |

Although seven of the nine abilities do find implementation in the car system, this is not the case for manipulation ability and cognitive ability. The modern car¥ example exposes that certain abilities are so strongly correlated with robots that their use as general mechatronic criteria can not be justified at the moment. For this reason, these abilities are not considered in the formulation of the proposed mechatronic index. That does not mean, of course, that these abilities must be excluded from any evaluation. For example, evaluating a car-washing machine the manipulation criterion should be considered and in the evaluation of a sophisticated manufacturing machine the cognitive ability criteria could be of high importance.

In [8], the three main characteristics of mechatronic systems are used as criteria for the formulation of the mechatronic index: intelligence, flexibility and complexity. The selected mechatronic abilities are closely associated with these three components of the mechatronics index as it is presented in Table 8.

The intelligence level of a system is determined by its control functions and/or it's ability for information processing. Intelligent functions such as self-diagnosing and self-repair support the dependability. The functions of negotiation and self-organization are correlated to decisional autonomy. The functions of supervision, fault diagnosis and coordination of processes are strongly dependent to the system ability to perceive. The flexibility component depends strongly on the system's configurability and adaptability.

Criteria like the cost and complexity should be used as well in the concepts evaluation. It is well known [8] that by increasing the intelligence and flexibility, the complexity is increased. Complexity is a system's characteristic which is calculated using a wide range of metrics [8]. The number of components, the interconnections among them, the degree of system's/component's customization are some of them. The detailed investigation of the complexity of mechatronic systems is out of the scope of this paper and is used only for completeness of the evaluation in the presented design case.

## 4. The aggregation function

The presented multiple abilities/criteria are aggregated in the

**Table 7**
Levels and normalised scores for decisional ability.

| Level | Description | Normalised scores |
|---|---|---|
| 0 | There is no ability to take decisions | 0 |
| 1 | The system is fully dependant to user decisions | 0.1 |
| 2 | The system makes decisions to choose its behavior from predefined alternatives based on basic perception and user input | 0.2 |
| 3 | It process the inputs and makes decisions continuously | 0.3 |
| 4 | Moment to moment decisions about the environment are taken | 0.4 |
| 5 | Internal model of the environment is used | 0.5 |
| 6 | The sequence of predefined sub-task is decided to perform a higher level task | 0.6 |
| 7 | Adaptation of its behavior to accommodate tasks constraints | 0.7 |
| 8 | The strategy altered as the system gathers new knowledge about the environment | 0.8 |
| 9 | Decisions about actions are altered within the time frame of dynamic events that occur in the environment | 0.9 |
| 10 | The system can fully compensate in real time events of the environment by altering its tasks and in the highest level | 1 |

proposed mechatronic index to facilitate the concepts evaluation. The aggregation methods may be categorised by the decision making approach in mechatronic design as well as by the interaction of the criteria. Usually, t-norms and averaging operators are used to model evaluation measures excluding t-conorms [8]. The aggregation methods for considering or not the interaction between the criteria are classified in:

- t-norms and averaging operators for representing independent criteria
- Choquet integral for interacting criteria.

More details concerning the requirements of the aggregation functions can be found in [12].

Designers usually consider that the criteria are independent to simplify the decision-making problem. However, for selecting the most appropriate aggregation function, it is important to identify the degree of interaction among the considered criteria. The interaction modelling can be identified by the investigation of the interactions inherited in the designed/evaluated system or deliberately specified by the designer according to his/her experience or intuition.

In the first approach, the relations are based on the fact that some levels of certain criteria are prerequisites for other ones of the dependent criteria. Interactions between criteria can be determined by the investigation of each level of a criterion with respect to other criteria levels. In this paper, an initial investigation is made for finding the lower level of abilities that depends on other criteria. A case is considered and the results are shown in Table 9.

To illustrate the approach of the criteria dependency investigation an exemplary case is presented. A mechatronic system to reach a configurability level 2, it means that there is a Dependability level 1, a decisional autonomy ability of level 2 and a Perception ability of level 1. This situation is happening when an autonomous reconfiguration is needed to overcome a failure.

In the first column of Table 9, the considered criterion level is presented. The rest of the columns shows the dependencies of this criterion level on other criteria levels. In order to obtain these dependencies every criterion/level is investigated exhaustively with all other criteria. In addition, this investigation is unidirectional and the inverse dependence is not applicable. For example, in Table 9 it is found that the 2nd level of configurability has a dependence with the 1st level of Dependability. This does not infer that the 1st level of Dependability depends on the 2nd level of configurability. Considering all the combinations of dependencies, at most 1414 (every level of each criterion with the sum of all other criteria excluding level 0) investigations should be made to determine at most 222 dependencies (37 levels in total). An exhaustive presentation overcomes the scope of the present paper.

The choice of using interacting or not criteria, as well as the interaction among them maps the designer priorities to the evaluation process. The process of determining the importance of interacting criteria requires more effort than the decision making with non-interacting criteria, but the evaluation is more reliable and objective.

Choquet Integral is a nonlinear fuzzy integral, which has been successfully used for the aggregation of interacting criteria [12]. It allows the designer to incorporate interactions into the evaluation process by providing an appropriate weighting factor not only for the importance of each criterion, but also for every subset of criteria. The most common interactions are redundancy, synergy ad compensation. The last one is considered, when a bad score of a criterion can be compensated by a good score of another one. Intolerant or tolerant criteria are expressed through pass or veto effect, respectively.

**Table 9**
Dependencies between criteria.

| Criterion/Level under consideration | Dependencies | | |
|---|---|---|---|
| Configurability level 2 | Dependability level 1 | Perception ability level 1 | Decisional autonomy level 2 |

**Table 10**
Interactions between criteria.

| Interaction | Description | Relation |
|---|---|---|
| Positive correlation | Good score in criterion $x_i$ implies a good score in criterion $x_j$, and vice versa | $\mu(x_i, x_j) < \mu(x_i) + \mu(x_j)$ |
| Negative correlation | Good score in criterion $x_i$ implies a bad score in criterion $x_j$, and vice versa | $\mu(x_i, x_j) > \mu(x_i) + \mu(x_j)$ |
| Veto effect | A bad score in criterion $x_i$ results in a bad global score | $\mu(T) \approx 0$ if $T \subset X - \{x_i\}$ |
| Pass effect | A good score in criterion $x_i$ results in a good global score | $\mu(T) \approx 1$ if $T \subset X,\ x_i \in T$ |

Considering a finite set of criteria $X = \{x_1, \ldots, x_n\}$, Choquet integral requires a weighting factor for the global importance of each criterion as well as for each subset of criteria [7]. The weight factor of a subset of criteria is represented by a fuzzy measure $\mu$ on the universe $X$ satisfying:

$$\mu(\varnothing) = 0;\ \mu(X) = 1;\ A \subseteq B \subseteq X \Rightarrow \mu(A) \leq \mu(B) \tag{1}$$

Note that Choquet integral is *additive* and therefore it suffices to define the n coefficients (weights) to determine the complete measure. In general, the $2^n$ coefficients corresponding to the $2^n$ subsets of X should be defined. These coefficients are dictated by the set of relationships between the criteria. In this paper, the 2-additive case [37] is adopted, where the importance and interactions are limited in pairs of criteria. In the context of this paper, four types of such relations are considered and are presented in Table 10.

After defining the weight factors, the evaluation process is advanced in the actual computation of the aggregated mechatronic index. Given the set of criteria $X$ and the fuzzy measure $\mu$, the Choquet integral of a function $f$: $X \to [0, 1]$ with respect to $\mu$ is defined by [12]:

$$C_\mu = C_\mu(f(x_1), \ldots, f(x_n)) := \sum_{i=1}^{n} (f(x_i) - f(x_{i-1}))\mu(A_{(i)}), \tag{2}$$

where $(.)_{(i)}$ indicates that the indices have been permuted so that $0 \leq f(x_1) \leq \ldots \leq f(x_n) \leq 1$, $f(x_0) = 0$ and $A_{(i)} := \{x_i, \ldots, x_n\}$.

If two or more solutions come up with the same index value, then all solutions are considered equivalent. The choice of the best solution is up to the designer, and the decision can be based on the considered importance of each criterion. The value of the proposed method is that the evaluation process is enriched so the designer can choose easily the best one according to his preferences.

## 5. The case study

The proposed index is used for the design of a small firefighting robot designed and constructed for student robot competitions. The main requirements are that the robot must be able to navigate in a small maze for searching and extinguishing small candle flames. The dimensions of the track are predefined and there are a number of penalties in case of e.g. wall touching and false¥ extinguishing. The fastest and the most accurate fire finding robot wins. In Table 11, the processed design information is presented in terms of Energy, Materials and Information flow [20].

In the following phase, the derivation of the alternative solutions is conducted. The design tree with the subfunctions is presented in Fig. 6. The components that are considered to configure the robot are classified in the following:

**Table 11**
Flow of energy, materials and information.

| Energy flow | Material flow | Information flow |
|---|---|---|
| Transformation of electrical power to kinetic | Flow of extinguishing air through system | Wall detection |
| Transformation of kinetic power to thermal | Motion of the robot | Flame detection |
| | | Control of the extinguishing system |
| | | Control of motion |
| | | Information processing and decisions |

- Sensors: For detecting the walls ($DSF_1$) and the flames ($DSF_2$).
- Information processing: A software component that is responsible for the motion planning of the robot ($DSF_3$) and the fan motor management ($DSF_4$).
- Power components: Energy storage ($DSF_5$) and energy management subsystems ($DSF_6$).
- Actuators: For the powertrain ($DSF_7$) of the robot, and the fan motor ($DSF_8$).
- Mechanical Design: For the chassis ($DSF_9$), that includes all the subsystems, the wheels/tires ($DSF_{10}$) and the fire detection/extiguishing module ($DSF_{11}$).

Then, the design tea generates the multiple concepts for every subfunction. For example for the distance sensor infrared and ultrasonic sensors, were considered. However, for some requirements the design team could not find multiple solutions; e.g. for the Fire Detection module only one type of sensor is selected. In this paper, for reasons of simplicity, the four subfunctions that had multiple solutions are presented in the following:

- Distance Sensor: $DSF_1 \rightarrow C_{1,j} \in \{Infrared, Ultrasonic\}, j = 1, 2$
- Motion Planning Algorithm: $DSF_3 \rightarrow C_{3,\ j} \in \{Localisation,\ Wall\ Following, Random\}, j = 1, 2, 3$
- Powertrain actuators: $DSF_7 \rightarrow C_{7,\ j} \in \{DC\ motors, Stepper\}, j = 1, 2$
- Chassis: $DSF_7 \rightarrow C_{9,\ \ j} \in \{Differential\ Drive,\ Double\ Chassis,\ Sychnronous\ drive\}, j = 1, 2, 3$

In practice, the alternative design solutions of the mechatronic system are derived by listing all combinations of the alternative design solutions to the subfunctions. In this case, the set of design alternatives is equal to 36. In order to accelerate the evaluation process, a selection method based on the experience of the design team is used. All the technically infeasible solutions are immediately rejected based on the following constraints:

- The design team is not familiar with the relevant technology.
- The assembly between selected parts is unacceptably complicated.
- The cost of some components is too high.

Taking into account the above constraints, the set of the design alternatives to be further evaluated are the following (Table 12):

- $DA_1 = \{C_{1,1}, C_{3,1}, C_{7,1}, C_{9,1}\}$
- $DA_2 = \{C_{1,2}, C_{3,2}, C_{7,2}, C_{9,1}\}$
- $DA_3 = \{C_{1,1}, C_{3,1}, C_{7,1}, C_{9,2}\}$
- $DA_4 = \{C_{1,1}, C_{3,3}, C_{7,1}, C_{9,3}\}$

.

The first two alternative solutions $DA_1$ and $DA_2$ are using the differential drive type, where the control of motion is achieved by adjusting independently the speed of the two wheels, which are symmetrically mounted to the chassis. These solutions differ in the motion planning algorithm too: The wall following algorithm is a well known method for scanning all external walls, while the localisation algorithm measures precisely the robot's location with respect to a fixed frame and simultaneously tracks possible locations of internal rooms. In $DA_1$, the actuators are DC motors equipped with rotational encoders for the estimation of the traveled distance, while in $DA_2$, stepper motors are selected. In addition, the distance sensors selected for the $DA_1$ and the $DA_2$ are infrared and ultrasonic, respectively.

In $DA_3$, the double chassis is included, where two identical chassis are on top of each other along perpendicular directions of the fixed wheels (see Fig. 7). A linear actuator brings one of them in touch with the floor depending on the motion direction. The actuators in $DA_3$ are DC motors, infrared sensors are used to detect obstacles and the motion planning algorithm is based on localisation.

In $DA_4$, the robot moves by a synchronous drive shown in Fig. 8. Three turnable wheels are assembled in each corner of the triangular chassis, which are coupled with a synchronous belt to be turned to the same direction at any time. When the wheels run with the same speed, the robot moves along a straight line. The orientation change of the robot is achieved by rotating independently the wheels with different speeds, provided that they are equipped with encoders.

In the next phase of the conceptual design, the appropriate set of

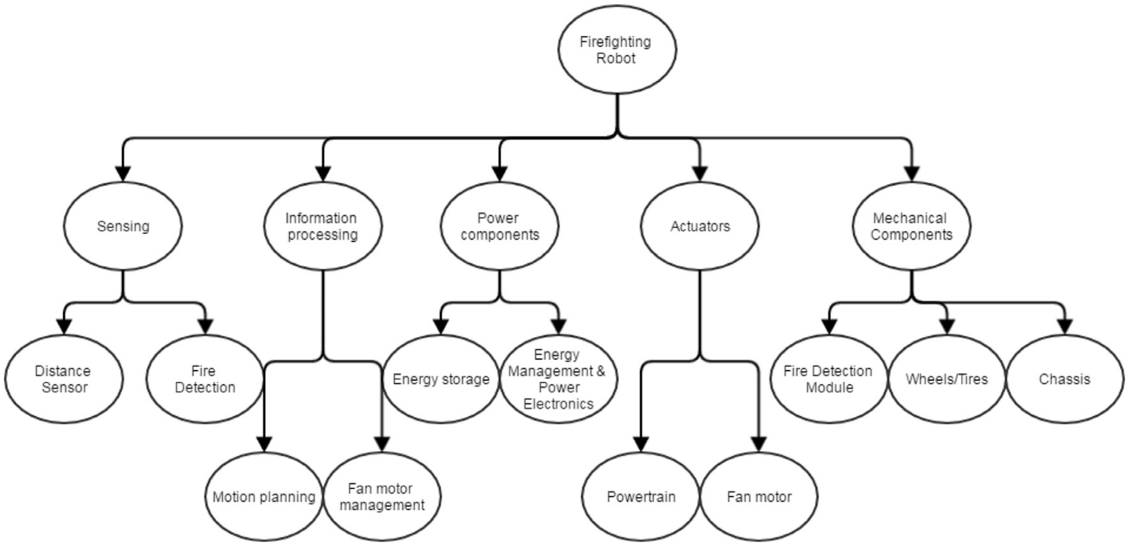

**Fig. 6.** Design tree for firefighting robot.

**Table 12**
The four alternative solutions selected by the design team.

| Design alternatives ($DA_k$) | $k = 1$ | $k = 2$ | $k = 3$ | $k = 4$ |
|---|---|---|---|---|
| Distance sensor | Infrared | Ultrasonic | Infrared | Infrared |
| Motion planning algorithm | Localisation | Wall following | Localisation | Random |
| Powertrain actuators | DC motors | Stepper motors | DC motors | DC motors |
| Chassis | Differential drive | Differential drive | Double chassis | Synchronous drive |

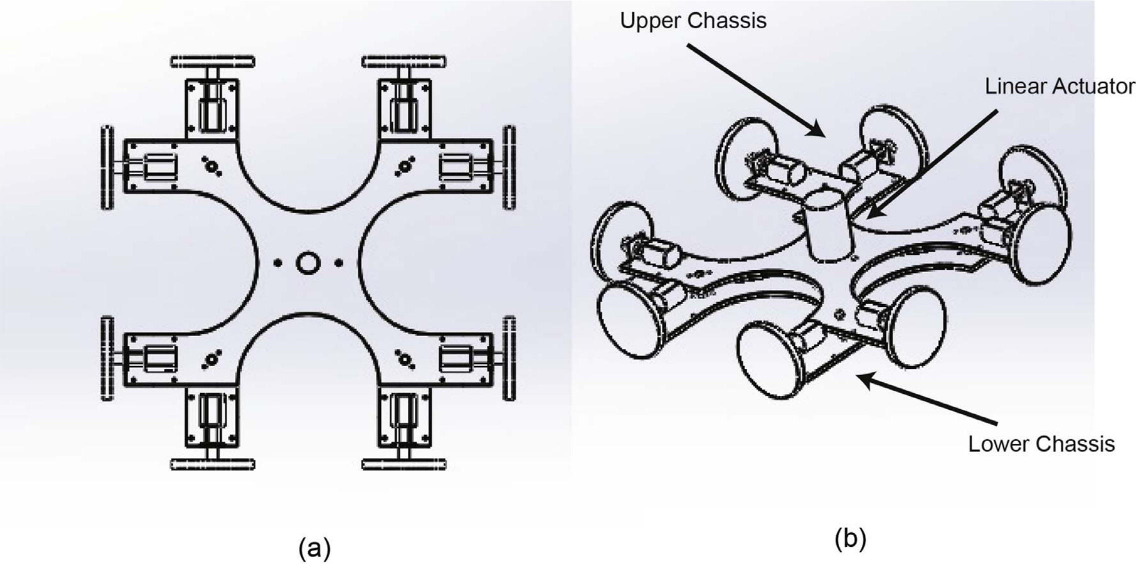

**Fig. 7.** Robot design with two identical chassis. (a) Top view (b) Orthographic projection showing the configuration of the two chassis.

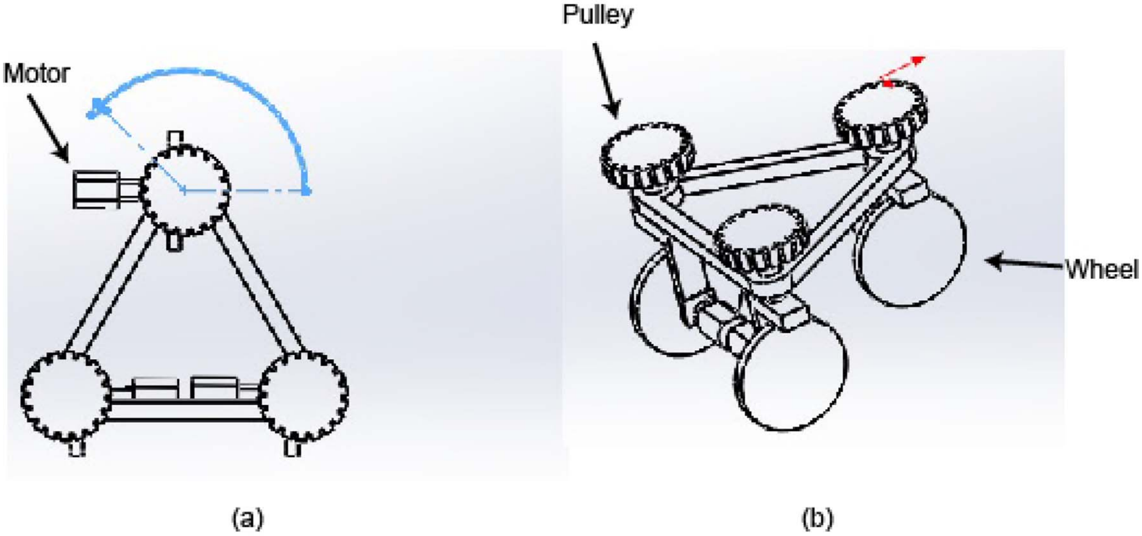

**Fig. 8.** Robot design with synchronous drive. (a) Top view (b) Orthographic projection showing the configuration of the pulley with the wheel.

criteria is determined. The proposed seven mechatronic abilities are considered plus the criteria of Labor/Cost and Complexity. For the Labor/Cost the sum of the resources utilised in building the mobile robot are taken into account. . It is an estimation based on the number and type of components that should be manufactured or purchased, and the manhours that should be spent for the assembly of the mechatronic system, writing software for control laws and/or adjusting control parameters and performing tests. This criterion depends on the familiarity of the design team with specific technologies and skills involved in the considered mobile robot. The score of each criterion for each alternative solution are shown in Table 13.

For the calculation of the Choquet Integral the fuzzy measures are required that are defined as it is shown in Table 14. The values representing the importance of the single criteria must be lower than the ones assigned to pairs of the criteria in order to satisfy Eq. (1). For simplicity, the importance of each criterion is specified by two values (0.16 and 0.05) corresponding in high and low importance, respectively. With the selected values, the designer has a wide range of values in order to determine the importance of the pairs of criteria. The designer should be careful, since a choice of very low and/or very high values limits the ability to define interaction. For example, assuming a low importance equal to $\mu(x_1) = 0.01$ and a high importance equal to

**Table 13**
Scores of each criterion per alternative solution.

| Criteria ($x_i$) | $DA_1$ | $DA_2$ | $DA_3$ | $DA_4$ |
|---|---|---|---|---|
| Configurability | 0.25 | 0.25 | 0.00 | 0.25 |
| Adaptability | 0.00 | 0.00 | 0.00 | 0.00 |
| Dependability | 0.33 | 0.16 | 0.33 | 0.33 |
| Interaction ability | 0.00 | 0.00 | 0.00 | 0.00 |
| Motion ability | 0.4 | 0.2 | 0.4 | 0.4 |
| Perception ability | 0.14 | 0.14 | 0.14 | 0.14 |
| Decisional autonomy | 0.45 | 0.45 | 0.45 | 0.45 |
| Labor/cost | 0.5 | 0.5 | 0.5 | 0.1 |
| Complexity | 0.5 | 0.5 | 0.25 | 0.1 |

**Table 14**
Single weights.

| Criteria ($x_i$) | Weight ($\mu(x_i)$) |
|---|---|
| Configurability | 0.16 |
| Adaptability | 0.05 |
| Dependability | 0.16 |
| Interaction ability | 0.05 |
| Motion ability | 0.16 |
| Perception ability | 0.05 |
| Decisional autonomy | 0.16 |
| Labor/cost | 0.05 |
| Complexity | 0.16 |

**Table 15**
Importance of interactions.

| Criteria | Relation | Set weight ($\mu(x_i, x_j)$) |
|---|---|---|
| Labor/cost complexity | Negative correlation | $\mu(\mathit{Labor/cost}, \mathit{complexity}) = 0.30$ |
| Labor/cost motion ability | Negative correlation | $\mu(\mathit{Labor/cost}, \mathit{motionAbility}) = 0.30$ |
| Complexity configurability | Positive correlation | $\mu(\mathit{Complexity}, \mathit{configurability}) = 0.18$ |

**Table 16**
The evaluation results.

| Solutions | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| Scores | 0.358 | 0.299 | 0.252 | 0.270 |

$\mu(x_2) = 0.16$ then the positive correlation among them is impossible to be defined since the following constraints must be true: $\mu(x_1) + \mu(x_2) > \mu(x_1, x_2)$ and $\mu(x_1, x_2) > \mu(x_2)$.

The importance of each pair is defined according to the interactions between criteria. In the context of fire-fighting robots competition, the robots have to move autonomously, therefore Decisional Autonomy is very important and is considered to have Veto Effect. The design team desires to reward systems with low Complexity and Labor/Cost , so the Labor/Cost and Complexity are negatively correlated. While designers strive to provide their systems with higher configurability, frequently the system becomes too complex. Configurability allows a more flexible functioning profile, which simplifies rather than complicates the robot. This profound relation is considered by the design team, which does not reward systems that presents good performance in both criteria. Motion Ability for a mobile robot is very important, so a dependable motion provides a clear advantage in the competition. The limited resources of Labor/Cost provides the essentials to either develop or equip the actual motion system and thus, the two criteria are connected with a Negative Correlation, which reflects a desire to reward a good performance for both criteria. All relations with the corresponding interactions are presented in Table 15. The above information is used to calculate the Choquet Integral (Eq. (2)) and the results are presented in Table 16, which shows that the best solution is $DA_1$. The $DA_1$ has the same performance characteristics with the $DA_4$, but the complexity and the cost of the latter solution are very high. In addition, $DA_3$ presents higher complexity, while the ability of the configuration is very limited. Finally, $DA_2$, is evaluated with lower dependability and motion ability compared to $DA_1$.

## 6. Conclusions

In this paper, a new mechatronic index is proposed for evaluating mechatronic alternatives in the conceptual design phase. The design criteria aggregated to the index are derived by investigating the mechatronic advances and from the Multi Annual Roadmap for Robotics in Europe, where the collective knowledge of experts is presented in a very compact form. After thorough investigation, seven robot abilities from the MAR are selected as generic mechatronic abilities and their adapted levels are scored. In formulating the proposed mechatronic index the complexity and the cost are taken into account on top of the seven criteria/abilities.

The importance of the criteria as well as their interaction is modelled with fuzzy measures and the discrete Choquet integral is used to formulate the design index. The 2-additive fuzzy measures are used to deal with the Choquet integral complexity risen from the considered interactive criteria.

The proposed mechatronics index is used to evaluate the alternative conceptual solutions for the design of a small firefighting robot. The design steps to determine the “best” solution among the conceptual design alternatives based on the proposed index are presented. The proposed index helped to select the alternative solution with the most important mechatronic characteristics.

The most important outcomes of this paper are the followings: (a). The designers can use a higher variety of criteria than using the previously proposed mechatronic indices to evaluate the conceptual design solutions. (b). The criteria have more scoring levels than the previously composed mechatronic indices helping the designers to justify their decisions for the selected concepts. (c). The designers have the ability to select the solution that will incorporate mechatronic characteristics. Particularly facilitates the rough quantification of a usually quite qualitative and intuitive evaluation of design solutions considering the mechatronic characteristics.

Future work includes: (a) to investigate and model the interactions within subsets of criteria with more than two members. (b) to develop a scoring method that maps better the advancement between the successive levels of each criterion and (c) to apply the method in other applications.

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