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A Design Approach for Complex Systems

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Abstract**:** ***The design of systems requires the integration of data from different fields (mechanical computer-aided design, electrical computer-aided design, automation, embedded software,.). The multi-technological character of Mechatronics makes the design of systems more complex. In this context a general knowledge of Mechatronics and Mechatronic products is necessary. The design problem of a mechatronic product requires the analysis of its structural, technological, and functional complexity. This paper presents an approach to the design of Mechatronic systems. This requires the characterization of the different types of the complexity of a product before presenting the design methodology, the modeling, and the simulation tools used in the different design phases.***

Keywords**:** ***Design process, Complex Systems, Mechatronic Design.***

I. INTRODUCTION

The appearance of mechatronic systems in the last twenty years or so can be considered a revolution for the industrial world. Indeed, the use of these systems has rapidly become widespread and currently influences almost all sectors of industry. In defining a mechatronic system, Chaabane says that the word "mechatronic system" can refer to both mechatronic components and mechatronic products. A Mechatronic product that has a partial level of Mechatronic integration, both functionally and physically. It combines mechanics with electronics and enables information processing. A product with the ability to process information, perceive, communicate, and act in its environment. It is characterized by a complete level of mechatronic integration, from the functional and physical point of view. Depending on the field of activity, the term "Mechatronic product" covers the notions of system, production equipment, autonomous subassembly, etc. [1]. Figure 1 illustrates the interconnection of the components of a Mechatronic system.

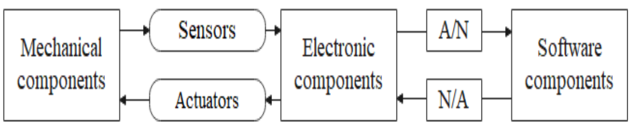

Fig. 1.Illustration of the Interconnection Of The Components of A Mechatronic System [2]

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The Mechatronic System (MS) in Figure 1 integrates mechanics, electronics, and software, but also hydraulic, pneumatic, and thermal systems.

This example shows that it is important that the system is designed as a whole. The synergy induced by mechatronic systems leads to an intelligent combination of technologies. It then leads to superior solutions and performance, which could not be achieved by separate applications [3]. NF E01-010 defines.

Mechatronics as an approach aiming at the synergic integration of mechanics, electronics, automation, and computer science in the design of a product in order to increase and/or optimize its functionality [4]. It should be noted that the aim of Mechatronics is to achieve an added value higher than the sum of the added values of the individual functions, i.e. it is not only a matter of assembling the components of different technological fields, but it is necessary to consider the Mechatronic system in its overall functionality during the whole design cycle as shown in figure 2 [5].

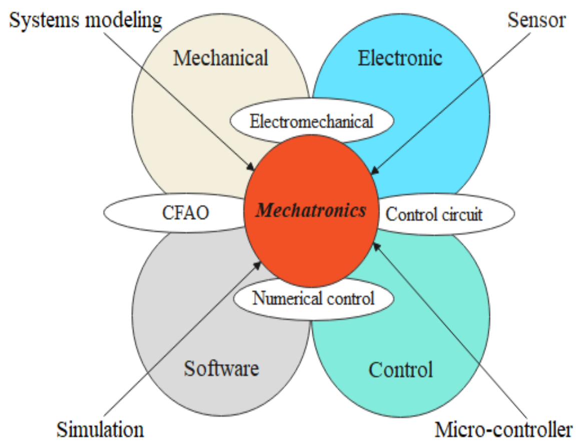

Fig. 2.Pluridisciplinarity of Mechatronics [5]

In order to study in detail the structure of a particular mechatronic system, it is important to recall the different canonical elements constituting a mechatronic system in general.

In a mechatronic system, the arrangement of these elements follows an architecture found in most automated systems consisting of three main parts: an action chain (also called the operating part (OP)), an information chain (also called the control part (CP)) and an acquisition chain [6]. If there is no acquisition chain, the system is said to be in an open loop. There is no way to control what is done. When this architecture (Figure 3) includes an acquisition chain, the system is said to be in the closed-loop. There is the feedback that gives the system a possibility of correction.

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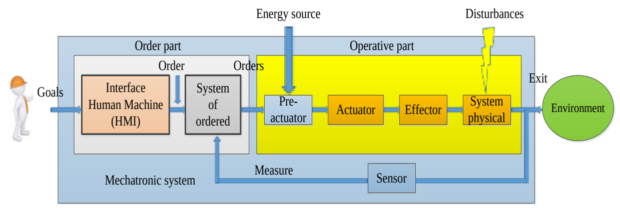

Fig. 3.The general architecture of a mechatronic system [6].

The control part, consisting of a man-machine interface and a control system, allows the comparison of the sensor signals with the setpoints to control the action chain. This action chain (pre-actuator, actuator, effector, and physical system) is a controlled system. The pre-actuator transmits energy to the actuators (high power) whose time forms are recorded according to the orders of the control part (low power). It is generally made up of distributors and contactors. The actuator converts the available energy (e.g. mechanical) into energy that can be used by the end effector (e.g. electrical). It usually consists of cylinders, electric motors, etc. The effector acts directly on the physical system. It can be, for example, manipulation tools such as pliers or cutting tools such as a drill. At the same time, the design of these systems has become increasingly complex due to their multidisciplinary nature [7] see Figure 7 in the Appendix. In this context, this paper aims to introduce the design of mechatronic systems. The design of these systems will be discussed after the analysis of the complexity of Mechatronic systems. The methodology of mechatronic design is discussed by addressing the modeling and simulation techniques and tools that can be used at each design level.

II. ANALYSIS OF THE COMPLEXITY OF A MECHATRONIC PRODUCT

Products can be characterized by simplicity or complexity using many methods (number of components, diversity of components, level of interdependence between them, product behavior, information flow, etc.) [8]. For Mechatronic systems, the complexity is usually structural, technological, and/or functional. The complexity of a system during pre-design can be defined based on the axiomatic approach proposed by Suh [9].

$$I_i = log_2\left(\frac{1}{P_i}\right) = -log_2\left(P_i\right) \quad (1)$$

With: I_i : the information content and P_i the probability of success of the functional requirements.

This metric evaluates the complexity of the adequacy of the physical architecture with respect to the functional requirements [10]. A metric characterizing the mechatronic complexity of a product is defined as follows [11] :

$$Mechatronic\ complexity = Complex\ (Mechanic \cdot Software \cdot Electronic) \quad (2)$$

The structural complexity of a mechatronic product basically indicates its components, their hierarchy, the links that connect them, the functional interactions between them, etc. [11]. The structural complexity is defined by equation 3 [13]:

$$Structural\ Complexity = \sum_{j=1}^{l} j \cdot N_j \quad (3)$$

With : N_j : the number of mechatronic elements at level j and l: the number of levels in the tree.

This metric allows to assess the complexity of mechatronic concepts already in the early design phases but does not take into account the multi-domain interactions. This shows the level of the structural complexity of mechatronic products already in the design phase. In addition to this, there is technological complexity. The technological complexity in mechatronics comes from the need for the complete integration of several technologies in a product. A mechatronic product is not only a marriage between mechanics and electronics but is more than a simple control system with complete integration of all this [14]. Due to the long compartmentalization of experts from different domains (mechanical, electronic, automatic, and computer), the diversity of design methods, the standards to be respected, the problem of management and knowledge exchange between experts, ... Researchers propose complexity metrics addressing size, couplings or interactions between elements and resolvability as illustrated in Table 1 [15], [16], [17].

Table I. Metrics of technological complexity.

Element	Description
The size	$C_{X_{size-process}} = \left[\begin{matrix} (M^0 + C^0 + P_{op}) \\ \cdot\ ln \left\| \begin{matrix} idv + ddv \\ +dr + mg \\ +a_{op} + e_{op} \\ +s_{op} + r_{op} \end{matrix} \right\| \end{matrix} \right]$ (1)
Couplings	$level * set\ size * number\ of\ sets + total$ (5)
Resolvability	$C_{X_{solvability}} = \sum \left(\begin{matrix} k_1 \cdot a_{op} + k_2 \cdot s_{op} \\ + k_3 \cdot e_{op} + k_4 \cdot r_{op} \end{matrix} \right)$ (6)
	$C_{X_{DOF\_prob}} = \left(\begin{matrix} \sum DOF(idv) + \sum DOF(ddv) \\ + \sum DOF(mg) - \sum DOF(dr) \end{matrix} \right)$ (7)
$C_{X_{solvability}}$	Measuring the complexity of the creditworthiness of a process
DOF	This is the degree of freedom, it is the result of the application of dr against, ddv and mg
M^0	Number of primitive modules available in a specific representation
C^0	Number of available relationships between all available modules
P_{op}	Number of unique process types
k_1, k_2, k_3 et k_4	Coefficient factors that account for the different reasoning complexities of the reasoning processes, the domain knowledge available and required for each operator, and the complexity of the designer to execute that operator
a_{op}	Number of analysis operators
e_{op}	Number of evaluation operators
r_{op}	Number of representation mapping operators
s_{op}	Number of synthesis operators
dg	Variable whose values are specified as the desired target of the design e.g. Target-Weight
idv	Variable whose values are controlled by the designer. Example: type of material, width, size, cross section.
ddv	A variable whose values are not directly controlled by the designer but are derived from independent variables, other dependent variables, and the design relationship. Example: length (of the beam), area (cross-section), weight, inertia.
mg	A variable that is used to determine how well the current design configuration meets the design objectives. For example, the differential pea.
dc	Variables that are constant in all domain-specific problems are not calculable or modifiable by the designer. Example: gravity.

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dr	Constraints that dictate the association between other design variables. These relationships can be used to propagate values between variables or validate values between variables. These can be used to define the type of objective. Example: Minimization (Objective-Weight, Weight), Equality ({Volume}, {Area, Length}), Equation ({Objective-Weight}, {Weight}, {Differential-Weight})

The functional complexity of mechatronic products results from the need for functional integration of the different components. Functional integration is defined by the NF E 01-010 standard as "a contribution of basic mechanical functions [4]. The use of simulation models allowing a multi-domain analysis of the system is required for components [11]. From the functional decomposition of a problem, Bashir and Thomson defined the complexity of a product (PC: Product Complexity) by the number of functions and the depth of their functional decomposition tree (hierarchies). The metric is expressed by the following relation [18]:

$$PC = \sum_{j=1}^{l} j * f_j \qquad (8)$$

$$f_j = \sum_{k=1}^{F_j} W_k \qquad (9)$$

Where W_k is the weight assigned to the function k of the level j, are the number of functions at a level j and l the number of levels. It should also be noted that the added value of a mechatronic product must be greater than the sum of the added values of its individual components [4], [14].

III. ANALYSIS OF THE DESIGN OF MECHATRONIC SYSTEMS

The study of complex product design theories and methodologies is an area that has been the subject of much research in recent years [19], [20]. Design is a complex process that allows going from a need (functionalities, performances) formulated with constraints to the detailed description of one or several solutions. The design process is generally iterative with the objective of meeting the requirements while satisfying the constraints. This is how Gero defines design as: "A process for arriving at a form from a formless description" [21]. To design modern (multi-technology, multi-component) products that are efficient and robust while reducing costs and lead times, designers must take into account requirements and constraints throughout the design process. Constraints can come from the customer, the designers, the design process, the manufacturing process, the tools, etc. The co-design of a complex product involves designers with different skills and different types of information that can be expressed differently depending on the designers' field of expertise. These designers must therefore work in synergy to propose solutions whose description is clear and well detailed. These solutions must meet feasible technical expectations. A design problem is specified as a set of functions, constraints to be satisfied, predefined components, and relationships between these different components [22]. According to this definition, solving a design problem means proposing a set of components with their interactions (physical and functional links, exchange of flows, etc.) allowing the functions to be carried out in compliance with the constraints. However, it may happen that some components do not yet exist at the time of the design. In this case, their description must enable them to be created before being integrated into the product [22]. The design process is done in several coherent and linked steps. The output of the previous step is usually the input to the next step. Several proposals are given in this sense. For example the Diagne process and the Pahl and Beitz process. The design process of a complex product can be summarized in three steps [15]: establishing the functional and physical accounting of the product with the needs and constraints, balancing the overall economics of the solution over all stages of the product's life, and finding the balance between constraints, performance, cost, schedule, and risk. On the other hand, Pahl and Beitz propose a decomposition of the design process into four (4) stages [23]: the elaboration of the specifications, the formalization, and specification of the principles, the overall design, and the detailed design. To design a product, one can start from new ideas to result in a new product or a modification and improvement of the existing product. There are two types of design: initial design and redesign. Each of these two types of design is in turn decomposed into two subtypes of design (redesign and creative design) [24]

IV. METHODOLOGY OF MECHATRONIC SYSTEMS DESIGN

In a competitive industrial environment, the traditional method which consisted in sequentially linking the disciplinary trades (mechanics, electronics, ...), design, manufacturing, assembly, distribution is no longer adapted. Indeed, this sequential process is too costly due to the sectorial and sequential definition of the parameters inherent to each trade and, moreover, leads to significant delays in the realization [25]. The sequentiality of the programmed and corrective activities also leads to a bad temporal localization of certain decisions. Faced with the current economic challenges, it is becoming essential to develop gateways aimed at making the tools and trades, specific to each discipline, interoperable in order to reduce development times, and therefore costs, and to make the company more reactive in a competitive context [26]. When designing new systems, projects are nowadays multidisciplinary in nature. More and more, systems are nowadays co-produced by project teams spread across several departments of the company or involving several companies on a common project. By using an efficient product development process, in an environment of efficient and creative cross-functional teams, it is possible to develop quality products quickly at competitive costs [25]. Generally speaking, the new strategy requires a parallel decision of a number of design activities called concurrent engineering. Concurrent engineering is a global multi-trade approach, a process that consists of engaging in parallel activities and tasks, services, and trades necessary for the development of the system.

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Concurrent engineering allows to optimize the design process of collaborative projects and to ensure the best coordination between the project stakeholders. The contribution of concurrent engineering is above all a gain in quality and time. The optimal sequencing of tasks ensures that the shortest path is followed and that problems can be anticipated because of the general sharing of information among team members. Concurrent engineering involves elements similar to those of mechatronic systems, such as the temporal character of the development process, development cycle (decomposition in phases: specification, design, manufacturing, verification, validation), the business aspect (mechanics, electronics, automation,...) intervene in the development, the multidisciplinary aspect (mechanics, electronics, software,...) and the systemic character (economic system, information system, production system, distribution system) [25]. Due to its complexity, a mechatronic system cannot be created by one person. However, it can be designed by a large number of people with different specializations provided that these people form a team [27]. Thus we observe a great analogy between concurrent engineering and the design of Mechatronic systems. Concurrent engineering makes it easier and faster to cope with changes in the system development process. This process involves steps that logically follow each other in a cycle and are well suited for the development of mechatronic systems. The different methods are mainly formed by the following three main phases: the pre-design or architectural design phase, the detailed design phase, and the assembly of the designed components [28]. Figure 5 shows us the process of system development.

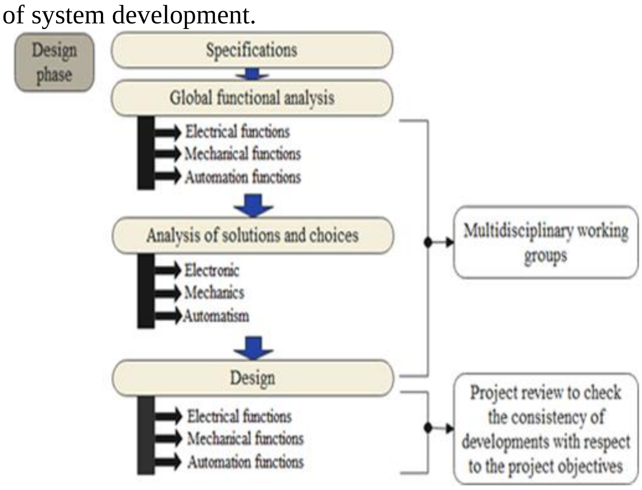

Fig. 4.System Development Process [3]

A mechatronic system consists of a computer, electrical, mechanical, ... These elements behave in different ways [29]:

- A computer element or program that behaves sequentially according to instructions for moving from one step to another. It is, therefore, a discontinuous system linked to conditional expressions;

- The other elements are real physical components, so they are subject to differential equations (possibly non-linear) completed by stress equations.

Mechatronic design tools should allow the understanding of the different domains of Mechatronics. In table 3, we present some tools according to the domains (mechanical, electronic, computer, and automatic) and the level of modeling (functional level, system-level, and component level).

Table II. Some Mechatronic Modeling Tools [30]

Disciplines	Functional level	Logic level	Physical level
Mechanics	SysML SADT APTE FAST	Modelica Matlab Sumilink Bond Graphs VHDL-AMS ADAMS	CATIA Solidworks ...
Electronics		Modelica Matlab Simulink Bond Graphs VHDL-AMS Spice	Speed Mentor Graphic ...
Control (Computer, automatic)	UML SysML	Modelica AUTOSTAR Matlab Simulink	Autostar-modelisar dSPACE(M)

V. CONCLUSION

Mechatronic systems are increasingly used in industry. All sectors are concerned: automotive, aeronautics, nuclear, space, and even fields like banking or medical. The development of a mechatronic system considered according to the concurrent engineering approach within the framework of a development cycle is a methodological approach to master the design of complex systems and products. In this paper, we have shown the complexities of a Mechatronic system according to its multi-technological aspect before presenting the methodology of designing a Mechatronic system, and finally, we have listed different modeling and simulation tools used during the design of these systems according to the different phases and levels depending on the disciplines of Mechatronics. For the validation of this approach presented in the article, it should be applied to design a Mechatronic system.

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