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A novel design approach for mechatronic systems based on multidisciplinary design optimization

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Abstract—In this paper, a novel approach for the multidisciplinary design optimization (MDO) of complex mechatronic systems. This approach, which is a part of a global project aiming to include the MDO aspect inside an innovative design process. As a first step, the paper considers the MDO as a redesign approach which is limited to the parametric optimization. After defining and introducing the different keywords, the proposed method which is based on the V-Model which is commonly used in mechatronics.

Keywords—mechatronics, Multidisciplinary Design Optimization (MDO), multiobjective optimization, engineering design.

I. Introduction

THIS paper present a novel approach for multidisciplinary design optimization (MDO) of mechatronic systems. This approach is a part of a global project which aims to include the multidisciplinary optimization process into the innovative design process.

As presented in figure 1, the design processes can be classified in 6 different processes, depending on the designer knowledge and knowledge about solving methods [1], [2].

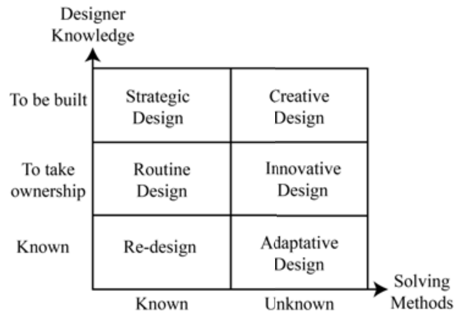

Fig. 1. Classification of the different design processes based on knowledge of the designer and about the solving methods

This classification, introduced by Scaravetti [1], is based on the fraction of new knowledge included into the process:

- The redesign process creates a new product from an existing solution in order to improve its performances. The parametric optimization approach used in MDO is one of the redesign solving methods.
- The adaptative design keeps initial functionalities by adapting the architecture of the product in order to satisfy new demands.

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- The routine design gives a solution of a new product which is totally based or adapted from existing solutions or cases (from a database for example).
- The innovative design combines existing elements or knowledge (from patents for example) to develop a new product.
- The strategy design develops new knowledge to develop new products
- The creative design defines the product in an abstract manner where knowledge and solving methods are unknown yet in engineering design.

In this paper, a novel approach for MDO is introduced. In order to achieve this, the mechatronics, the design process for mechatronic systems and the multidisciplinary design optimization will firstly be introduced and defined based on literature. The proposed approach will then be presented. This approach will finally be analyzed and future works be introduced.

II. The mechatronics

The *mechatronics* term has been invented in 1969 by a Japanese engineer Mori from the Yasukawa Electric company [3], [4].

Many definitions of the mechatronics can be found in the literature as the followings [5]:

- ”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” [6];
- ”Mechatronics is the synergetic combination of mechanical engineering with electronics and intelligent computer control in the design and manufacturing of industrial products and processes” [3];
- ”Many technical processes and products in the area of mechanical and electrical engineering show an increasing integration of mechanics with electronics and information processing. This integration is between the components (hardware) and the information-driven function (software), resulting in integrated systems called mechatronic systems” [7]

In 2008, AFNOR, the French Standard Organization, normalized the definition of the mechatronics (NF E01-010) [8]: the mechatronics is ”a synergistic combinaison of mechanical, electrical, control and computer engineering during the design or the manufacturing process of a product in order to improve or optimize its functionalities".

Mechatronic products must also perceive his surroundings, treat this information, communicate and act on its environment, present a complete level of mechatronic integration, i.e. coupling mechanics, electronics and control fields, regarding both functional and physical views.

The integration process of mechatronic product is, as mentioned above, a two-dimensional phenomenon [9]: functional integration, corresponding to the integration degree of the device with the others, and physical one, representing the assembly level of heterogeneous technologies into a module. Since a couple of year, both functional and physical interactions are increasing even if there is no correlation between both aspects.

The soar of mechatronic is strongly connected with the expansion of computer, which are always faster, and the miniaturization of printed circuits allowing them to be directly integrated into mechanical bodies.

In order to increase this integration, research works are currently done in the field of the optimal design, specially using multicriteria optimization, of mechatronic systems as [10], [11], [12], [2], [13], like robots, driving-aid systems (ABS, ESP, ...). The actual tendency goes to global optimization, namely optimizing the whole system, instead of local one.

III. Design process of mechatronic systems

In 1988, G. Pahl and W. Beitz [14], [15] proposed a systematic approach for the engineering design process.

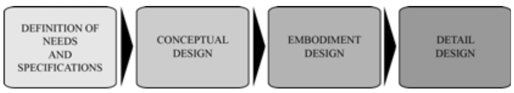

Fig. 2. Design engineering process (Pahl & Beitz)

As shown in figure 2, this approach contains 4 different steps [5]:

- The aim of the first step is to define the product requirements document containing the user specifications and definition of the needs.
- In the conceptual design part, a first product concept which is defined as a description of the proposal solution under the form of an assembly of integrated ideas and concepts (what it should do, how it should behave and looks like). This description should be understandable by the customers of the product.
- For the embodiment design, the previously defined product concept is transformed into technical solutions that are corresponding with the concept: how should be the product (components, shape, structure, bodies, etc.) in order to satisfy the product requirements?
- And finally, once a technical solution is obtained, this solution can be developed in order to get all information that are needed to manufacture the product: pieces nomenclature, detailed plans of each body... The detailed design process should indeed prepare the production and all operational documents.

This design process is very used in the literature but it has mainly been designed for mechanical engineering or monodisciplinary design, not for multidisciplinary design for which this approach is not efficient enough.

For the design of mechatronic systems, an another approach is used by mechatronic designers : the V-Model [16], as shown in figure 3.

This approach is composed with two main phases: the "top down" step which corresponds with the specification and design steps and the "bottom up" phase which aims to validate and integrate the different technologies of the product. As shown in figure 3, the design approach includes four levels:

- The functional level where the customer needs are technically specified.
- The system level represents a more physical aspect of the final product: the architecture and the subsystems are defined in this level.
- The subsystem level where each subsystems, defined in the previous step, are considered as a part of the final system. These subsystems are themselves divided into several subsystems : the components.
- The component level achieves the design process.

IV. Multidisciplinary Design Optimization

The Multidisciplinary Design Optimization (MDO) is, as presented in [17]:

- A methodology for the design of complex engineering systems and subsystems that coherently exploits the synergism of mutually interacting phenomena.
- Optimal design of complex engineering systems which requires analysis that accounts for interactions amongst the disciplines (or parts of the system) and which seeks to synergistically exploit these interactions.
- How to decide what to change, and to what extent to change it, when everything influences everything else.

To simplify, Jaroslaw and Haftka [18] described the MDO as a methodology for the design of systems where the interaction between several disciplines must be considered, and where the designer is free to significantly affect the system performance in more than one discipline.

In the Multidisciplinary Design Optimization (MDO) process, optimization methods are used to solve design problems that includes several disciplines. These methods have been designed to incorporate all relevant discipline simultaneously during the design process by exploiting the interactions between the disciplines.

A general formulation of a MDO problem has been given by [19] as:

$$\begin{aligned} \text{Minimize } & f(x,y,z) \\ \text{With respect to } & z \in \mathcal{Z} \\ \text{Subject to } & g(x,y,z) \leq 0 \qquad (1) \\ & h(x,y,z) = 0 \qquad (2) \\ & \forall i \in \{1,\ldots,n\}, \forall j \neq i, y_i = \{c_{ji}(x_j,y_j,z_j)\}_j \qquad (3) \end{aligned}$$

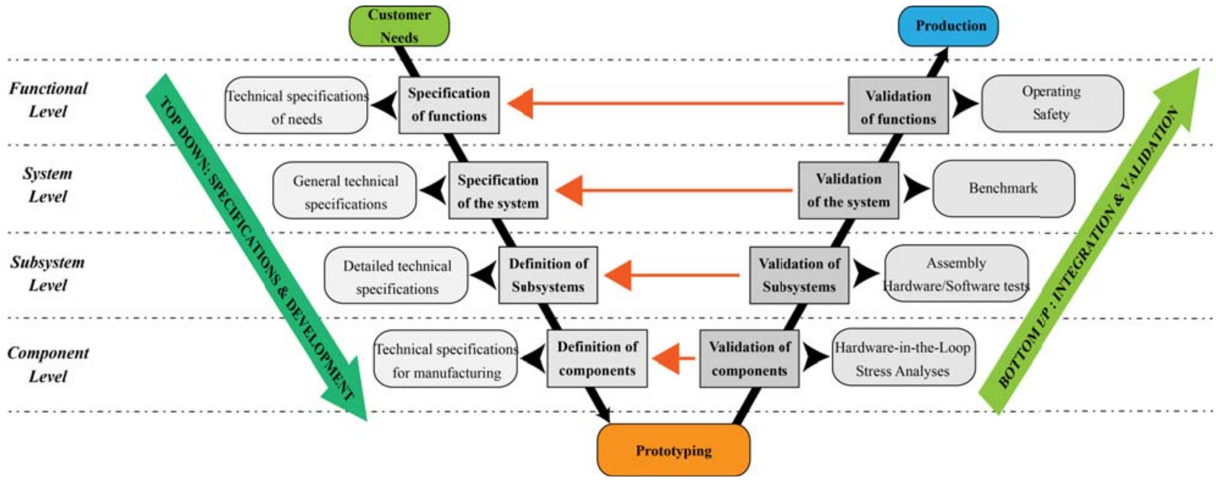

Fig. 3. V-Model approach for designing mechatronic systems

$$\forall i \in \{1, \ldots, n\}, R_i(x_i, y_i, z_i) = 0 \qquad (4)$$

where z are the design variables, y are the coupling variables and x the state variables. These state variables are not design variables but they can vary during the disciplinary analysis.

Different formulations of MDO problems have been developed. These methods can be divided into two main parts depending on whether the resolution is carried on one (monolevel MDO) or more (multilevel MDO) successive phases.

A. Formulation of MDO using monolevel approaches

By using these methods, the whole system is global optimized using a single optimization process. Most common formulation of a MDO formulation using monolevel approaches are [5], [17], [20]:

- Multidisciplinary Design Analysis (MDA)
- Multidisciplinary Feasible (MF)
- Individual Discipline Feasible (IDF)
- All-At-Once (AAO)

The MDO problem formulation has a great impact on the algorithm required to solve it [21].

B. Formulation of MDO using multilevel approaches

For these methods, the system is considered as to be composed of monodisciplinary subsystems which are optimized first, before optimizing the whole system.

Some of the common used multilevel formulations are:

- Collaborative Optimization (CO)
- Concurrent SubSpace Optimization (CSSO)
- Bi-Level Integrated Systems Synthesis (BLISS)
- Analytical Target Cascading (ATC)

The main inconvenient of this approach is the time it takes to optimize the system using common solving tools: instead of optimizing a single optimization problem, multiple processes need to be successively performed.

V. A Novel MDO Approach for the Design of Complex Mechatronic Systems

The proposed approach considers the problem of the multilevel MDO of mechatronic systems.

As seen in III and specially in figure 3, the design process of a mechatronic system is a four level process, from the functional level to the component level. In reality, all of those four levels are not considered while optimizing a mechatronic system : the functional level, and often the component levels, are missed.

A. The global approach

The approach, summarized in figure 4, extends the V-Model for the design of mechatronic systems with the modeling and the optimization process which aims to improve the prototype. This approach considers four different steps:

- The definition and specification phase from the Top-Down part of the V-Model
- The modeling phase which aims to obtain a parametric model of the different components, the subsystems, the system and the functions.
- The optimization phase which optimizes the model of the prototype.
- The interaction and validation phase finishes the design process.

As shown on figure 5, the optimization process of the mechatronic system should follow the same order as the ”Bottom Up” phase, which is in charge of the integration and verification steps, from the V-Model.

This figure also shows that, for the component level, the case where a same component can be used in different systems (with or without the same functionality) should be taken into account while optimizing a subsystem.

This can be done by considering state variables and constraints depending on the other subsystem for the optimization problem of the subsystem: see IV for some formulation of MDO problems.

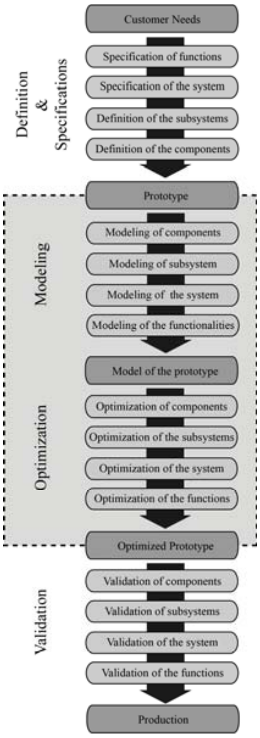

Fig. 4. Schema of the proposed design approach for the design of mechatronic systems

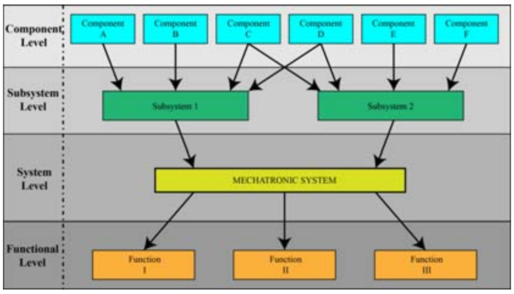

Fig. 5. Schema of the proposed design approach for the design of mechatronic systems

The approach is divided as follow:

- Each component are optimized first. This operation can be done in parallel.
- Once each component are optimized, these components are combined together into subsystems. The second optimization level occurs: each subsystems are optimized. The different interactions between the other subsystems may be considered by formulating each subsystem as a MDO problem.
- The system itself, which is composed of the different subsystems (optimized in the previous step), is then optimized as a MDO problem.
- The functionalities of the mechatronic product can finally be optimized.

During the whole approach, components, subsystems, system and functions are optimized using multiobjective optimization methods.

B. Modeling phase

Because the optimization process is a mathematical-based tool, it is important to have a model of the system. The model is a mathematic representation of a system or a phenomenon that can be simulated.

This modeling phase constitutes the first step that has been added to the V-Model.

This step should be considered as the most important because, as far as the optimization step only considers parameters, the quality of the final product depend on the model used.

The modeling phase is generally done by modeling the component first, the subsystem then, and finally the system.

To create the model, modeling software as Matlab/Simulink [22] are often used but, for complex systems, the use of object-oriented language as Modelica [23] which considers each component as one class of the system, allows faster modeling ability as Matlab [24].

C. Optimization of the prototype

Once the prototype is modeled, it is possible to optimize it. This optimization follows a four level process in the same order as the modeling aspect.

Each optimization process in the different steps are considered as a multiobjective optimization problem, that can be formalized as a MDO problem using the different methods presented in section IV.

1) Multiobjective optimization: The parametric multiobjective optimization is very used in order to solve MDO problems with some contradictory objectives. In this case, the major is that, as far as the optimization problem does not find a single optimal solution but several ones (often more than one thousand solutions), the Pareto front, it is necessary to select one or a dozen of candidate solutions.

This selection may be hard to do if the number of possible solutions becomes too high: this selection step can be partially done automatically by using decision-making tools, as Electre or Promethee methods [25].

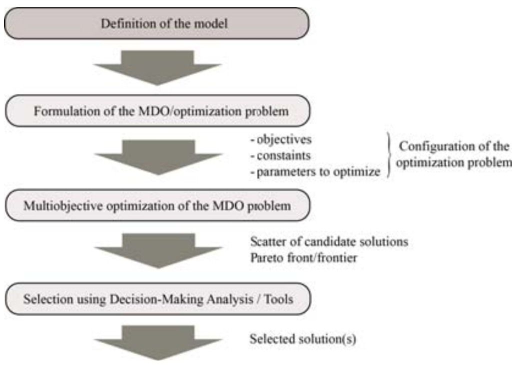

Fig. 6. General principle of the multiobjective optimization of systems

The multiobjective optimization process can then be divided in four different parts (see figure 6):

- In the first step, a mathematical model of the system has to be defined.
- The optimization problem is formulated into the second step, based on the specifications, the model and, if needed, the MDO formulation approach.
- The previously formalized optimization problem is solved using multiobjective methods, as genetic algorithms or Particle Swarm Optimizer in the third step. This resolution lead to the Pareto front, a scatter of possible solutions.
- The final step uses decision-making tools to select one or several solutions from the Pareto front.

For the optimization of the components or the subsystems, it is important that, for the selection process, more than one solution is selected because the integration of "optimal" subsystems does not necessary lead to an optimal system.

VI. Conclusion and perspectives

In this paper, a first novel approach for the multidisciplinary design optimization of mechatronic systems were presented. This method should now be applied to the optimization of a real mechatronic system.

Additional future works will be done to extend the domain of the possible solutions given by the parametric optimization. This will should probably been done by including the optimization aspect (a redesign process) into the case-based reasoning method (an approach for routine design) [26], [27].

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