Challenges and future trends in Uncertainty-Based Multidisciplinary Design Optimization for space transportation system design

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Abstract

Space vehicle design is a complex process requiring to handle multidisciplinary analysis, multi-objective optimization, computational and organizational complexity. Strategies relying on Multidisciplinary Design Optimization (MDO) methods can be applied to solve this optimization problem. MDO methods facilitate the resolution of constrained optimization problems by taking advantage of the inherent couplings and synergism between the disciplines in order to decrease the computational burden and/or to increase the quality of the global optimal design [Sobieszczanski-Sobieski and Haftka, 1997]. Unlike the sequential disciplinary optimizations performed with classical design methods, the interactions between the disciplines are directly incorporated in the MDO methods [Balesdent et al., 2012b]. However, including all the disciplines simultaneously significantly increases the complexity of the problem and its solving. In addition to the multidisciplinary aspect of the problem, a multi-objective approach is often necessary to meet the different requirements. These objectives might be antagonist resulting in a necessity of trade-offs between the different performances of the space vehicle.

This paper presents a comprehensive survey of recent developments in Uncertainty-Based Multidisciplinary Design Optimization (UMDO) and their applications to space transportation system design. The article highlights the specificities and current research challenges in UMDO for the preliminary design phase applied to spacecraft with a focus on launch vehicles. It also intends to identify several ways of improvements that could be investigated in future research.

The preliminary design phase results in an initial formulation of the vehicle design problem. This phase corresponds to the identification of the optimum design among all the possible alternatives that meet the requirements. The alternative selected is at a high level of design definition. The detailed design phase will go deeper into the architecture selected.

In the early design studies, only few pieces of information are available, relying mostly on historical data, and the uncertainties on the final design and performances are large. The alternative design space is wide, including different concepts and technologies. Many types of uncertainties can be distinguished, such as uncertainties on the design variables, on the disciplinary models, on the physical phenomena taken into account (*e.g.* wind gust, *etc.*). MDO methods for space vehicles have been implemented and different approaches have been experimented ([Braun et al., 1996], [Durantė et al., 2007], [Balesdent et al., 2012a], [Castellini and Lavagna, 2012]) to improve the accuracy of the optimum, the efficiency of the algorithms and to handle the complexity of space vehicle designs. However, most of these techniques rely on deterministic formulation, in which uncertainties are not taken into account. Since it is essential to be able to quantify the quality of the optimum found under practical conditions and to have a degree of belief in this optimal solution, we need to include uncertainty analyses in the MDO process. The designer should be able to assess the precision of this optimum and the decision maker to take decision about the architecture of the spacecraft based on the information provided by the MDO method. Furthermore, the architecture of the design should not have to change in the further design phases of the development of the space vehicle: it would avoid repeating computationally intensive analyses and offer the possibility to concentrate on higher precision analyses on the architecture chosen.

Different strategies in terms formulation of the problem can be adopted [Yao et al., 2011]:

- Robust based design optimization: it allows to ensure that the performances (evaluated through metrics

of interest that match the customer requirements) achieved by the space vehicle will not degrade due to uncertainties existing at the preliminary design stage.

- Reliability based design optimization: it allows to ensure that the spacecraft will achieve performance requirements with a predefined minimum confidence (reliability rate for rocket launches for instance). It implies choices in terms of redundancies, architectures and technologies to avoid further design changes to occur in future design phases due to a violation of the overall system reliability.
- Reliability and robust based design optimization: is a combination of the two preceding types of optimization.

In the first part of the article, the general process to solve a UMDO for a space vehicle in the preliminary design phase will be introduced. This process relies on two steps: modeling and optimization. The modeling includes two parts: the deterministic modeling of the spacecraft and the modeling of the uncertainties. The deterministic modeling, in the preliminary design phase, relies on simplified models of all the disciplines involved in a space vehicle: aerodynamics, propulsion, trajectory, sizing, cost, *etc.* This modeling does not differ from the deterministic MDO discipline models. For instance, in a simplified rocket propulsion model, the mixture ratio, the pressure in the combustion chamber and the expansion ratio are input design variables of the model to compute the specific impulse of the engine. By knowing the three inputs and the equations mapping the inputs to the output, the output is uniquely defined. However, uncertainties in the input variables, in the parameters involved in the equations, in the assumptions made to apply the equations often exist. The modeling of uncertainties is the basis for uncertainty-based design optimization. It requires to identify, to classify uncertainty sources and to model these uncertainties by using appropriate mathematical representations (probability, evidence theory, possibility theory, intervals). Sensitivity analysis can be implemented to screen out uncertainties with minor effects on the space vehicle design to simplify and decrease the computational cost of the UMDO process. Eventually, propagation of uncertainties from each disciplinary model to the overall system model has to be implemented. The propagation methods can be classified in two categories: intrusive (polynomial chaos expansion, *etc.*) and non-intrusive (Monte Carlo, Taylor, First order and second order reliability methods, *etc.*) whether a reformulation of the disciplinary models is necessary or not. The propagation of uncertainties can induce a large computational burden if it is not well handled. The second step of the UMDO process corresponds to the optimization under uncertainty of the problem. Several algorithms have been applied in the past for UMDO problems (gradient based or gradient free) with adequate formulations (robust and/or reliability based design optimization)([Zhang, 2007]). Some formulations attempt to propagate the uncertainties and perform the optimization simultaneously. These optimization procedures will be discussed to analyze their advantages and drawbacks, and to highlight currently implemented alternatives.

In the second part of the article, the specificities and challenges of UMDO due to the preliminary design phase of spacecraft will be discussed. We will detail two types of challenges: those due to the preliminary design phase and those due to the space transportation system design with a focus on launch vehicles.

The preliminary design phase imposes challenges on an UMDO problem. The design space is large because it includes a broad choice of architectures (number of stages, boosters, engines, type of propulsion, type of propellant, sizing, optimal control *etc.*). Moreover, the design space is made of discrete and continuous design variables. As the architecture of the space vehicle is not defined yet and the design space is large, simplified physical discipline models are used to reduce the computational cost of the UMDO process. However, these simplified models introduce epistemic uncertainties that need to be quantified. The modeling of uncertainties, in the preliminary design phase, is a challenge since it often relies on few data, especially in the case of new concepts or technologies where no historical or experimental information is available. For the sensitivity analysis, due to the large design space, different uncertain variables dominate depending on the region of the design space, imposing to differentiate the uncertainty modeling in the UMDO process. For instance, in a launch vehicle, the uncertain variables can differ depending of the considered stage and flight phase. The UMDO procedure can be decomposed between a single level procedure and a decomposition and coordination based procedure depending on the interlocking of the optimization and uncertainty analysis loops. Decomposition based procedures are inspired from existing procedures applied in deterministic MDO (Individual Discipline Feasible, Bi-Level System Synthesis, Collaborative Optimization, Analytical Target Cascading, *etc.*), but further research on the choice and characterization of these formulations has to be done for UMDO problems.

The design of space vehicle results in specific challenges for the UMDO problem. Firstly, the dynamics of the space vehicle are often very non linear. If the uncertainties are modeled with probability distributions, the propagation of non linearity dynamics results in skewed distributions. However, the actual optimization formulations only incorporate the mean and the standard deviation of the output distribution without taking into account the higher moments as skewness or kurtosis. New formulations incorporating the asymmetry of distribution need to be developed. Secondly, another challenge resulting from the UMDO of a space vehicle is the propagation of uncertainty over a null support. Indeed, due to the presence of different disciplines in the design process, many disciplinary couplings have to be handled (*e.g.* for a launch vehicle, couplings between structure and trajectory with respect to the load factor). In most of the MDO methods, the disciplines are decoupled introducing coupling variables and corresponding coupling equality constraints in the optimization problem. However, in terms of probability, two random variables that need to be equals are expressed through a null support which does not allow the propagation of uncertainties. The same problem arises in the formulation of space vehicle design optimization due to equality constraints (for instance, final orbit to insert a spacecraft). The couplings often involve an entanglement of different levels in optimization and the implication in terms of uncertainty propagation has to be studied. Finally, to cope with the computational burden (*e.g.* Monte-Carlo simulations for the uncertainty propagation), meta-models can be used in the design process. In this case, it is essential to be able to quantify the uncertainties introduced by the involved surrogate models in the optimization process ([Baudoui et al., 2012], [Janusevskis and LeRiche, 2012]).

These specificities and challenges will shape the future researches in the field of UMDO applied to space vehicles. In the last part of the paper, we will conclude about the adequacy of existing UMDO techniques with regards to the particular needs of space vehicle design and we will identify several ways of improvements that could be further investigated.

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