Uncertainty modeling in autonomous robust spacecraft system design

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In the last few years, much research has been dedicated to the development of decisions support systems for the space system engineers or even of completely automated design methods capturing the reasoning of the system experts. However, the problem of taking into account the uncertainties of the variables and models to determine an optimal and robust spacecraft design has not been tackled effectively yet. Based on the *clouds* formalism we propose a novel approach to process the uncertainty information provided by expert designers and incorporate it into the automated search for a robust optimal design.

Survey:

The design of a spacecraft is a challenging task. The complexity and multidisciplinarity makes it difficult to have a complete survey and a deep understanding of the whole design process. A recent step forward towards a multidisciplinary approach in the early phases of space system design has been achieved by concurrent engineering. Design facilities where these methodologies are implemented are, among others, the ESA Concurrent Design Facility [1] and the NASA Goddard Integrated Mission Design Center [2]. In these facilities it is common practice of preliminary spacecraft design to handle uncertainties by assigning intervals, or safety margins, to the uncertain variables, combined with an iterative process of refining the intervals while converging to a robust optimal design. The assignment and refinement of the intervals is done by the system experts who assess whether the worst-case scenario, determined for the design at the current stage of the iteration process, is too pessimistic or too optimistic. The goal of the whole iteration includes both optimization of the design and safeguarding against uncertainties.

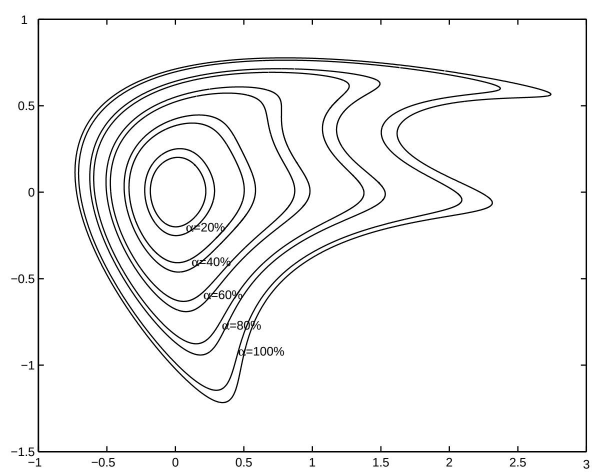

Fig. 1 Confidence regions from a 2-dimensional cloud.

The available uncertainty information in the early phase of a spacecraft design is often very limited, mostly there are only interval bounds on the uncertain variables, sometimes probability distributions for single variables without correlation information. When the amount of uncertainty information available is small, well known traditional methods from probability theory or fuzzy theory (e.g., fuzzy clustering) face several problems. Simulation techniques like Monte Carlo also require a larger amount of information to be reliable. The lack of information typically endangers these methods to underestimate the effects of the uncertain tails of the probability distribution (cf. [3]). Similarly, a reduction of the problem to an interval analysis after assigning intervals to the uncertain variables as described before (e.g., 3 σ boxes) entails a waste of valuable uncertainty information which would actually be available but not involved in the uncertainty model. Moreover, in higher dimensions the numerical computation of the error probabilities is very expensive or impossible, even given the knowledge of multivariate probability distributions.

Generally speaking, the task of robust and autonomous space system design cannot be regarded as a single task, but consists of two tasks that have to be accomplished conjointly. First, the design should be robust; in other words: the design should be safeguarded against uncertain perturbations. Second, the design should be found autonomously; this indicates the existence of a method which is able to find the optimal design choice automatically. The optimality of a spacecraft design can depend on multiple objectives, such as the cost or the mass of the spacecraft or both at the same time. The ESA Advanced Concepts Team performed an Ariadna study [4] in cooperation with the University of Vienna on the application of the clouds theory in space design optimization. This study presented an initial step on how clouds could be used to handle uncertainties in spacecraft

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design. Going further in that direction, we have developed a new methodology to gather all available uncertainty information from system experts, process it to a reliable worst-case analysis and finally optimize the design seeking the optimal robust design.

The basic concept of our approach consists of three essential steps within an iterative framework. First, the expert provides the underlying system model, given as a black-box model, and all currently available uncertainty information on the input variables of the model. The uncertainty information can be provided on the one hand as bounds or marginal probability distributions on the uncertain variables. On the other hand, the engineers can adaptively improve the uncertainty model, even if their expert knowledge is only little formalized, by adding correlation constraints to exclude scenarios deemed irrelevant for the worst-case analysis. The information can also be provided as real sample data, if available. Second, the information is processed to generate a cloud. Clouds allow the representation of incomplete stochastic information in a clearly understandable and computationally attractive way, mediating between aspects of fuzzy set theory and probability distributions (cf. [5]). Parameterized by given confidence levels, the clouds provide a nested collection of regions of relevant scenarios affecting the worst-case for a given design (cf. Figure 1) and thus produce safety constraints for the optimization. Third, optimization methods minimize a certain objective function (e.g., cost, mass) subject to the functional constraints which are represented by the system model, and subject to the safety constraints from the cloud. We have developed heuristic optimization techniques that take advantage of inherent characteristics of spacecraft design problems, e.g., discrete design choices. The results of the optimization are returned to the expert, who is given an interactive possibility to provide additional uncertainty information afterwards and rerun the procedure, adaptively improving the uncertainty model.

In a case study on the background of the NASA's Mars Exploration Rover (MER) mission (cf. [6], [7], [8]) we could show that our methods apply to real-life problems of early phase spacecraft system design.

Conclusions from our studies:

- At present, in most instances of the spacecraft design, reliability is only assessed qualitatively by the experts. We present a step forward towards quantitative statements about the design reliability.
- Our approach is generally applicable to real-life problems of robust design optimization, especially with discrete design choices. The advantages of achieving the optimal, robust design autonomously are undeniable.
- The adaptive nature is one of the key features of our approach as it imitates real-life design strategies. The iteration steps, when an expert excludes worst-case irrelevant scenarios, significantly improve the uncertainty information and we are able to process the new information to an improved uncertainty model afterwards.
- An additional value of our uncertainty model is the fact that one can capture various forms of uncertainty information, even those less formalized. There is no loss of valuable information, and the methods are capable of handling the uncertainties reliably, even if the amount of information is limited.

Summing up, our methods offer an exciting new approach to face the highly complex problem of robust and autonomous system design, an approach which is easily understandable, reliable and computationally realizable. See [9] for more details on our methods.

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