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Conceptual Remote Sensing Satellite Design Optimization under uncertainty

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ABSTRACT

This paper focuses upon the development of an efficient method for the conceptual design optimization of Remote Sensing Satellites (RSS) under uncertainty. There are many acceptable optimal solutions for implementation of satellite subsystems in a space system mission. Every solution should be assessed based on the different criteria such as cost, mass, reliability and payload resolution. In the present paper satellite mass and imaging payload resolution were considered as system level objective functions to obtain the system optimal solution during the conceptual design phase. Furthermore, two Multidisciplinary Design Optimization (MDO) frameworks; Multidisciplinary Design Feasible (MDF) and distributed Collaborative Optimization (CO) were applied to the multi-objective design optimization problem under uncertainty. Also, various uncertainties involving environment, operation, geometry, subsystems, etc. were considered in the Reliability Based Multidisciplinary Design Optimization (RBMDO) frameworks. In the present study, MDF, CO, Reliability Based Multi-disciplinary Design Feasible (RB-MDF) and Reliability Based Collaborative Optimization (RB-CO) frameworks were evaluated and compared. The methodology was based on the utilization of Monte Carlo simulation method for accounting uncertainties in design process and applying genetic algorithms and sequential quadratic programming to system level and discipline level optimizers. Results obtained in this study, have shown that the introduced method provides an effective way of accounting uncertainty in a complex space system design such as the conceptual design optimization of a spacecraft.

1. Introduction

Conceptual design of space systems is a complex and decision making process which aims at choosing from a collection of choices implying an irrevocable allocation of resources. Recently, emphasis has been on the advances that can be achieved through the interaction between two or more disciplines. Thus, it is fundamentally a multidisciplinary and multi-objective process. The traditional method of designing space systems, normally includes numerous design loops, which does not guarantee to reach the best optimal solution. The principled application of formal optimization techniques to complex system design has led to the rapid development of an optimization field named Multidisciplinary Design Optimization (MDO).

MDO is a design approach for the coupled engineering systems that coherently exploits the synergism of mutually interacting phenomena [1]. In recent years, there has been an increasing amount of literature on MDO domain beginning with aerospace industries, but now they are used in various kind of enterprise (automotive industries, marine industries, etc.) to improve the quality of products [2–5]. As a rule, MDO techniques bridge the gap between subsystem analysis and optimal system design by providing a different optimization framework for design groups. The framework supports design improvement by methodically considering the system level penalties of various disciplinary components and configuration options. Preliminary works on MDO were undertaken by Schmit [6] and Haftka [7]. As a result, the growth of systems complexities, couplings between disciplines and the development of new optimization techniques have led to develop new MDO architectures. Generally, MDO architectures can be classified into two categories: monolithic formulations and distributed formulations [8]. Monolithic formulations that include All-At-Once (AAO) [9], Multidisciplinary Design Feasible (MDF) [10], Individual Discipline Feasible (IDF) [11], and Simultaneous Analysis and Design (SAND) [12] architectures, apply a single system-level optimizer to the whole problem. On the other hand, distributed formulations such as Collaborative Optimization (CO) [13], Concurrent Subspace Optimization (CSSO) [14], Analytical Target Cascading (ATC) [15], and

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Nomenclature

AAO	All-At-Once
ADCS	Attitude Determination and Control
AiO	All-In-One
ATC	Analytical Target Cascading
BLISS	Bi-level Integrated Systems Synthesis
C&DH	Command and Data Handling
CO	Collaborative Optimization
CSSO	Concurrent Subspace Optimization
DSM	Design Structure Matrix
EPS	Electrical Power Supply
FORM	First-Order Reliability Method
GA	Genetic Algorithms
GEO	Geosynchronous Earth Orbit
ICE	Integrated Concurrent Engineering
IDF	Individual Discipline Feasible
IS	Importance Sampling
MCS	Monte Carlo Simulation
MDB	Mission Design Block
MDF	Multi-disciplinary Design Feasible
MDO	Multidisciplinary Design Optimization
PDF	Probability Density Function
RB-CO	Reliability Based Collaborative Optimization
RBDO	Reliability Based Design Optimization
RB-MDF	Reliability Based Multi-disciplinary Design Feasible
RBMDO	Reliability Based Multidisciplinary Design Optimization
RDO	Robust Design Optimization
RSS	Remote Sensing Satellite
SAND	Simultaneous Analysis and Design
SDB	System Design Block
SORM	Second-Order Reliability Method
SQP	Sequential Quadratic Programming
TCS	Thermal Control System
TT&C	Telemetry, Tracking and Command
UMDO	Uncertainty Multidisciplinary Design Optimization

Bi-level Integrated Systems Synthesis (BLISS) [16], use subspace optimizations to promote discipline autonomy. All space missions contain a set of elements or components (e.g., launch segment, ground segment, payload, etc.) [17]. Satellite systems are among the most considerable segments in planning of space missions. Satellite conceptual design phase is an interdisciplinary field. The last goal of this process is to manufacture a Satellite that fulfill the requirements of the customers. The conceptual design phase [18–20] of a satellite contains various interactions between specialized disciplines such as payload, orbit, power, TT&C, C&DH and structural analysis to mention a few, which sometimes confronts with conflicting objectives and constraints [5,19–23].

During the past 30 years, the growing demand for optimal and reliable systems, along with the increasing computational power, have improved the role of optimization techniques in design of complex systems. For this reason, the conceptual design process of space systems has been clearly developed because of the dominant role that optimization techniques have played in this field. Moreover, applying the appropriate design optimization techniques to the design process not only can solve the problem satisfactorily, but also increases the design performance, decreases the design costs and guarantees the stability of space systems design.

There have been many studies on the literature that propose systematic design optimization methodologies to solve a space system design problem [5,24–27]. For example, in reference [28] the satellite design optimization based on normal cloud model was carried out considering only the payload and power supply subsystems. Kim [29] used meta-heuristic algorithms to minimize the total cost of space system development based on the technology choice at conceptual design phase in AAO framework. Hassan [30] applied Genetic Algorithms (GA) to multi-objective design optimization method for the conceptual design of a GEO satellite communication system. Also, mission design optimization of a small remote sensing satellite has been done using genetic algorithms within CO framework [5]. Furthermore, Spangelo and Cutler [31], performed a general optimization technique to solve a spacecraft design optimization problem using a Monte Carlo random search algorithm.

The mentioned methods on the design optimization of space systems are all limited to deterministic approach, in which all involved variables and parameters are considered to be certain. The deterministic optimization approaches allow us to find the most optimum system configuration under various performance conditions, but the major problem with these methods is the negligence of uncertainties (or tolerances) in design, manufacturing and operating process. It has been demonstrated that, the absence of uncertainties in the deterministic optimum design considerations may lead to unreliable systems [32]. Space systems throughout their life cycles are normally confronted with uncertainties. Tolerances in orbital elements, environmental conditions, production, modeling and operation are the most important sources of uncertainties in these systems. However, in a deterministic MDO approach of the space systems design process, the described uncertainties are not considered. It should be noted that neglecting uncertainties in the deterministic design methods usually results in a difference between the actual system and the deterministic optimum design which in many cases may lead to the missions failure [33]. Traditionally, in the deterministic design methods, a safety factor can compensate this drawback. Moreover, this approach often results in an increase in the system operation and production costs and also does not guarantee its reliability [34].

In recent years, two major approaches that take different uncertainties into account have been introduced to be used in uncertainty-based design problems; Reliability Based Design Optimization (RBDO) and Robust Design Optimization (RDO). However, there are conceptual differences between these methodologies. Compared with the deterministic approach, RDO tries for optimal designs that are less sensitive to uncontrollable uncertainties which mostly occur in the real design space [35], while in the RBDO methodology, the designer seeks a reliable optimum solution by transforming the deterministic constraints into probabilistic counterparts, in which failure probability is limited to pre-defined boundaries [36].

Although, the RBDO approach is mainly focused on structural engineering [32], it has been recently used for other applications (including aircraft [37,38], automotive [3,33], and control [39] designs). Because of the current competitive global market in space industries, the reliability and cost of space systems have been considered as design goals. Normally, there has to be a trade-off between low cost and high reliability in the conceptual design process of these systems.

In the study carried out by Ubelhart et al. (2006) [40] the non-deterministic approach was applied to conceptual design of the optical structure of a space telescope and Hassan et al. (2008) [41] applied a genetic algorithm with Monte Carlo sampling to probabilistic reliability-based design optimization of a communication