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On-orbit servicing system assessment and optimization methods based on lifecycle simulation under mixed aleatory and epistemic uncertainties

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ABSTRACT

To assess the on-orbit servicing (OOS) paradigm and optimize its utilities by taking advantage of its inherent flexibility and responsiveness, the OOS system assessment and optimization methods based on lifecycle simulation under uncertainties are studied. The uncertainty sources considered in this paper include both the aleatory (random launch/OOS operation failure and on-orbit component failure) and the epistemic (the unknown trend of the end-used market price) types. Firstly, the lifecycle simulation under uncertainties is discussed. The chronological flowchart is presented. The cost and benefit models are established, and the uncertainties thereof are modeled. The dynamic programming method to make optimal decision in face of the uncertain events is introduced. Secondly, the method to analyze the propagation effects of the uncertainties on the OOS utilities is studied. With combined probability and evidence theory, a Monte Carlo lifecycle Simulation based Unified Uncertainty Analysis (MCS-UUA) approach is proposed, based on which the OOS utility assessment tool under mixed uncertainties is developed. Thirdly, to further optimize the OOS system under mixed uncertainties, the reliability-based optimization (RBO) method is studied. To alleviate the computational burden of the traditional RBO method which involves nested optimum search and uncertainty analysis, the framework of Sequential Optimization and Mixed Uncertainty Analysis (SOMUA) is employed to integrate MCS-UUA, and the RBO algorithm SOMUA-MCS is developed. Fourthly, a case study on the OOS system for a hypothetical GEO commercial communication satellite is investigated with the proposed assessment tool. Furthermore, the OOS system is optimized with SOMUA-MCS. Lastly, some conclusions are given and future research prospects are highlighted.

1. Introduction

Throughout the lifecycle of a satellite, there are myriads of uncertainties, such as component failures, environmental hazards, end-user market changes, etc. In the traditional one-off paradigm, the only way to resume the failed space mission or change/upgrade the existing capability is to replace the failure or obsolete satellite with a new one, which results in extremely high cost. To solve this problem, an alternative paradigm is developed based on on-orbit servicing (OOS), which can respond to the uncertain events flexibly by means of on-orbit repair, refueling, function upgrade, etc. However, certain price has to be paid to implement OOS, as the satellite owner should not only

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develop the target satellite to be serviceable, but also develop the servicing satellite as well as other logistic units to support OOS, which constitute an OOS system [1]. If the extra expenditures of OOS cost too much and result in lower benefits per unit cost compared to that of the traditional paradigm, OOS would not be economically attractive. Therefore, the utilities of the OOS paradigm should be assessed and compared to the traditional paradigm, so as to check whether it is beneficial to employ OOS [2]. Furthermore, the utilities can be used to guide the design and optimization of the OOS system, which is so-called the Value-Centric Design Methodology (VCDM) [3]. With reference to the OOS assessment literature [4–8], the widely used utility metrics including lifecycle cost, benefit, and net value, are used in this paper to assess the OOS paradigm, according to which the OOS system is further optimized.

To assess the OOS system, the main difficulty is that the uncertainty effects throughout the lifecycle are extremely complex, e.g. the target satellite end-user market may change with time, the satellite components may run into failure, etc. In response to the preceding uncertainties, the satellite owner may have multiple decision options, which may be followed by different sequences of uncertain events thereafter. The mixture of these time-continuing uncertain effects, the discrete uncertain events, and the multiple subjective options makes it impractical to describe all the possible states of the OOS system throughout the lifecycle with finite number of uncertain variables. Thus the propagation effects of the uncertainties on the OOS utilities cannot be modeled in the closed-form formula either. An effective way to solve this problem is to simplify the uncertain scenarios and only consider part of the uncertain effects, e.g. the market change [4,6]. A more accurate way is to take advantage of computer simulation technologies to imitate the lifecycle evolution process under all the uncertainties. A lifecycle simulation is a sample of the possible realization of the real OOS system. By repeatedly running the lifecycle simulation, the uncertain distribution of the OOS utilities can be analyzed with certain algorithm. In [5], the lifecycle is discretized into a finite number of time steps. At each time step, the end-user market price and the component states of the target satellite are simulated following the prescribed uncertain distribution. The corresponding benefit and cost at this time step are calculated, which are aggregated into the total lifecycle cost and benefit. If uncertain events happen and invoke the satellite owner to make decision, the predefined "if…then…" rules are used to guide the decision making process. However, this decision making logic can hardly obtain the most appropriate OOS strategies to optimize the utility and accordingly cannot show the superiority of the OOS paradigm in terms of flexibility and responsiveness. Hence in this paper, the lifecycle simulation of the OOS system under uncertainties is investigated, based on which the dynamic programming approaches in [4,6] are integrated to simulate the optimal decision making process.

In the lifecycle simulation, the uncertainties considered in this paper include both the aleatory and epistemic types. The aleatory type describes the inherent variation of the OOS system, which are generally treated as random variables and handled with probability theory. For example, the component failure and the launch failure can be modeled with probabilistic distribution functions based on the ground test data or past flight data. The epistemic uncertainties result from lack of knowledge, which are very popular in conceptual design phase as there is not sufficient information to build the probabilistic models of the aleatory uncertainties and there also exist various kinds of subjective vagueness and imprecision [9,10]. For example, it is impossible to accurately forecast the future customer market in the design phase. Even given the mathematical model structure about the market trend based on the past experience, the model parameters could be hardly predicted. Instead the parameter values may change within one or several intervals. Therefore, these parameters should be treated as epistemic uncertainties rather than simply as fixed values under strong assumption. Among the approaches addressing the representation and propagation of epistemic uncertainties, evidence theory is a more general and promising method when very limited knowledge is available and only several possible continuous or discontinuous intervals can be given to roughly describe the uncertainty distribution [11]. Therefore, the representation and propagation of mixed aleatory and epistemic uncertainties are addressed with combined probability and evidence theory in this paper. Specifically, a Monte Carlo lifecycle Simulation (MCS) based unified uncertainty analysis (UUA) approach MCS-UUA is proposed to analyze the uncertain distribution of the OOS system utilities under mixed uncertainties. Based on MCS-UUA, the OOS utility assessment tool is developed.

With the preceding OOS utility assessment tool, the OOS system can be optimized. However, if the MCS-UUA based utility assessment tool under mixed uncertainties is directly nested in the optimization, the computational burden will be unaffordable. To address this computational problem, it is proposed to employ the framework of Sequential Optimization and Mixed Uncertainty Analysis (SOMUA) [12] to organize the optimization. SOMUA decomposes the nested optimization and uncertainty analysis problem into separate deterministic optimization and uncertainty analysis subproblems which are solved sequentially and alternately until convergence is achieved. The deterministic optimization problem can be solved with existing general optimization solvers, and the uncertainty analysis of the OOS utility can be implemented with MCS-UUA. This optimization algorithm is termed as SOMUA-MCS.

The rest of this paper is structured as follows. Firstly, the OOS lifecycle simulation procedure is investigated, the OOS utility models are established, and the uncertainties thereof are modeled. Secondly, the method to analyze the propagation effects of the mixed uncertainties on the OOS utilities is studied. The uncertainty analysis approach MCS-UUA is proposed, based on which the OOS system utility assessment method under mixed uncertainties is developed. Thirdly, the OOS system optimization algorithm SOMUA-MCS is proposed. Fourthly, the OOS system for a hypothetical Geostationary Earth Orbit (GEO) commercial communication satellite is investigated to demonstrate the effectiveness of the proposed OOS assessment method, and SOMUA-MCS is used to optimize the OOS system under