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# Preliminary integrated analysis for modeling and optimizing space stations at conceptual level

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ABSTRACT

Key disciplines at the conceptual design stage for space station are introduced, which are configuration, dynamics and control, and power disciplines. The main variables and parameters in the three disciplines are presented, and the relevant disciplinary analysis models are developed. The integrated analysis framework of the space station is obtained afterward. Then, the multidisciplinary optimization for solar array configuration is taken as an example of the space station optimization based on the integrated analysis model. The optimization problem is modeled with the use of the collaborative optimization (CO). The system-level and three disciplinary optimization models are introduced. In the optimization process, MATLAB is utilized for simulation, and the adaptive genetic algorithm (AGA) is applied as the basic optimization algorithm. It is shown that the optimization problem is effectively solved with the use of the CO and AGA. Moreover, using the integrated analysis framework, the parameters of space station are successfully calculated with high computational efficiency at the conceptual design stage.

## 1. Introduction

Space station is a long-life spacecraft, which generally operates in space for more than 10 years. For instance, Russian space station Mir used to operate for about 15 years [1], and the International Space Station (ISS) has been in space for about 20 years [2]. Generally speaking, the space station is usually comprised of several modules and with complex configuration. At the conceptual design stage, many design variables are involved, and a large number of parameters in various disciplines are needed to evaluate the performance of the space station. Sometimes, different expectations are held by different disciplines for the same design variable. For instance, power discipline expects large total area of solar arrays to generate more power. In dynamics and control discipline, small annual windward area is expected to reduce propellant consumption for orbit maintenance during the operation period. Then, small total area of solar arrays is required. Hence, the conceptual design and optimization of the space station is of great complexity. Long, highly iterative, and costly design cycles are usually required. Nevertheless, with the use of an integrated analysis framework as well as optimization methods, the efficiency of the conceptual design for space station can be improved.

Many studies have investigated conceptual design framework and optimization in the field of aerospace. Rowell et al. described disciplinary modeling, optimization methods and frameworks for space transportation systems conceptual design and analysis [3]. Two general approaches were introduced for integrating these disciplinary models into computational frameworks for automated vehicle synthesis and optimization in this study. Jilla and Miller developed a multiobjective, multidisciplinary design optimization (MDO) methodology for mathematically modeling and conceptual design of the distributed satellite system [4]. Antoine and Kroo presented an integrated framework and the relevant design tools for aircraft conceptual design, including noise prediction code, engine simulator, and aircraft analysis and optimization modules [5]. Perez et al. proposed an integrated control-configuration aircraft design sizing framework based on the multidisciplinary design optimization [6]. Cavagna put forward a design tool called NeoCASS (Next generation Conceptual Aero-Structural Sizing Suite) for the aero-structural analysis and MDO of aircraft layouts at the conceptual design stage [7]. The whole methodology was based on the integration of geometry construction, aerodynamic and structural analysis codes that combine depictive, computational, analytical, and semi-empirical methods. Ziemer et al. introduced the Conceptual Design Tool (CDT) for conceptual aircraft design [8]. The design data from several disciplines and design tools were integrated and reorganized into a single structure to be viewed and analyzed together. Kontogiannis and Ekaterinaris described the preliminary design, performance evaluation and optimization process of an un-

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manned air vehicle (UAV) [9]. Dufour et al. researched on the multidisciplinary optimization of an aircraft carried sub-orbital spaceplane [10]. The optimization contained three disciplines: the aerodynamics, the structure and the trajectory. Panagiotou et al. described the conceptual design of a hybrid solar Medium-Altitude-Long-Endurance Unmanned-Aerial-Vehicle (MALE UAV) [11]. The relevant methods for estimating weight, aerodynamic and performance parameters were included. Zhang et al. investigated parameterization and optimization of hypersonic-gliding vehicle configurations during conceptual design [12]. These works help to improve the conceptual design efficiency and quality for various aerospace vehicles on the basis of integrated design and optimization methodologies.

The collaborative optimization (CO) approach, is a widely used multidisciplinary design optimization method. As a two-level and distributed approach, it breaks down a complex MDO problem into a system-level optimization problem and several disciplinary optimization problems. In the disciplinary optimization, each discipline is made independent temporally and then does not require data input from other disciplines [13,14]. Thus, all disciplinary optimizations can be implemented independently and concurrently, which means relatively fast optimization process and high efficiency. In addition, the architecture of CO method is similar to organization structure of aerospace project management. Therefore, it is convenient to apply CO to an aerospace optimization problem. There have been many application cases in the optimization design for the aircraft [15–18], launch vehicle [19–21], and spacecraft [22,23].

The main contribution of this paper is to develop the integrated analysis framework and model for space station, and apply it to the conceptual design and optimization of space station to enhance the design quality. In addition, with the use of CO, the disciplines involved can be optimized concurrently, which helps to improve the optimization efficiency. The article is structured as follows. In Section 2, the key disciplines of space station at the conceptual design stage are introduced. Subsequently, the disciplinary analysis models are developed in Section 3. In section 4, the integrated analysis framework for space station is presented. Then, the multidisciplinary optimization for solar array configuration is introduced as an example of the conceptual design for space station in Section 5. This section contains system-level and disciplinary optimization models based on the CO. In Section 6, the optimization results are described and discussed. Finally, conclusions are presented in Section 7.

## 2. The key disciplines of space station at the conceptual design stage

In this paper, a space station with a representative configuration is taken into consideration. It is comprised of three modules, one service module and two identical experiment modules. Its overall configuration is like the letter “T” (shown in Fig. 1) [24]. The four solar arrays on the two experiment modules are with the same size. In addition, the two solar arrays on the service module are also the same.

At the conceptual design stage, configuration, dynamics and control, and power disciplines play key roles. In this paper, only the three disciplines are taken into account.

In the configuration discipline, dimensions of the modules and solar arrays are crucial design variables. They pose a great effect to the performance of the space station. In addition, the dimensions of the solar arrays on different modules should be constrained to avoid collision interference among the solar arrays and the modules.

In the dynamics and control discipline, at least 5 parameters are needed to evaluate the performance of the space station. First of all, the annual average windward area of the space station, denoted by $S_{ya}$, directly affects the annual propellant consumption for orbit maintenance. The less $S_{ya}$ is, the less propellant needs to be transferred to the space station by freighter spacecrafts per year. In the optimization of space station, $S_{ya}$ can be considered as the objective function. Then, TEA (Torque equilibrium attitude) is applied to make the gravity gradient torque to balance the aerodynamic disturbing torque. Thus, the propellant for attitude control of the space station is saved. In the TEA mode, the maximum of pitch angle $\theta_{em}$ should be constrained, and the angular momentum amplitude per orbit circle $h_m$ should not exceed the control capability [25,26]. Finally, the basic natural frequencies of deployed solar arrays on the service and experiment modules, denoted by $f_{hw}$ and $f_{sw}$, respectively, should not be too low. Otherwise, it is highly difficult to control the vibration of the solar arrays as well as the attitude of the space station.

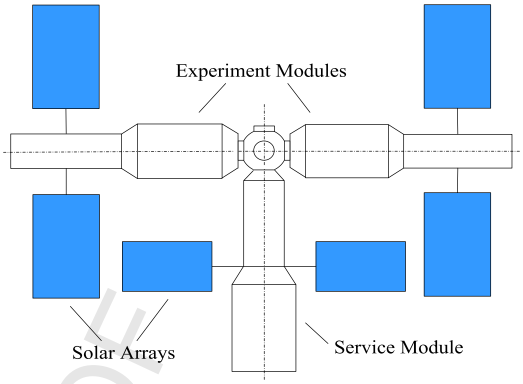

**Fig. 1.** The overall configuration of the space station.

**Table 1**
Key variables and parameters of the three disciplines.

| Discipline | Variables or parameters |
|---|---|
| Configuration | The dimensions of the modules<br>The dimensions of the solar arrays |
| Dynamics and control | $S_{ya}$, $\theta_{em}$, $h_m$, $f_{hw}$, $f_{sw}$ |
| Power | $P_1$, $P_3$ |

In the power discipline, the average power generated by all the solar arrays on the space station per orbit circle $P_3$ should be plenty for use. Meanwhile, as the service module is the core of the whole space station, the average power generated by its solar arrays per orbit circle $P_1$ should also be high enough.

The key variables and parameters in the three disciplines mentioned above are displayed in Table 1.

## 3. Disciplinary analysis modeling

To calculate the parameters of the space station, disciplinary analysis models are developed in this section. The models described in Sections 3.1.4, 3.2.3, 3.2.4, 3.2.8, and 3.3.1–3.3.4 are novel. Others are built with existing methods [27].

### 3.1. Analysis modeling for the configuration discipline

#### 3.1.1. Mass center location

At first, the body-fixed coordinate of the space station $O_b x_b y_b z_b$, a right-hand coordinate system, is defined in Fig. 2. In this coordinate, the mass center location is given, denoted as $(x_m, y_m, z_m)$.

#### 3.1.2. Moment of inertia

The moment of inertia of the space station is given in the following form:

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