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# Developing an optimal layout design of a satellite system by considering natural frequency and attitude control constraints

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## ABSTRACT

In recent years, there has been a growing research interest in layout design optimization of satellite systems. The layout design optimization of a satellite system is a complex process having a large number of design variables and constraints. This paper presents a hybrid optimization algorithm, which globally explores the design search space using Particle Swarm Optimization (PSO) and gradient-based Sequential Quadratic Programming (SQP) to rapidly locate optimum design point. The majority of the previous research works mainly focused on finding reasonable placement of components in satellite layout design, with some specific requirements, which are essential for the satellite stability, control and performance such as attitude control, non-interference and overlap constraints. In this study, additional requirements such as structural stiffness and natural frequency constraints are also considered. The proposed approach is employed on a simplified international global communication satellite. The obtained results indicate that the consideration of natural frequency and attitude control constraints in the configuration layout design of a satellite system can significantly improve the stability and control of the satellite and thus frequency coupling between satellite and launcher can be prevented. In addition, the results indicate that the proposed method provides an effective way of solving layout design optimization problem of satellite systems.

## 1. Introduction

The layout design of a satellite system is a complex process because it must balance simultaneously several factors, such as payload objectives, required position of center of mass of the satellite, moments of inertia, equipment heat dissipation, geometrical and performance constraints and system requirements, among others. Moreover, satellite system design involves a large number of different components relating to various functional subsystems, such as payload, attitude control, structures, power, data handling, communication and propulsion. Furthermore, applying optimization techniques to layout design problems can increase the system performance with the required position for the system's center of mass, preference of moment of inertia in a given direction, minimization of electromagnetic interference, avoidance of high heat dissipation equipment being positioned close to another and improved system stability and control. The avoidance of resonance between launcher and satellite structures is one of the most crucial parameters of a satellite system design. Configuration layout design of the components can affect natural frequency of the system, which can significantly impact on the occurrence of resonance.

In recent years, emphasis has been on the advances that can be achieved with the utilization of optimization techniques to space system layout design problems. Therefore, various layout design optimization techniques have been developed. The majority of the previous research works took into account the problem of positioning components from different subsystems in such a way that there is no interference and overlap between the components while satisfying certain geometrical, performance and system constraints [1,2]. Nevertheless, the overlap between components (geometric interfaces) [3], and the non-equilibrium (i.e. imbalance) of the system are the two main comprehensive constraints in layout design problem [4]. A variety of methods have been utilized in the satellite layout design problems, with each having its advantages and limitations. For instance, layout design of a satellite module utilizing Genetic Algorithm (GA) was introduced in [5]. In this work, a selection strategy was introduced in GA algorithm based on the fast and elitist multi-objective genetic algorithm [6] and engineering requirements. In addition, knowledge fusion design method was employed in satellite layout design problem [7]. The mentioned work integrates online human knowledge, prior knowledge and computational knowledge

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## Nomenclature

| | | |
|---|---|---|
| $a_i$ | Length of a cubic component (along $x$-axis) | mm |
| $a_k$ | Step length parameter | |
| $b_i$ | Width of a cubic component (along $y$-axis) | mm |
| $C_o$ | Satellite center of mass located in the $xyz$ coordinate system | |
| $d$ | Diameter of the inner circle of satellite | mm |
| $d_k$ | Search direction of the SQP optimization algorithm | |
| $D$ | Diameter of the body of satellite | mm |
| $g_k$ | Non-interference and overlap constraints ($k = 1, 2, 3, \ldots, 375$) | mm |
| $g_{376}/g_{377}/g_{378}$ | Static balance of the satellite (along $x/y/z$-axis) | mm |
| $g_{379}/g_{380}/g_{381}$ | Allowable error with respect to actual center of mass of the satellite in the $xyz$ directions (along $x/y/z$-axis) | mm |
| $h_i$ | Height of all components (along $z$-axis) | mm |
| $H_i, i = 1, 2$ | Height of the (first/second) floor | mm |
| $H_t$ | Total height of the satellite | mm |
| $H_k$ | Positive definite approximation of the Hessian matrix of Lagrangian function | |
| $I_{ij}$ | $i, j$th component of moment of inertia matrix ($i, j = x, y, z$) | $\mathrm{kg\,m^2}$ |
| $J_{xi}$ | Moment of inertia of the $i$th component with respect to the $x$ axis | $\mathrm{kg\,m^2}$ |
| $J_{xic}, J_{yic}, J_{zic}$ | Moments of inertia of the $i$th cylindrical component with respect to the local coordinate | $\mathrm{kg\,m^2}$ |
| $J_{xis}, J_{yis}, J_{zis}$ | Moments of inertia for the $i$th cubic component with respect to the local coordinate system | $\mathrm{kg\,m^2}$ |
| $J_{yi}$ | Moment of inertia of the $i$th component with respect to the $y$ axis | $\mathrm{kg\,m^2}$ |
| $J_{zi}$ | Moment of inertia of the $i$th component with respect to the $z$ axis | $\mathrm{kg\,m^2}$ |
| $k$ | Number of non-interference and overlap constraints | |
| $m_i$ | Mass of the $i$th components | kg |
| $n$ | Number of components | |
| $n_1$ | Number of iteration used in PSO algorithm | |
| $n_2$ | Number of iteration used in SQP algorithm | |
| $O$ | Origin of $xyz$ coordinate system | |
| $O'$ | Origin of $x'y'z'$ coordinate system | |
| $p_{gb}$ | Global best value in PSO algorithm | |
| $p_{pb}$ | Personal best value in PSO algorithm | |
| $Q_i$ | Location of components in each floor, $i = 1, \ldots, 4$ | |
| $q_i$ | Number of components on top or under of each floor, $i = 1, \ldots, 4$ | |
| $r_i$ | Radius of $i$th (cylindrical and cubic) component | mm |
| $R_t$ | Radius of inner cylindrical shape of the satellite | mm |
| $R_m$ | Position of centroid in the $xoy$ plane | mm |
| $r_n$ | Radius of component $n$ | |
| $u_i, v_j$ | Lagrangian multipliers | |
| $v_j(t)$ | Velocity of a particle (PSO algorithm) | |
| $w$ | Inertia weight factor | |
| $x$ | Location of component in the $x$ axis | mm |
| $x_e$ | Expected $x$ position relative to centroid of the whole satellite system | mm |
| $x_i$ | The coordinates of a cubic component in the $x$ direction | mm |
| $x_{2i-1}$ | Location of components in the $x$ axis ($i = 1, 2, 3, \ldots, 54$) | mm |
| $x_{2i}$ | Location of components in the $y$ axis ($i = 1, 2, 3, \ldots, 54$) | mm |
| $x_{Li}$ | Lower bounds for $i$th design variable | mm |
| $x_m$ | Position of center of mass of a component along $x$ axis | mm |
| $x_{2n-1}$ | Position of center of mass of component $n$ in the $x$ directions | |
| $x_{2n}$ | Position of center of mass of component $n$ in the $y$ directions | |
| $x_j(t)$ | Poison of a particle (PSO algorithm) | |
| $x_{Ui}$ | Upper bounds for $i$th design variable | mm |
| $y$ | Location of component in the $y$ axis | mm |
| $y_e$ | Expected $y$ position relative to centroid of the whole satellite system | mm |
| $y_i$ | The coordinates of a component cubic in the $y$ direction | mm |
| $y_m$ | Position of the center of mass in the $y$ axis | mm |
| $z$ | Location of a component in the $z$ axis | mm |
| $z_e$ | Expected $z$ position relative to centroid of the whole satellite system | mm |
| $z_i$ | Coordinates of a component (cubic and cylindrical) in the $z$ direction | mm |
| $z_m$ | Position of the center of mass of a component in the $z$ axis | mm |
| $t$ | Thickness of plates of each floor | mm |
| $\alpha_i$ | Rotation of angle of the cubic components in the plane of $oxy$ | rad |
| $\nabla V_i$ | Sum of the non-interference constraints in each floor | mm |
| $\delta x_e, \delta y_e, \delta y_z$ | Allowable error in $x, y, z$ axis | mm |
| $\delta\theta_x, \delta\theta_y, \delta\theta_z$ | angles between the principal axes of inertia of the satellite with the principle axes $ox$, $oy$ and $oz$, respectively | rad |
| $\theta_i$ | Angle of rotation in $xoy$ plane with respect to the axis $z$ | rad |
| $\theta_x, \theta_y, \theta_z$ | Angles between the principal axes of inertia of the satellite with the principle axes $ox$, $oy$ and $oz$, respectively | rad |
| $\varepsilon$ | Stopping criteria (differences between objective function values of the last two iterations in optimization process) | |

utilizing evolutionary computation and therefore combining the advantages of human and evolutionary algorithm for solving layout design optimization of a satellite module. Similarly, human and computer interaction utilized for solving layout design problem as discussed in [8] and computer interaction using qualitative and quantitative multiple factors in objective function of a quadratic model are used to formulate multi-goal layout design problem [9]. Physical layout constraints are also utilized to model geometrically the layout of instruments and in particular antennas [10].

There are several studies in the literature that introduce systematic optimization methodologies for solving satellite layout design problems. A survey of computational approaches to 3D layout problems was introduced in [11]. Cooperative and co-evolutionary scatter search for satellite module layout design were introduced in [12], while the global optimal solution to the 3D layout optimization model with behavioral constraints was proposed in [13]. A coupled shape and topology optimization method for multi-component layout design problem was reported in [14]. Optimal layout design of a satellite employing an evolutionary method with

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