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Optimal design of the satellite constellation arrangement reconfiguration process

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Abstract

In this article, a novel approach is introduced for the satellite constellation reconfiguration based on Lambert's theorem. Some critical problems are raised in reconfiguration phase, such as overall fuel cost minimization, collision avoidance between the satellites on the final orbital pattern, and necessary maneuvers for the satellites in order to be deployed in the desired position on the target constellation. To implement the reconfiguration phase of the satellite constellation arrangement at minimal cost, the hybrid Invasive Weed Optimization/Particle Swarm Optimization (IWO/PSO) algorithm is used to design sub-optimal transfer orbits for the satellites existing in the constellation. Also, the dynamic model of the problem will be modeled in such a way that, optimal assignment of the satellites to the initial and target orbits and optimal orbital transfer are combined in one step. Finally, we claim that our presented idea i.e. coupled non-simultaneous flight of satellites from the initial orbital pattern will lead to minimal cost. The obtained results show that by employing the presented method, the cost of reconfiguration process is reduced obviously.

Keywords: Satellite constellation; Reconfiguration process; Lambert targeting problem; Optimal design; IWO/PSO algorithm

1. Introduction

A satellite constellation can be described as a number of satellites with identical types and performances, which are designed to present at complementary and similar orbits to achieve a common goal (Wertz, 2009). Thus, a constellation is a group of satellites which provides services in cooperation with each other. Satellite constellations are primarily used for global or zonal coverage of the earth's surface. Among the applications of satellite constellations, global positioning, global telecommunications and Earth observation, can be indicated (Wertz, 2009).

The satellite constellation reconfiguration is the alteration and transformation of a primary satellite constellation into a new satellite constellation arrangement, in order to maintain the system in an optimal state (Davis, 2010). Another overall concept of the satellite constellation reconfiguration is the intentional changing of the relative arrangement of the satellites through implementing orbital maneuvers, in order to achieve the desirable changes in the coverage, efficiency, and capacity of the satellite constellation (Scialom, 2003).

The satellite constellation reconfiguration may be required due to the following major reasons:

- The requirement of staged increase in the satellite constellation capacity.
- Meeting the mission requirements in confronting with loss of capacity by reconfiguring the remaining satellites.
- Changing the mission requirements by reconfiguring the orbital pattern.

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In order to reduce the economic risks, Olivier de Weck, introduced a staged deployment method for designing Low Earth Orbit (LEO) communication satellite constellations. He finally showed that, using this strategy, the life-cycle costs for similar systems in Iridium communication satellite constellation can be reduced by more than 20% (Chaize, 2003; de Weck et al., 2003, 2004). Uriel Scialom conducted a study on the reconfiguration of LEO satellite constellations with a global coverage requirement, similar to Iridium and Global Star communication satellite constellations. He offered a technical way for the staged deployment method (Scialom, 2003; de Weck et al., 2008). The intended impulsive orbital maneuvers consist of a simultaneous plane change and Hohmann maneuvers and finally a phasing maneuver on the target orbits. As we know phasing maneuver requires additional cost and time. Also, in his study, in order to solve the problem of the optimal assignment of satellites to the desired orbital pattern, the Auction algorithm has been used (Scialom, 2003; de Weck et al., 2008). Siddiqi conducted a study on the determination of an optimal target constellation considering minimum reconfiguration cost to increase capacity. To this aim inter and intra satellite constellation reconfiguration has been employed. Intra satellite reconfiguration involves changing the spatial position of the satellites, and intra satellite reconfiguration which means changing the position of the components of each satellite, such as antennas. In his work, Sequential Quadratic Programming (SQP) algorithm and Simulated Annealing (SA) algorithm have been used to determine the optimal target constellation (Siddiqi et al., 2005). Using multi-objective genetic algorithm, Ferringer introduced a framework for the reconfiguration of the Global Positioning Constellation (GPS) in case of loss of capacity in the system for any reason, and only with the use of the remaining satellites, in order to meet the requirements of the mission. In this study, in order to perform the reconfiguration operation, a phasing maneuver is intended on circular orbits (Ferringer, 2009; Ferringer et al., 2009). Owis reconfigured a satellite constellation, with the use of Approximating Sequence Riccati Equations, assuming circular and coplanar pattern for both initial and target orbits. He used optimal control methods for satellite constellation reconfiguration (Owis, 2013). Appel optimized the maneuvers required for performing the operation of satellite constellation reconfiguration in terms of fuel consumption using electrical propulsion (Appel et al., 2014). Circi investigated the procedure of meeting the mission requirements of a satellite constellation, such as: the intended coverage area, and revisit time, through changing the orbital configuration of the constellation. In his study, Hohmann transfer maneuver is intended for the orbital transfer of satellites between the coplanar initial and target orbits, and the plane change maneuver is intended for the orbital transfer of satellites between the non-coplanar initial and target orbits (Circi et al., 2014).

According to the above explanation, each satellite constellation reconfiguration problem consists of a configuration design of the final constellation and an orbital transfer problem. The optimal design of satellite constellations is widely regarded by researchers during the past years (Kim and Chang, 2015; Ulybyshev, 2008; Knauer and Büskens, 2010) which is not in the scope of this article. Related to the second issue it is noteworthy that the problem of optimal orbital transfer of satellites to the desired configuration is divided into two tasks; the optimal transfer of a set of satellites from an initial orbit to a final orbital pattern and the assignment of each satellite to a specific final position in an optimal manner. Cost reduction and elimination of the other constraints on the shape or orientation of initial and final orbits are important issues in planning an appropriate orbital transfer method.

Pontani conducted a research on Particle Swarm Optimization (PSO) of impulsive orbital transfers. His research aimed to determine a globally optimal orbital transfer between the initial and target orbits, which might not be coplanar, coaxial, or even with a common point (Pontani and Conway, 2012). Bae conducted a study of spacecraft formation reconfiguration, using the impulsive control. In his article, Lambert's problem for designing the transfer orbit of satellites, has been modified according to the relative dynamics governing the satellite formation (Bae and Kim, 2013). Healy used the Lambert targeting theorem, for the orbital transfer of a spacecraft to the position of the space debris (Healy, 2014). Butikov investigated impulsive orbital maneuvers needed for several different space flights assuming coplanar initial and final orbits (Butikov, 2015).

2. State of the art

In this article, a new approach is presented for the satellite constellation reconfiguration, based on Lambert's theorem by considering the issue of reducing risks and costs. Hence, the constellation reconfiguration problem is taken into consideration with the two constraints of overall fuel cost minimization and the final configuration. In order to meet the both constraints, the idea of simultaneous deployment of satellites on the desired orbital pattern is suggested. So that there will be no need to implement phasing maneuvers in order to form the desired orbital pattern. Consequently achieving the final configuration is assured faster and also at a lower cost. Furthermore, it will be shown that simultaneous flight of satellites from the initial orbit will not satisfy the constraint of overall fuel cost minimization. In order to fix this problem, the idea of coupled non-simultaneous flight of satellites from the initial orbit, is presented.

In addition, a method for modeling the objective function will be introduced in which the both important tasks of determining the sub-optimal transfer orbits and optimal