European Journal of Operational Research 242 (2015) 10–20

Contents lists available at ScienceDirect

European Journal of Operational Research

journal homepage: www.elsevier.com/locate/ejor

Discrete Optimization

Reconfiguration of satellite orbit for cooperative observation using variable-size multi-objective differential evolution

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ARTICLE INFO

Article history:
Received 13 August 2013
Accepted 21 September 2014
Available online 10 November 2014

Keywords:
Satellite orbit reconfiguration
Variable-size optimization
Multi-objective differential evolution
Evolutionary computations
Estimation of Distribution Algorithm

ABSTRACT

A novel self-adaptive variable-size multi-objective differential evolution algorithm is presented to find the best reconfiguration of existing on-orbit satellites for some particular targets on the ground when an emergent requirement arises in a short period. The main contribution of this study is that three coverage metrics are designed to assess the performance of the reconfiguration. Proposed algorithm utilizes the idea of fixed-length chromosome encoding scheme combined with expression vector and the modified initialization, mutation, crossover and selection operators to search for optimal reconfiguration structure. Multi-subpopulation diversity initialization is adopted first, then the mutation based on estimation of distribution algorithm and adaptive crossover operators are defined to manipulate variable-length chromosomes, and finally a new selection mechanism is employed to generate well-distributed individuals for the next generation. The proposed algorithm is applied to three characteristically different case studies, with the objective to improve the performance with respect to specified targets by minimizing fuel consumption and maneuver time. The results show that the algorithm can effectively find the approximate Pareto solutions under different topological structures. A comparative analysis demonstrates that the proposed algorithm outperforms two other related multi-objective evolutionary optimization algorithms in terms of quality, convergence and diversity metrics.

1. Introduction

A distributed satellite system (DSS) may be needed to perform cooperative observation to satisfy the mission requirements in the case of emergency, because the characteristics of temporary reconnaissance missions, such as earthquake relief, flood monitoring and terrorism combat, launch of a new satellite may be uneconomic. Fortunately, there are hundreds of satellites carrying out various tasks in low Earth orbit. If necessary, the existing on-orbit satellites can be optimally reconfigured as a generalized DSS which performs cooperative observation of some particular targets during a specified time period. It is desirable in most cases to expand the performance of this generalized DSS by orbital maneuvers under affordable cost.

Observing some given targets within an assigned time frame is an orbit design problem. The initial orbit design can be solved from ground track points (Abdelkhalik, 2010; Abdelkhalik & Gad, 2011; Vtipil & Newman, 2010; Wall & Conway, 2009). An optimization problem in satellite constellation was constructed to pursue better revisit time (RT) or resolution according to the user requirements (Chen, Mahalec, Chen, He, & Liu, 2013; Williams, Crossley, & Lang, 2001). The number of satellites in the above orbit designs is predefined, but it may be a design variable in the satellite reconfiguration case. Therefore, it is necessary to optimize the number of satellites and specify which satellites from an alternative set to perform orbital maneuver. This is a variable-size optimization problem because the number of satellites defines the state vector length during optimization. Moreover, reconfiguration is a typical multi-objective optimization problem that requires a trade-off between the multi-mission metrics. In this study, the reconfiguration of on-orbit satellites aims to improve the coverage metrics during a short period. To avoid drastically shortening the lifetime of the satellites, the reconfiguration only relates to changing the relative locations of satellites on the initial orbit.

The contribution of this study is twofold. First, three types of coverage metric are designed to assess the performance of reconfiguration: the average revisit time (ART) for single target, the total coverage time (TCT) for multi-targets and the coverage statistics based on task scheduling (CSTS) which measures performance with respect to user requirements. Then satellite reconfiguration is formulated as a multi-objective optimization problem that considers coverage metrics, fuel consumption, and maneuver time. Second, the fixed-length encoding scheme combined with expression vector in chromo-

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http://dx.doi.org/10.1016/j.ejor.2014.09.025

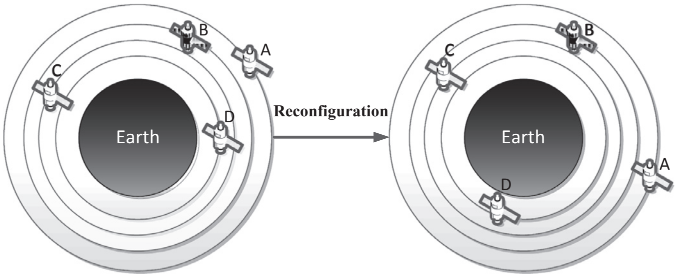

Fig. 1. Concept of on-orbit satellite orbit reconfiguration.

some building operator, multi-subpopulation diversity initialization, mutation based on estimation of distribution algorithm (EDA) (Ferringer & Spencer, 2006), adaptive crossover and modified selection operators are integrated into the multi-objective differential evolution to manipulate variable-length chromosomes and finally optimize the topological structure (satellite combination) and component values (maneuver variables of each satellite involved in reconfiguration) simultaneously.

The effectiveness of the proposed algorithm is verified by three case studies. The comparison with two other related multi-objective optimization algorithms demonstrates that the proposed algorithm performs better in terms of quality, convergence and diversity metrics defined on Pareto front.

2. On-orbit satellite reconfiguration

2.1. Background

Reconfiguration which is traditionally used in satellite constellation refers to implementing a series of essential maneuvers to maintain or improve the performance if some satellites fail (Larrañaga & Lozano, 2002). Various reconfiguration issues have been solved, such as optimal reconfiguration and formation-keeping for formation flying satellites (de Weck, Scialom, & Siddiqi, 2008); optimal reconfiguration of satellite formation to continue operation after loss of one satellite (Park, Park, & Choi, 2011); reconfiguration of GPS constellations after loss of capacity (Ahn & Spencer, 2002). A general framework was proposed to transform an initial constellation A into constellation B and was employed in communication satellites (Larrañaga & Lozano, 2002). In these examples, a reconfiguration is accomplished via orbital maneuvers of on-orbit satellites from a constellation with a known number of maneuvered satellites.

In this study, it is not required that the satellites involved in reconfiguration are from the same constellation. These satellites, which form a more generalized DSS for a temporary mission in a short period, may have been launched for performing specific tasks at different phases. They lie in different orbits with no active control to maintain relative positions. Although one or more classical orbital elements of a satellite can be changed to satisfy the mission requirements, the satellite in most cases is kept close to its initial orbit during the whole lifetime after it arrives at its mission orbit. Orbital maneuvers, especially non-coplanar maneuvers, are seldom carried out; otherwise the lifetime of the satellite will be drastically shortened.

An economic approach of reconfiguration is to rearrange the relative positions through phase changing in order to obtain a desired performance in a specified period. In the case of a modest transfer time, phase changing may require an acceptable fuel cost (Ferringer, Spencer, & Reed, 2009). Fig. 1 visualizes the concept of reconfiguration. It is assumed that there are four alternative satellites in different orbits providing the desired performance for some specific targets. The number of satellite combinations for orbital maneuver are 2^4. If satellites A, C and D are chosen to rearrange their relative positions from satellite B which is kept on its original orbit, the four satellites form a generalized DSS to perform cooperative observation.

In this study, satellite reconfiguration is defined as "adjusting the relative locations of multiple on-orbit satellites through changing the mean anomaly". Not only the best combination but also the optimal maneuver values for each satellite should be computed with the design goal of maximizing the performance with minimum total fuel consumption and minimum maneuver time.

2.2. Computation of objective functions

The following notations are defined prior to the presentation of the objective functions.

Parameters

a_{tgt} semimajor axis of the target orbit

a_{phase} semimajor axis of the phase orbit

H orbit height

K the number of satellites in reconfiguration

K_{int} revolutions of satellite on phasing orbit

K_{tgt} revolutions of satellite on target orbit

Lat_T, $Long_T$ the target's latitude and longitude

Lat_{SSP}, $Long_{SSP}$ the sub-satellite point's latitude and longitude

m^i the number of gap durations of satellite i

MT_{total} total maneuver time

P the performance of the satellite system

R_e equatorial radius of the Earth

t_0 initial time of the scene

w_i priority weight for target i

w_p penalty weight

w_{tgt} angular velocity of the target orbit

$w_s^{i,j}$, $w_e^{i,j}$ jth start and end time of coverage window for satellite i

$t_s^{i,j}$, $t_e^{i,j}$ jth start and end time of gap duration for satellite i

α_i the target i on the schedule $(=1)$ or not $(=0)$

λ Earth central angle

$\eta^{\max}$ half maximum angle of field of view

η half current angle of field of view

ρ angular radius of the Earth

μ gravitational parameter

θ_0 angle of the target is ahead or behind of the interceptor

ν true anomaly

Δt step length of satellite propagation

ΔV_{total} total velocity changes

2.2.1. Coverage metrics

Coverage metrics assess the satellite-provided performance for a set of targets. Three types of coverage metric are used in this study: average revisit time (ART), total coverage time (TCT) and coverage statistics based on task scheduling (CSTS). Visibility between satellites and targets need to be determined so as to compute these coverage metrics.

Visibility depends on many factors, such as the location of the target, the number of satellites in the DSS, and each satellite's