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Onboard autonomous mission re-planning for multi-satellite system

Zixuan Zheng, Jian Guo [*], Eberhard Gill

Delft University of Technology, The Netherlands

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ABSTRACT

This paper presents an onboard autonomous mission re-planning system for Multi-Satellites System (MSS) to perform onboard re-planing in disruptive situations. The proposed re-planning system can deal with different potential emergency situations. This paper uses Multi-Objective Hybrid Dynamic Mutation Genetic Algorithm (MO-HDM GA) combined with re-planning techniques as the core algorithm. The Cyclically Re-planning Method (CRM) and the Near Real-time Re-planning Method (NRRM) are developed to meet different mission requirements. Simulations results show that both methods can provide feasible re-planning sequences under unforeseen situations. The comparisons illustrate that using the CRM is average 20% faster than the NRRM on computation time. However, by using the NRRM more raw data can be observed and transmitted than using the CRM within the same period. The usability of this onboard re-planning system is not limited to multi-satellite system. Other mission planning and re-planning problems related to autonomous multiple vehicles with similar demands are also applicable.

1. Introduction

Operating a space mission usually requires two types of systems: human-operated systems and autonomous systems. Human-operated systems can help satellites to react to unexpected situations or new mission objectives. Such circumstances are typically highly complex and cannot be handled by preconceived discrete actions and sequences. On the other hand, autonomous systems can help operators to reduce the amount of pre-defined on-board behaviors, such as deployment of antennas and solar panels, detumbling, and three-axis attitude orientation. Depending on the characteristics of the specific mission, these two types of operating systems may be combined. With the increased complexity for future space missions, autonomous systems will have more competences than before. Several space missions, such as DS-1, EO-1, BIRD, and PROBA, were all implemented with autonomous systems. In the mission Deep Space 1 (DS-1) [1], the Remote Agent (RA), a remote intelligent self-repair software was developed by Jet Propulsion Laboratory (JPL). The RA consists of three components: the Planner/Scheduler (PS), the Executive (EXEC), and a model-based Mode Identification and Recover engine (MIR) [2]. The Earth Observation One (EO-1) mission experimentally applied an autonomous system for data recognition of observed images. Meanwhile, the CASPER [3] planner was used for on-board mission planning and re-planning. This planner used iterative repair to support continuous modification and updating of a current working plan. The Bi-spectral and Infrared Remote Detection (BIRD) mission has remarkable fire-detection qualities through a neural network classifier, and real-time hot-spots detection globally [4]. The PROBA mission was an European Space Agency's (ESA) project [5] used an autonomous system to control the satellite, including its data communications, general operations, resources management, and payload operations.

Meanwhile, with the rising demands and complicated requirements, many space missions require more than one satellite to fulfill their mission objectives. Using the Multi-Satellite System (MSS) for these missions is a good choice. There are several space missions using multi-satellite systems and implement onboard autonomy to improve their operational performance. The Autonomous Sciencecraft Constellation (ASC) [6] flight demonstration uses TechSat-21 satellites [7] from the US Air Force. The onboard flight system includes following autonomous sub-systems: the Burton sub-system is responses for model-based mode identification and recovery; the CASPER planner helps to plan and re-plan activities, along with uplink and downlink information; the ObjectAgent cluster management software helps three TechSat-21 satellites to perform formation flying. Another mission, called Three Corner Sat (3CS) [8], which was launched in 2002. The onboard autonomous system [9] used the Spacecraft Command Language (SCL) robust execution system, the CASPER planning system, the SELective MONitoring system (SELMON), and a satellites formation flying coordination package. NASA launched several space missions consisting of

* Corresponding author.
E-mail addresses: Z.Zheng@tudelft.nl (Z. Zheng), J.Guo@tudelft.nl (J. Guo), E.K.A.Gill@tudelft.nl (E. Gill).

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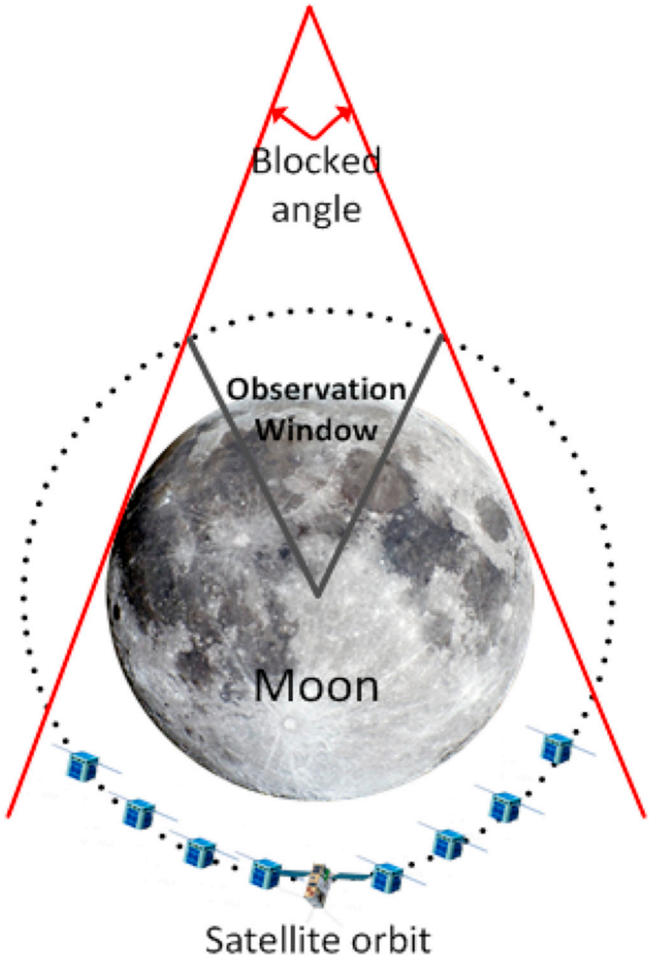

Fig. 1. Shielded area.

multi-satellite systems. The most recent mission is called Magnetospheric Multiscale (MMS) [10], which was launched in 2015. This mission includes four identical spacecrafts which use dynamic magnetic system to study the magnetic reconnection around the Earth. It combines onboard science processing framework and the Adaptive Network Architecture (ANA) [11–13] to perform the higher efficiency and better performance.

Within the functionality of autonomous systems, our research interests lays in the mission planning and scheduling part. The basic idea of mission planning is that computer or operator need to base on the mission requirements to generate feasible control sequences. These sequences will guide all the sub-systems to perform certain behaviors in the defined time or order. This procedure is very complex due to massive characteristics associated with communication capabilities, constraints from mission scientific requirements, onboard storage capacities, and upload and download time windows. Due to the complexity of mission planning and scheduling, early studies focused on single satellite planning. Bensana et al. [14] treated the single-satellite mission planning problem as a constraint satisfaction problem. They used the Depth-first-search and the Russian-dolls search as exact methods and used Tabu Search (TS) as an approximate method to solve the planning problem for SPOT5 satellite mission. Gabrel et al. [15] proposed a graph-theoretic model for both the medium- and the short-term sequencing and present algorithmic solutions by using properties of the model. Poter and Gasch used an improved greed algorithm in LandSat 7 satellite [16] for mission planning. Vasquez et al. [17] presented a Partition-based approach (UPPB) to divide the main problem into multiple subproblems and solved each sub-problem by enumeration algorithm. Lin et al. [18] modified the mathematical programming method for the mission to acquire a near-optimal solution.

Mission planning problems for multi-satellite systems are more complicated and even unpredictable with the increasing number of variables and constraints. For same applications, the MSS provides increasing benefits over single satellite system, many researchers have shifted their interests to mission planning problems for MSS. Frank et al. [19] used a constraint-based interval (CBI) framework to represent onboard resources and presented a heuristic to guide the search procedure for resources. Lematre et al. [20] compared two methods, suggested that Constraint Programming (CP) was more flexible than Local Search (LS) method in problem recognition, but the LS method can provide better performances on results' accuracy. Abramson et al. [21] formulated the problem as a mixed-integer problem, with the objective to maximize the total observing time of the target, and used the classical algorithms for the shortest path problem. Dungan et al. [22] provided a declarative model and a stochastic sampling method. The optimization method was based on resource contention heuristics. Globus et al. [23,24] used Genetic Algorithm (GA) to solve the same problem, and compared simulation results with using various other methods, like Hill-climbing, Simulated Annealing (SA) and Differential Evolution (DE). Chien et al. [25,26] presented a sensor web detection and real-time response architecture to coordinate a MSS to track unexpected ground phenomena. Wang et al. [27] proposed a multi-objective scheduling method using Strength Pareto Evolutionary Algorithm 2 (SPEA-2) to solve scheduling problem. Bianchessi et al. [28] used the TS heuristics to generate mission plans and associated it with an upper bounding column generation algorithm to evaluate the performance of their solutions. Mansour et al. [29] implemented a multi-objective GA to solve the SPOT5 mission planning problem. Wang et al. [30] used a priority-based conflict-avoidance heuristics algorithm and a Decision Support System. Wu et al. [31] proposed using a Hybrid Ant Colony Optimization method mixed with iteration local search (ACO-ILS) to solve both common tasks and emergency tasks.

Based on above literature review, which covers several methods and algorithms for solving the MSS mission planning problems, we can draw some conclusions. Firstly, MSS mission planning problems are more complicated than single satellite mission planning problem, many typical planning methods cannot be used in MSS. Using artificial intelligence methods can provide good solutions. Secondly, many methods have been employed for mission initial planning problems, such as exact algorithms, approximate algorithms, and heuristic algorithms. Compare to other two types of methods, heuristic algorithms show good performance on large size, more complicated problems. Thirdly, nearly all the studies tried to avoid the mission re-planning part. They focused on regular mission planning problems. However, in real-world space missions, unforeseen situations such as spacecraft entering safe mode or failures of sensors, antennas or actuators. This paper aims to solve the MSS mission re-planning problem by implementing a combination of a heuristic algorithm called Hybrid Dynamic Mutation Genetic Algorithm (HDM-GA) [32] and re-planning techniques such as inserting, deleting and modifying which applied in some Unmanned Aerial Vehicles (UAVs) and Autonomous Underwater Vehicles (AUVs) applications.

2. Problem formulation

Our goal is to solve the multi-satellite system onboard mission re-planning problems under certain emergency situations. The reference mission used throughout this paper is the Orbiting Low Frequency Antennas for Radio Astronomy mission (OLFAR) [33]. To turn this real-world problem into a solvable mathematical problem, we will formulate the problem in this section. Firstly, relevant scientific requirements and payloads will be introduced. Then, based on possible emergency situations which may occur during mission operations, three re-planning scenarios will be considered. Finally, the mathematical model including variables, parameters, boundaries, operational constraints, and objectives will be formulated.