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Swarm satellite mission scheduling & planning using Hybrid Dynamic Mutation Genetic Algorithm

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ABSTRACT

Space missions have traditionally been controlled by operators from a mission control center. Given the increasing number of satellites for some space missions, generating a command list for multiple satellites can be time-consuming and inefficient. Developing multi-satellite, onboard mission scheduling & planning techniques is, therefore, a key research field for future space mission operations. In this paper, an improved Genetic Algorithm (GA) using a new mutation strategy is proposed as a mission scheduling algorithm. This new mutation strategy, called Hybrid Dynamic Mutation (HDM), combines the advantages of both dynamic mutation strategy and adaptive mutation strategy, overcoming weaknesses such as early convergence and long computing time, which helps standard GA to be more efficient and accurate in dealing with complex missions. HDM-GA shows excellent performance in solving both unconstrained and constrained test functions. The experiments of using HDM-GA to simulate a multi-satellite, mission scheduling problem demonstrates that both the computation time and success rate mission requirements can be met. The results of a comparative test between HDM-GA and three other mutation strategies also show that HDM has outstanding performance in terms of speed and reliability.

1. Introduction

With the development of space technology, satellites provide us more and more benefits, such as Global Positioning System (GPS), satellite communication, weather forecasting, and Earth observation. However, with increasing societal requirements, some space missions cannot be carried out by a single satellite, so Swarming is rapidly becoming an important topic in aerospace research. The central concept of swarming is that a large group of spacecraft perform challenging and complex tasks, even though a single, small satellite is rather limited with regards to sensing, processing, computing and acting capability. This idea is particularly interesting given the trend towards miniaturization of space systems.

On the one hand, it appears that a swarm, consisting of small satellites, can perform better in some space missions than a single, large satellite. Meanwhile, using multiple small satellites instead of one giant satellite can reduce the out-of-service risk caused by subsystem malfunction. Usually, a swarm satellite system will bring one or two additional, small satellites in reserve in case of damage. On the other hand, real space missions are strongly dependent on the ground segment and on the flight engineers who monitor the enormous amount of telemetry data sent back to Earth during the satellite operations. There is no doubt that as the number of satellite grows, the complexity of control and coordination of these satellites by engineers will increase dramatically. Meanwhile, for some deep space missions or complex tasks, due to a long transmission time for communication or short communication windows, there is not enough time for engineers to control all the onboard behaviors from a control center.

We, therefore, need swarm satellite systems capable of receiving a highly simplified mission and then decompose it into multiple submissions. Based on the status of each satellite, the onboard computer would automatically generate the scheduling sequence for each satellite in such a swarm constellation. This paper will present an implementation of using an improved Genetic Algorithm (GA) as a mission scheduling and planning technique in a real space mission environment.

1.1. Mission background

Our nominal mission is based on Delft University of Technology's next generation mission named "OLFAR [1]". The primary scientific objective of this mission is to observe the universe in the hitherto unexplored, very low frequency (below 30 MHz) electromagnetic spectrum range. At this frequency range, observation from Earth is severely hampered by the strong ionospheric distortion and absorption,

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also known as man-made radio frequency interference (RFI). To overcome this problem, space-borne observation is needed. The Moon can help to block these RFI, and so RFI-free observation can be made at the far side of the Moon.

The concept of our nominal mission is to have some satellites, each carrying three orthogonal dipole antennas, provide full polarization, omnidirectional detection. These satellites are considered Daughter Satellites (DS). Based on OLFAR scientific requirements [2], from the perspective of operation period and mission budget, the number of DS are planned as eight in total. During the mission, the signals received from the different Daughter Satellites are received and stored by a bigger satellite called Mother Satellite (MS). The MS responds to transmit back to Earth when at the near-side of the Moon. All the DSs and the single MS form a swarm satellite system as the operational component in lunar orbit.

1.2. Research motivation

Unlike normal space missions, OLFAR mission consists of several DSs and one MS. As the number of satellites increases, generating command signals can be a laborious procedure which not only requires the operators to have specialized knowledge but also takes too much time for command transmission. In addition, due to the requirements, observation will be made at the far side of the moon to avoid RFI. During this period, the swarm cannot receive command signals from the Earth. If any emergency situation occurs, the satellites cannot rely on the ground station. All these problems and dangers led to the desire of onboard autonomy's development. The most important part of this is a scheduling algorithm.

The mission scheduling problem is often considered as Non-deterministic Polynomial Complete (NPC) problem [3]. There are many algorithms used to solve this, such as Tabu Search, Linear Programming, Simulated Annealing and Genetic Algorithm. Tabu Search (TS) was created by Glover in 1986 [4]. After its publication, TS has been widely used on job-shop scheduling and machine scheduling problems. Hertz [5] mentioned using TS as the method for flow-shop sequencing problems, and about 90% of the case were succeeded. Even though many researchers improved TS to overcome some of its problems, the early convergence problem remains the main reason why TS is not popular in real mission planning situation. Simulated Annealing (SA) is another technique that people used for planning. Yamada [6] use SA for job-shop scheduling and Xhafa [7] use SA for satellite ground station scheduling. However, due to the limited amount of cooling time of SA, its efficiency and accuracy are unpredictable. Linear Programming (LP) also been widely used for space mission scheduling and optimization problems [8–10]. Although LP shows great potential in these articles, the linearity of relations and the single objective limited it in a real-life situation, where the objective function and constraints may not be linear.

Since John Holland popularized Genetic Algorithm (GA) in the early 1970s, research in GAs remained largely theoretical until first International Conference on Genetic Algorithms was held in Pittsburgh, Pennsylvania, 1985. After this conference, GA began to be widely used in many fields such as Computer-Automated Design, Industry Engineering, Car Design, Mission Scheduling, Fuzzy System Training and Machine Learning. For scheduling problems, Shi [11] used GA to solve job-shop scheduling problem in 1996, while in the same year, Shtub [12] and Dorn [13] all proposed using GA for general scheduling problems. In space mission scheduling problems, GA also plays an important role. Back in 2007, Chilan and Conway [14] used a binary GA for the outer loop planning and a real-valued GA for the inner loop. Gad and Abdelkhalik [15,16] developed hidden genes method and dynamic population size method to find flyby sequence and optimal trajectory. In 2012, Xhafa [17] presented a relevant formulation of satellite scheduling and various forms of optimization objectives, mainly using GA for satellite ground station scheduling.

Tangpattanakul [18] presents a biased random-key genetic algorithm, which been used for multi-user, Earth observation scheduling problem. All these articles show the excellent performance of using GA as a scheduling tool for a space mission. However, most of the scheduling problems are focused on trajectory, resources, and antenna allocation. Few of them are concerned with behavior planning within a group of the satellites. This paper is intended to use an improved Genetic Algorithm as a tool to help onboard computers create right behavior control sequences for every member of this swarm system.

The rest of this paper is organized as follows. In Section 2 we reformulate the OLFAR mission into a behavior scheduling optimization problem. Section 3 focuses on our new mutation strategy, Hybrid Dynamic Mutation, along with the performance evaluation to compare it with other three mutation strategies. Mission simulation results and analyses will be illustrated in Section 4. Finally, in Section 5, we include some conclusions and recommendations for future work.

2. Problem formulation

This section presents the details of how to formulate the part of real OLFAR mission into a behavior schedule optimization problem.

2.1. Blocked area

As mentioned in the introduction, to be able to detect low-frequency electromagnetic spectrum, we cannot observe from the Earth due to RFI. The moon provides a natural shield. There is a particular area of the moon that is blocked by itself from Earth interference, called “Blocked area.” Our mission will operate in this area.

From Fig. 1 we can see that when satellites move into Umbra area, which brings the full shadow, the interference from the Earth will be blocked by the Moon itself. This is the window we want our satellites to observe and capture raw data from space.

The distance from Earth to Moon is called Lunar distance. The average value is 384,402 km. Based on gravitation and classical physics, we can calculate the blocked angle from moon's coordinate.

When satellites travel along the Moon orbit, their observation window depends on orbit height H and blocked angle θ_{blk}. Considering the blocked angle is a constant, with the constant orbit height and average Moon radius R_M, we can get precise observation window angle θ_{obs} for each satellite through the following equation:

$$\theta_{obs} = \theta_{blk} - 2*\arccos\frac{R_M}{R_M + H} \quad (1)$$

2.2. Objective function

The objective function of optimization scheduling can be formed by mission requirements. The general idea of optimization in this mission is under same constraints and status of satellites, and the whole system can get maximum raw data in same operation time. To generate the best time sequence for each Daughter Satellite (DS), schedule tool needs to consider all the constraints from hardware, software, and reality situation. At this stage, we only concerned about DS's observation period and communication period with Mother Satellite (MS). Assume that all eight DSs can be used in observation mission. The purpose of scheduling process is to generate a timeline (Fig. 2), where each schedule entry refers to an individual activity, in this case, are their time points for observation start To_S, observation end To_E, communication with MS start Tc_S and communication end Tc_E.

For each circle in orbit, each DS needs these four variables to control their observation and communication payloads. Depend on total observation time required. The computer will decide how many cycles needed. All DSs will keep a linear array fleet. DS 1 will be the first one, and MS will stay in the middle and DS 8 will be the last satellite in