

## Onboard autonomous mission re-planning for multi-satellite system

Zheng, Zixuan; Guo, Jian; Gill, Eberhard

**DOI**

[10.1016/j.actaastro.2018.01.017](https://doi.org/10.1016/j.actaastro.2018.01.017)

**Publication date**

2018

**Document Version**

Accepted author manuscript

**Published in**

Acta Astronautica

**Citation (APA)**

Zheng, Z., Guo, J., & Gill, E. (2018). Onboard autonomous mission re-planning for multi-satellite system. *Acta Astronautica*, 145, 28-43. <https://doi.org/10.1016/j.actaastro.2018.01.017>

**Important note**

To cite this publication, please use the final published version (if applicable).  
Please check the document version above.

**Copyright**

Other than for strictly personal use, it is not permitted to download, forward or distribute the text or part of it, without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license such as Creative Commons.

**Takedown policy**

Please contact us and provide details if you believe this document breaches copyrights.  
We will remove access to the work immediately and investigate your claim.

# Onboard Autonomous Mission Re-Planning for Multi-Satellite System

Zixuan Zheng<sup>a</sup>, Jian Guo<sup>a,\*</sup>, Eberhard Gill<sup>a</sup>

<sup>a</sup>*Delft University of Technology*

---

## 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.

*Keywords:* Multi-satellite system, onboard autonomy, mission re-planning, multi-objective genetic algorithm

---

## 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

---

\*I am corresponding author

*Email addresses:* Z.Zheng@tudelft.nl (Zixuan Zheng), J.Guo@tudelft.nl (Jian Guo ), E.K.A.Gill@tudelft.nl (Eberhard Gill)

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 had been 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 to data recognition of observed images. Meanwhile, used the CASPER [3] planner 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 is 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; the ObjectAgent cluster management software help three TechSat-21 satellites to perform formation flying. Another mission, called Three Corner Sat (3CS) [8], 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 multi-satellite systems. The most recent mission, called Magnetospheric Multiscale (MMS) [10], 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][12][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. Since MSS provides for some applications 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.

### 2.1. Background

The objective of the OLFAR mission is to develop a space-based low frequency radio telescope that will explore the universe’s dark-age, map the interstellar medium, and discover planetary and solar bursts in other solar systems. This mission will be operated in Lunar orbit to avoid high Radio Frequency Interference (RFI) found at frequencies below 30 MHz, originating from the Earth, and shielded at the Moon’s far-side. This shielded area (in Fig.1) provides an Observation Window (OW) for the OLFAR to observe and collect raw data from deep space. The scientific instrument requirements of the OLFAR mission are provided in [34]. The mission requirements related to this paper are shown in Tab. 1

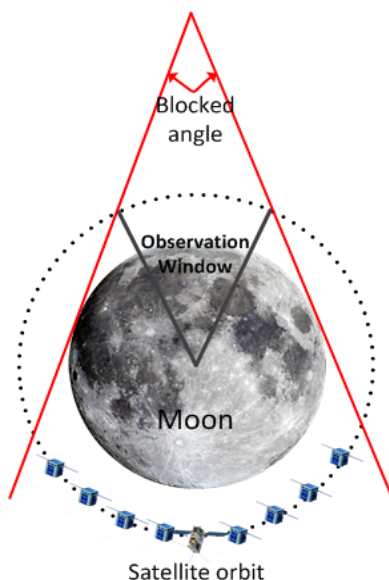


Figure 1: Shielded area

Table 1: OLFAR mission requirements

Operation satellite number	(1) 1 Mother Satellite; (2) Minimally 5, baseline 8 satellites and calibration and redundancy. Also for higher reliability and longer lifetime;
Orbit-related	(1) 300 km above Moon surface; (2) Absolute orbit knowledge: 30 m; (3) Relative orbit knowledge: 3 m;
Interferometry	(1) Linear formation flying; (2) Reconfigurable formation, baseline from 100 m - 100 km;
Payload	(1) Three orthogonal dipoles for each DS (2) Raw data downlink to MS as 6 Mbps through ISL; (3) Raw data observation rate through antenna can reach 48 Mbps; (4) Three channels receiver 0.1 MHz to 50 MHz;
Observation	(1) All observation need to be done within the observation window; (2) Onboard memory cannot be overwritten during observation;
Communication	(1) All satellites need to keep radio silence within the observation window; (2) MS can only communicate with one DS at same time;

Single radio antennas have limited directivity, in order to map and tomography the system requires large baselines between antennas to overcome the weak astronomical signals. The OLFAR mission is consists by one Mother Satellite (MS) and eight identical Daughter Satellites (DSs), forming a reconfigurable constellation in the moon orbit [35][36][37]. Considering the total cost as well as the increased robustness of using MS, the OLFAR instrument nodes choose to use small satellite platform. The primary functions of the MS are containing all the DSs during the launch, releasing them after reaching the orbit, and acting as a centralized control center in space to up- and down-link from the Earth and each DS. All eight DSs are identical and act as data collection nodes. The onboard memory unit capacity of each DS is 128 *Gbits*. The inter-satellite communication is a two-way RF link which enables a 6 *Mbps* data transmission rate.

All the DSs are docked on the MS during launch. They will be in a similar orbit as the MS after deployment. This fleet is designed to be reconfigurable in Lunar orbit. It can change the baseline to provide interferometric observations and perform polarimetry with radio signals received from antennas in each DS. The OLFAR mission requirements are shown in Fig. 1.

## 2.2. Emergency situations

During the mission operation, whether it is the initiative change on mission objective, or the extreme system failure due to the complex space environment, either case can lead to the invalid of the old mission plans. We assume these cases are the emergency situations. In this paper, we take these emergency situations into account. For OLFAR mission, observing from space to get raw data and send these data back to earth are two most important aspects need to be considered. Therefore, the emergency situations we concerned in this paper only related to observation and communication. Based on this, three possible scenarios are assumed as follows:

## 1. Scenario *A*

When taking into account the vicious space environment, there are plenty ways such as a comet, asteroid, or meteoroid to destroy a spacecraft. Therefore, the first scenario we need to consider is facing the total number downsizing of the fleet.

## 2. Scenario *B* & *C*

In this paper, observation and communication are two main parts we considered. Therefore, we assume that during the operations, observation equipment and communication equipment may facing partial-failure and become semi-functional operation due to the system error, circuit aging, or other unknown factors. Meanwhile, in these two scenarios, both malfunction number of satellite and equipment functional percentage can be switched between 0 – 8 and 0% – 100%, respectively. Scenario *B* represents observation system partial-failure, and *C* represents communication system partial-failure.

### 2.3. Mathematically model

#### 2.3.1. Notations and variables

##### a. Notations

*O*: satellite operation orbit. This orbit range can be changed due to other science objective.

*M*: Daughter Satellites group, in total there are eight at mission start.

*S*: DSs onboard storage capacity.  $S_m$  is for DS  $m$ ,  $m \in M$ . The unit of this capacity is converted to the observing time duration without downloads.

*T*: satellite cycle time.  $T(o)$  denotes the total operation time for whole fleet related to satellite orbit  $o \in O$ .

*J*: target set. For different target  $J$  represents different number of total cycles. It can also represents the total amount of observation time or other scientific objectives.

*OW*: observation time window set, which consists of two parts, observation start time  $os$  and end time  $oe$  for satellite  $m$  at cycle  $j$  in orbit  $o$ .

*CW*: communication time window set, also consists of two parts, communication start time  $os$  and end time  $oe$  for satellite  $m$  at cycle  $j$  in orbit  $o$ .

*E*: emergency situation set. It consists of four parts, emergency occurred time  $e \in T$ , emergency scenario  $s \in \{1, 2, 3\}$ , position matrix for damaged satellites  $n$ , and functional percentage matrix  $p$ .

*R*: data transmission rate set. It consists of two parts, data observation rate  $ov$  and data communication rate  $cv$  for satellite  $m$  at time  $t$ .

##### b. Variables

Table 2: Variables needed for re-planning

Property	Variable	Description
Observation time point	$\mathbf{X} = \{x^s(m), x^e(m)\}$	time point for observation behavior start and end for DS $m$
Communication time point	$\mathbf{Y} = \{y^s(m), y^e(m)\}$	time point for communication behavior start and end for DS $m$
Onboard storage capacity	$s_m(t)$	onboard storage capacity for DS $m$ at time point $t$
Observe and communication speed	$\mathbf{R} = \{ov_m(t), cv_m(t)\}$	$ov$ means the data observe speed, $cv$ means data communicate speed
Objective accomplished situation	$j(t)$	sum of the total data transmitted to the MS

### 2.3.2. Planning model

Based on previous assumptions, this mission planning problem can be formed as a multi-objective optimization problem with two objectives, one is to maximize the sum observation time, another is to minimum the sum of the communication gap.

Objective function:

$$OF1 : \left\{ \max \sum_{j \in J} \sum_{m=1}^M [(x_{jom}^e - x_{jom}^s) + (y_{jom}^e - y_{jom}^s)] \right\} \quad (1)$$

$$OF2 : \left\{ \min \sum_{j \in J} \sum_{m=1}^M (y_{jom+1}^s - y_{jom}^e) \right\} \quad (2)$$

Objective function (1) consists of two parts: summed rewards for total observation time and communication time for all eight DSs. Objective function (2) represents the idea of minimize the total communication gap between each DS and MS.

Behaviors order constraints (Eq.3, Eq.4): these constraints represent the right logical order for both observation and communication. During the mission, every observation behavior and communication behavior should follow the logical order, which is the end time should be later than the start time.

$$x_{jom}^s - x_{jom}^e \leq 0 \quad (3)$$

$$y_{jom}^s - y_{jom}^e \leq 0 \quad (4)$$

Onboard storage capacity (Eq.5): when DSs are operating data observation behavior, all the data will be stored in the OBC until they can download the raw data to MS, then the OBC can erase the hard disk to provide more room for next observation behavior. However, during the observation, the total observe time is limited by storage capacity at that time. Therefore, this constraint represents the total observation time should less than storage capacity.

$$(x_{jom}^e - x_{jom}^s) * r_{mt}^{Obs} \leq s_{mt} \quad (5)$$

Data transmission limitation (Eq.6): the raw data is captured through three orthogonal antennas on each daughter satellite. After leave the OW, DS can build the communication channel to transfer the data to MS. However, during this process, the total amount of data can be transmitted is limited by available data. It means that one DS cannot transmit more data than it contained.

$$(y_{jom}^e - y_{jom}^s) * r_{mt}^{Com} \leq S_m - s_{mt} \quad (6)$$



Communication order (Eq.7): this constraint comes from mission assumption. During the communication period, in a view to guarantee the quality of data transmission, only one DS can communicate with MS at a same time.

$$y_{jom}^e \leq y_{jom+1}^s \quad (7)$$

Boundaries (Equ.8): besides all these constraints, for each variable, there also need boundary to limit search area and rationalize the planning problem. Firstly, all the observation behavior which contains both observe start time  $x^s$  and end time  $x^e$  need to operate within the observation window. Similarly, communication behavior that starts time  $y^s$  and ends time  $y^e$  should all out of the observation window. All the onboard storage capacity  $s_m$  should less than original capacity  $S_m$ , but bigger than zero.

$$\forall x_{jom} \in OW, y_{jom} \in CW, 0 \leq s_m \leq S_m \quad (8)$$

### 3. Architecture of onboard re-planning system

The architecture of our re-planning system contains both ground part and space part as shown in Fig.2. The space part is composed of several sub-systems: a general planner, a decision-maker and a re-planner in the MS, a plan executor and a status monitor in every DS.

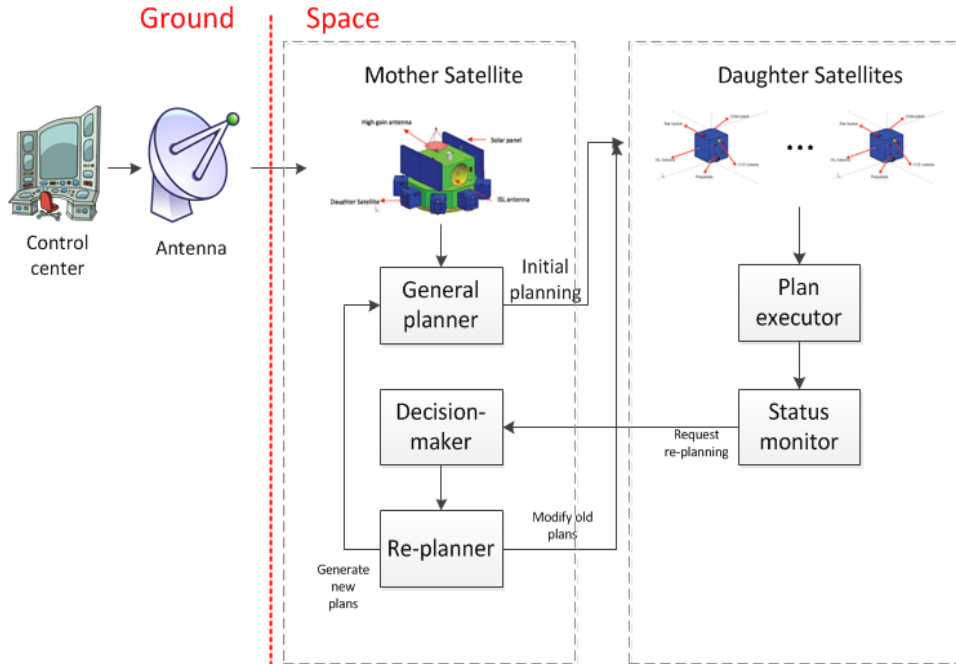


Figure 2: General architecture of mission planning & re-planning system

### 3.1. General planner

The general mission planner is the key component for solving mission onboard planning problems, as shown in Fig.3. This module has been designed for being able to receive the high-level mission commands from the control center and providing suitable procedures and control sequences for every satellite in the system. In this paper, command signals can only be processed and assigned from the MS. Thus, MS receives input and requires from the ground center, as the high-level mission (e.g. Which area to observe, Total observation time, etc.). Once it received the mission objective and updated available resources, the mission planning problem can be established. The planner proceeds according to the following steps:

#### a. Sampling the operation area

The objective of this step is to define the mission operation area. The OLFAR mission uses the Moon as a shield to avoid RFI, all the satellites will operate in lunar orbit. As mentioned in Sec 2.1, the blocked area (Fig.1) provides an Observation Window for OLFAR mission to observe low frequency radio from space. The blocked angle and observation angle can be calculated by following equations:

$$\alpha_{blk} = \arcsin \frac{r_E - r_M}{D} \quad (9)$$

$$\alpha_{obs} = \pi - \alpha_{blk} - 2 * \arccos \frac{r_M}{r_M + H_o}, o \in O \quad (10)$$

In Eq.9, the  $r_E$  and  $r_M$  represent radius of the Earth and the Moon.  $D$  stands for the Lunar Distance (LD), this parameter varies over the course of the orbit of the Moon, from 356,500 km at the perigee to 406,700 km at apogee. Orbit height  $H_o$  in Eq.10 represents the satellite operations height above the Moon surface, this parameter is related to actual orbit  $O$ . As the result of this step, the suitable sampling area is obtained.

#### b. Mission decomposition

In this step, the highly simplified mission objective is expanded and transformed into mathematical form, which planner can understand. Based on the information got from the previous step, the planner can distribute main mission objective into several sub-mission objectives. For each sub-mission, related input parameters can be generated by task requirements. Therefore, the high-level mission can be decomposed and formed into a multi-objective satisfaction problem.

#### c. Initial planning

After decomposed high-level mission in the previous step, for each DS, individual tasks need to be generated based on specific requirement. However, in this paper, for each DS, they shared the same objective which is to observe and collect raw data from space. As mentioned in Sec 2.2, observation and communication are two main tasks for every DS. The general planner performs initial mission planning at this step and send control sequences to each DS.

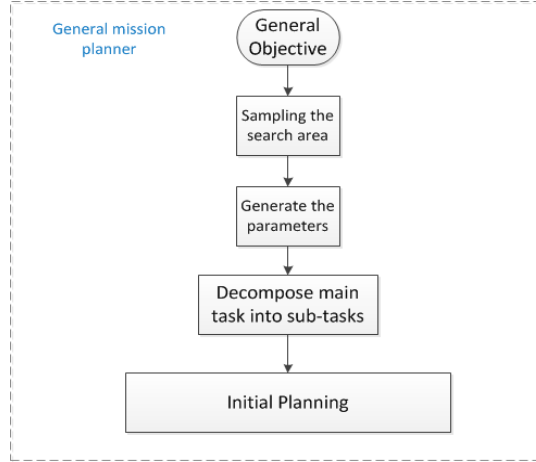


Figure 3: General mission planner

### 3.2. DS plan executor and status monitor

The structure of these two systems is illustrated in Fig.4. Based on the control sequences send from the MS, each DS can perform independently. However, a self-check procedure needs to be performed ahead to define the status of each agent. The status check is implemented during self-check, it carries basic information about its own health situation. Once the status shows the unhealthy signal, the system goes to decision-making part for further check. The executor can proceed under the condition of healthy status signals. The monitor has the ability to monitor plans execution performance during the mission operation. If any plan that generated by the mission planner is invalid, the monitor can abort current process and request for a re-do. Once all the plans have been executed, the monitor will check whether the mission objective has been satisfied or not. If necessary, it can ask the general mission planner to provide new plans for the new objectives.

### 3.3. Decision-maker

In our research, the decision-making process is activated by the unhealthy status signal sent from DS self-check module. Since the status signal only provides simple information about satellite health condition, to fully understand the current status for unhealthy satellite, an emergency communication channel between unhealthy DS and MS need to be established immediately. Through this channel, MS can do detailed examination on target DS to allocate error of this DS. Based on emergency situation assumptions made in Sec 2.2, the decision-maker has to react to these three situations. When MS can build the communication link with target DS, it will trigger the self-check. The structure of decision-maker is illustrated on the upper part of Fig.5.

### 3.4. Re-planner

Based on the decision made by decision-maker from the previous step, the re-planner received a signal about which situation it is facing, the first step is to evaluate whether this request is within the capacity range. Considering previous case assumptions, any cases

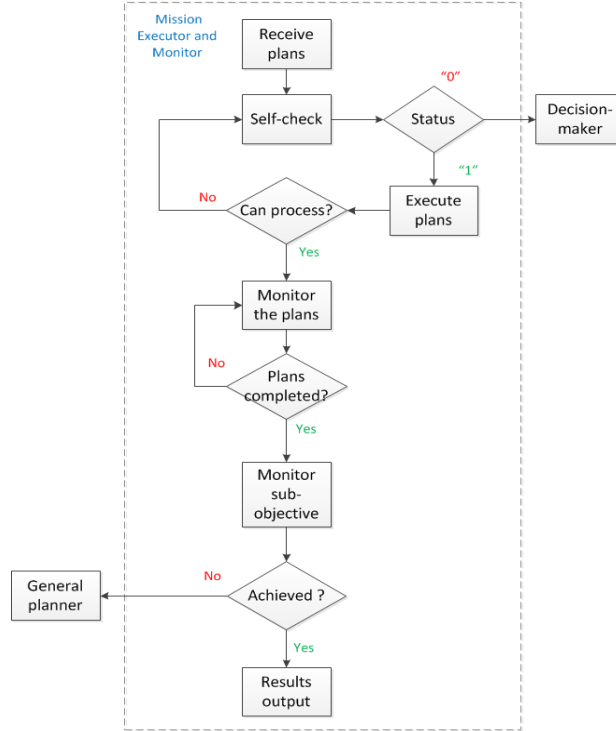


Figure 4: DS plan executor & monitor

beyond those three can not activate the re-planning procedure. Meanwhile, during mission operation, new mission objectives can also trigger the re-planner. Since the OLFAR mission is operated through eight DSs and one MS, different cases combine with unpredictable malfunction satellites number lead to very diverse re-planning situations. In some situations, by changing the sequence order of old plans and inserting or deleting some actions can get new valid plans, while in some other situations, based on new objectives or operation environments, re-planner need to create new plans without consulting the initial plans. Therefore, during this evaluation, the re-planner need to choose whether to modify old plans or generate new plans.

The difference between initial planning and re-planning is the total number of plans need to be handled and how to manage them. In initial planning, the system needs to generate whole mission plans for each satellite within the fleet according to the mission objective. However, in re-planning, first option is try to modify the old plans instead of creating new plans. In this mission, considering the unique observation constraint, all the satellites need to keep radio silence within the observation window. This causes the tradition re-plan methods unable to react. Based on this unique constraint, we proposed two re-planning methods with own principles, which corresponding to different user preferences. These two methods contains similar core algorithm along with re-planning techniques such as changing sequences order, modifying old plans, deleting old plans, and under most severe cases to recreate mission plans for rest of mission or even new missions. The procedures of the re-planner are shown in the lower part of Fig. 5. The details of these two methods will be

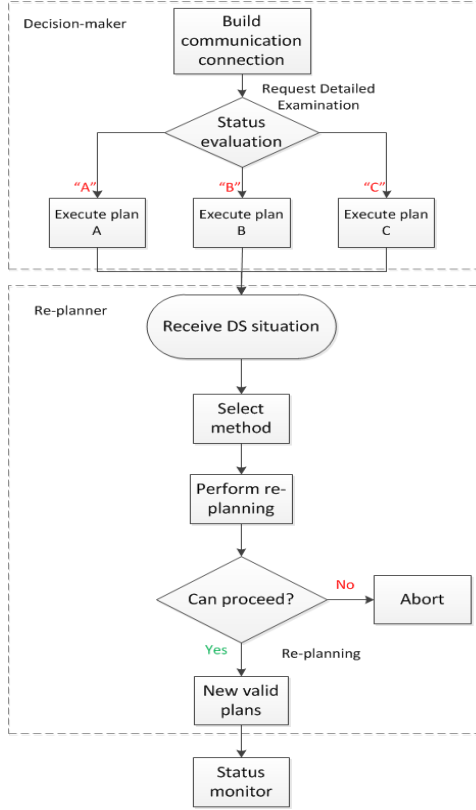


Figure 5: Decision-maker & Re-planner

explained in next section.

#### 4. Re-planning methods

This paper aims to solve the multi-satellite system mission planning & re-planning problem. Due to the unique requirements from OLFAR mission, along with the emergency situations which can happen during the operation, effective re-planning methods which can cope with common tasks and emergency tasks synthetically is necessary needed.

This section will propose two re-planning methods, which are called the Cyclically Re-planning Method (CRM) and the Near Real-time Re-planning Method (NRRM). Both methods consist of a core planning algorithm which is developed from Genetic Algorithm (GA). The differences between these two methods lay in the strategies of selecting the re-planning time point and choosing a number of unfinished tasks during the re-planning process. The efficiency and accuracy of these two methods are different when targeting different scenarios under different time. Each method has its own strengths and weaknesses, so the specific choice depends on the user's requirements.

##### 4.1. Core algorithm

As mentioned in Section 2, this onboard mission planning problem is a Non-deterministic Polynomial Complete (NP-Complete) problem. Based on OLFAR mission requirements and

some of our assumptions, we incorporate observation and communication together in one model (Sec 2.3), which is very complicated. The requirement of maintaining the onboard storage level as non-negative for every DS causes the nonlinear constraints in the model. Therefore, the combination of linear constraints and nonlinear constraints increase the difficulty for solving the problem. Some preliminary experiments on algorithm selection are done in our previous research. Due to the intractability and the large scale of the original problem, exact optimization algorithms such as linear programming was given up at first choose. Meanwhile, in real applications, the oversubscribed feature is common, constraints programming could not provide solutions for most oversubscribed situations. The nonlinear constraints in the model also cannot be handled by this type of algorithm. Therefore, algorithms such like mix-integer programming, greedy search, local search or dynamic programming are all not feasible. For our problem, the planning algorithm should be flexible and extensible to adapt every possible scenarios. The GA is a meta-heuristic algorithm inspired by the process of natural selection, which been proved have great potential on both sides. However, basic GA has drawbacks in early convergence and long computation time. To overcome these disadvantages, many researchers have made improvements on GA crossover and mutation operators.

In this paper, we employed the improved GA called Hybrid Dynamic Mutation GA (HDM-GA) [32] as the core algorithm for our problem. The HDM-GA consists of two mutation operators; these two operators work independently during mutation procedure, one is for the normal mode, another is for escape mode. For the normal GA, there exists a termination generation number  $T_g$ , which means that if the average value of fitness function has not changed over several generations, the algorithm will stop. Within HDM, there is another condition  $T_N$  which will trigger the switch between normal mode and escape mode ahead these termination criteria been reached. Before this trigger reaches the critical point, the algorithm will use normal mutation rate  $r_{normal}$ , once it crosses the line, the algorithm will use escape mutation rate  $r_{escape}$  try to jump out of the local minimum. To expand the search area, the mutation rate in escape mode is larger than normal mode.

## 4.2. *Cyclically re-planning method*

### 4.2.1. *Principle*

As the name implies, this cyclically re-planning method (CRM) is executed once every cycle to perform mission planning & re-planning for every satellite within the system. Instead of planning once for every satellites behavior at the beginning of the mission, the CRM chooses to repeat the planning procedure at every cycle due to latest satellite status. There are several advantages for using this method: Firstly, when dealing with a real-world mission, the entire operation required time can be a very extended period. During each cycle, for each DS in the fleet, it requires at least four variables to control observation and communication behaviors, which are the start time point and end time point for each behavior. With the long operation time, the total variables for planning algorithm to calculate will be a huge array. Using CRM to perform planning at each cycle can reduce the variable number and make it become a constant due to fixed satellite number and behaviors for each planning procedure. Secondly, considering the large scale of variables, the dimension of constraint matrix for

entire planning problem will be much greater than single cycle planning problem. Therefore, employing the CRM can reduce the complexity of solving the optimization problem at each cycle. Thirdly, when facing different re-planning scenarios, the CRM will follow certain procedures to build the communication link between MS and each DS at a fixed point in time. It can eliminate the problem that some initial time sequences in MS is occupied by building the emergency link with damaged DSs. Finally, once the variable array and constraint matrix have been formulated, under the usual scenario, the former parameters can be used directly with the only boundary need to be changed, when planner facing emergency scenarios, the model can still be modified based on pervious one. The re-planning computation time will decrease as the number of iterations increases. All these advantages make the CRM as a fast calculation and easy operation re-planning method.

#### 4.2.2. Steps

During the planning & re-planning produce, steps of using this method are as follow:

- (1) At the end of each cycle, MS need to activate re-planning procedure by evaluating the status of each DS through the stored beacon signals. During the operation, these beacon signals are sent every certain period which is designed by the user. However, due to the OW constraints, all the DSs need to keep radio silence during that time. Therefore, when MS receives an unhealthy beacon signal from the DS which just comes out of the OW, this signal can only indicate that something went wrong during this observation period, it cannot provides MS the exact re-planning time. In this case, MS has different strategies to react to different emergency scenarios.
- (2) Once the emergency scenario has been determined from the last step, MS has to evaluate how many DSs are still functional. Meanwhile, several important parameters need to be updated according to re-planning time, such as onboard storage capacity  $s_{mt}$  for DS  $m$  at time  $t$ , mission objective completed information  $j_t$  at time  $t$ , and data observe rate and transmission rate  $r_{mt}$ .
- (3) Based on the information about basic parameters, the new array of variables and new constraint matrix need to be formed according to problem model. Then, based on different scenarios, the algorithm will follow certain procedure to generate behavior sequences for next cycle.

The pseudo-code of this method is shown as follow:

---

## Pseudo code 1 Cyclically re-planning method

---

**Input:** daughter satellite set  $M$ , target set  $J$ , cyclically operation period  $T$ , observation window  $OW$ , communication window  $CW$ , emergency situation  $E$ , data transmission rate  $R$

**Output:** Behaviors plans  $X$

```

1: function  $X \leftarrow CRM(M, J, T, OW, CW, E, R)$ 
2:   counter=1
3:   while counter  $\leq J$  do
4:     for  $i = 1 : M$  do
5:       if  $beaconsignal_i = 1$  then
6:          $E_i \leftarrow 0$ 
7:       else
8:          $E_i \leftarrow \{e_m, s, n_m, p_m\}$ 
9:       switch  $s$  do
10:        case  $s = 0$   $\triangleright$  Regular situation
11:           $x \leftarrow function(HDMGA\{M, J, T, OW, CW, counter, E, R\})$ 
12:        case  $s = 1$   $\triangleright$  Scenario A
13:           $[Num, 1] = size[find(E \neq 0)]$ 
14:           $M \leftarrow M - Num$ 
15:           $x \leftarrow function(HDMGA\{M, J, T, OW, CW, counter, E, R\})$ 
16:        case  $s = 2$   $\triangleright$  Scenario B
17:           $R = \{[ov_m t * p_m, cv_{mt}]\}$ 
18:           $x \leftarrow function(HDMGA\{M, J, T, OW, CW, counter, E, R\})$ 
19:        case  $s = 3$   $\triangleright$  Scenario C
20:           $R = \{[ov_m t, cv_{mt} * p_m]\}$ 
21:           $x \leftarrow function(HDMGA\{M, J, T, OW, CW, counter, E, R\})$ 
22:         $s_{counter} \leftarrow S - f(X)$ 
23:         $x_{counter} = x$ 
24:        counter = counter + 1
25:    $X = [x_1; \dots x_J]$ 
return  $X$ 

```

---

### 4.3. Near real-time re-planning method

#### 4.3.1. Principle

Unlike the CRM, the near real-time re-planning method (NRRM) follows a different strategy for mission re-planning procedure. In the previous method, in order to reduce the total number of variables and the complexity of constraint matrix, we choose to plan the satellite behaviors at beginning of each cycle. The NRRM on the other hand chooses to use the strategy that does entire initial planning at the beginning of the mission and reacting to emergency scenarios by near real-time protocol. The strengths of this method are as follow: firstly, even though the NRRM spend more computation time on planning algorithm than the CRM due to the large scale of variables and bigger dimension of constraint matrix. However, for real-world application, when the MS received the mission objective from the control center, there is not data for MS to download from DSs before the first observation in the OW. The initial planning from NRRM has no impact on mission operation before MS enter the OW for the first time. Secondly, using NRRM can react to the emergency scenario much quicker than the CRM. Although based on the scientific requirement that during the OW all the satellites need to keep radio silence, the NRRM can base on the exact damaged satellite position and situation to decide when to activate the re-planning procedure. Therefore, this method is called near the real-time method, which means for some scenarios, MS can react immediately, for other scenarios, MS needs to figure out when to do re-planning without jeopardizing the observation behaviors. Thirdly, since the whole



mission behavior sequences for every DS has been planned during the initial planning, under any emergency scenario, the NRRM can react based on initial plans. During the re-planning, some re-plan techniques such as deleting, inserting, and modifying can be employed by the NRRM, which can accelerate the re-planning computation time.

#### 4.3.2. Steps

The procedures of using the NRRM for solving the mission planning & re-planning problems are as follow:

- (1) Based on the mission objective, in the beginning, the NRRM need to do initial planning for the first mission operation period. This includes the observation and communication behaviors for eight DSs and one MS.
- (2) After the initial planning, the NRRM keeps low power operation, which only monitors the health condition for each DS. Once the emergency occurred, the NRRM need to react differently based on the specific situation, determining the relevant parameters which including the start time point for the re-planning procedure, under re-plan variables number, current status for each DS, and the mission objective achieved situation.
- (3) Considering the different scenario, the NRRM will employ different re-planning techniques to reduce the unnecessary time consumption on healthy DSs. Meanwhile, the core algorithm will be based on the trigger time of re-planning and other parameters to re-plan all the behaviors for the rest of the mission.

The corresponding pseudo-code is shown in Pseudo-code.2.

## 5. Simulations and analysis

To analyze the performance of our re-planning methods, multiple simulation cases have been designed based on the emergency scenarios announced in Sec. 2. Each case represents a unique emergency scenario. For each case, we apply two re-planning methods (CRM & NRRM) mentioned in Sec.4 to perform mission re-planning procedure separately. Furthermore, we analyze the performance based on several criteria such as the computation time, the completion of the mission objective, and the efficiency value of each method.

### 5.1. Simulation assumptions

Basic parameters and the detailed information about each simulation case will be explained in this part.

#### 5.1.1. Simulation parameters

The OLFAR mission will operate around lunar orbit to prevent the RFI from the Earth. Based on the mission scientific requirements, some basic parameters about the simulation environment are illustrated based on the task background (Sec.2.1). (1) To simplify the simulation environment, the orbit which the OLFAR mission will operate is consider as a

---

## Pseudo code 2 Near real-time re-planning method

---

**Input:** daughter satellite set  $M$ , target set  $J$ , cyclically operation period  $T$ , observation window  $OW$ , communication window  $CW$ , emergency situation  $E$ , data transmission rate  $R$

**Output:** Behaviors plans  $X$

```

1: function  $X \leftarrow NRRM(M, J, T, OW, CW, E, R)$ 
2:    $E \leftarrow 0$ 
3:    $X_{initial} \leftarrow function(HDMGA\{M, J, T, OW, CW, E, R\})$  ▷ Initial planning
4:   for  $i = 1 : T * J$  do
5:     if  $E_t \neq 0$  then
6:        $E \leftarrow \{e_m, s, n_m, p_m\}$ 
7:        $[a, b] = size(n_m)$ 
8:       if  $Pos_{MS} < n_m(a)$  then ▷ Error Detection
9:          $r_t = Outtime(DS_a)$ 
10:      else  $Pos_{MS} > n_m(a)$ 
11:         $r_t = Outtime(MS)$ 
12:       $\{M, J, T, S, R\} \leftarrow update\{r_t, e_m, s, n_m, p_m\}$ 
13:      switch  $s$  do
14:        case  $s = 0$  ▷ Regular situation
15:           $X = X_{initial}$ 
16:        case  $s = 1$  ▷ Scenario A
17:           $X_{initial} \leftarrow deleting\{e_m, n_m\}$ 
18:           $X \leftarrow function(HDMGA\{X_{initial}, M - a, J, T, OW, CW, E, R, r_t\})$ 
19:        case  $s = 2$  ▷ Scenario B
20:           $X_{initial} \leftarrow modifying\{e_m, n_m, p_m\}$ 
21:           $X_{initial} \leftarrow inserting\{r_t, e_m, n_m, p_m\}$ 
22:           $X \leftarrow function(HDMGA\{X_{initial}, M, J, T, OW, CW, E, R_{new}, r_t\})$ 
23:        case  $s = 3$  ▷ Scenario C
24:           $X_{initial} \leftarrow modifying\{e_m, n_m, p_m\}$ 
25:           $X_{initial} \leftarrow inserting\{r_t, e_m, n_m, p_m\}$ 
26:           $X \leftarrow function(HDMGA\{X_{initial}, M, J, T, OW, CW, E, R_{new}, r_t\})$ 
return  $X$ 

```

---

circular orbit and the orbit height is 300 km above the moon surface ( $H = 300$  km); (2) The total DS number  $M$  is set as shown in Tab.1 to be eight; (3) Based on the science requests and the separate design for the MS, all the DSs are emitted one by one from the MS with predetermined time intervals. All the satellites form a linear array configuration, which in our cases the position of the MS is set as the center of the fleet,  $MS_{pos} = 5$ ; (4) The distance between each satellite can be shrink or expand due to different mission objectives, in our cases, the distance is  $D = 100$  km; (5) The initial onboard storage capacity for each DS is the same, which is  $\{S_m = 128$  Gbits,  $m \in M\}$ . At this stage, the storage capacity of the MS is beyond our research. We assume that the downlink speed for MS to Earth is suffice and the storage capacity of the MS is never full; (6) The original data transmission speed of the observe rate and the download rate are set as  $ov = 48$  Mbps and  $cv = 6$  Mbps respectively. Furthermore, since the purpose of this simulation process is intended to test whether the re-planning methods can qualify when facing various emergency situations, the mission objective should be a relatively smaller one which can help to narrow down the total simulation time. Therefore, we set the total operation periods as  $J = 4$  to be our simulation objective for each case.

### 5.1.2. Study cases

These simulation cases come from the three different scenarios announced before in Sec.2.2. For each case, we need to provide emergency situation set  $E : \{e_m, s, n_m, p_m\}$

for the re-planner to simulate the real emergency. In order to test the performance of each re-planner, the simulation environment for the same case of each re-planner should keep the same. Meanwhile, to verify the diversity of the real situation each case contains different information.

- Case A

This case aims to simulate the scenario A, which represents the completely damaged of several DSs during the mission operation. To simulate this situation, we assume that the emergency occurred time to be the time point that the MS is in the OW. Based on the fixed orbit height, the cycle operation time can be calculated by Eq.9 and Eq. 10 ( $T = 8243s$ ). Combine with the MS position in the fleet; we set the emergency time  $e_m$  to be  $12000s$  since the mission began. Meanwhile, to increase the diversity of this case, we assume that there are three DSs are damaged, two of them are ahead than the MS in the fleet, and one is behind the MS. The emergency situation set can be written as  $E : \{e_m = 12000s, s = 1, n_m = [1, 3, 5], p_M = []\}$ .

- Case B & C

These two cases are to simulate the scenario B and C, which represents the partially damaged on observation and communication equipment of several DSs during the operation. Following the same idea from case A, the emergency time, in this case, is set as same as the previous case. The total number of particle-failure DSs are four with two in front of the MS and two behind the MS. The functional percentage of each DS is different. Our assumptions on case B about the emergency set is  $E : \{e_m = 12000s, s = 2, n_m = [2, 4, 6, 8], p_m = [20\%, 40\%, 60\%, 80\%]\}$ , and the assumptions on case C is  $E : \{e_m = 12000s, s = 3, n_m = [1, 3, 5, 7], p_m = [20\%, 40\%, 60\%, 80\%]\}$ .

## 5.2. CRM simulation results

Based on the simulation assumptions, we first employ the CRM to solve all the cases.

- Results of case A

The simulation results of using the CRM to solve the case A are shown in Fig.6. In this figure, it contains two sub-figures represent behaviors sequences for one fatal-failure DS and one unharmed DS as example. The blue line with blocks on the top represents initial plans made by the MS based on the mission objective, each block stand for a behavior operation period. The black line represents the mission cyclically re-planning procedure under normal circumstances. The red line with blocks stands for new plans which been made by the CRM, each block stands for a behavior new operation period. The bottom blue line is the re-planning procedure line when the emergency has been detected. The gray dash line separates four cycles for the whole operation time. The X-axis stands for the onboard time since the mission start at 0. The Y-axis represents the plan number with the range from 0 to 16, which helps to distinguish each behavior.

To explain the results in this figure, several aspects need to be mentioned. (1) The black block line illustrates the strategy of the CRM, which is performing the re-planning at the beginning of each cycle. All the sub-figures contain this line to show that every

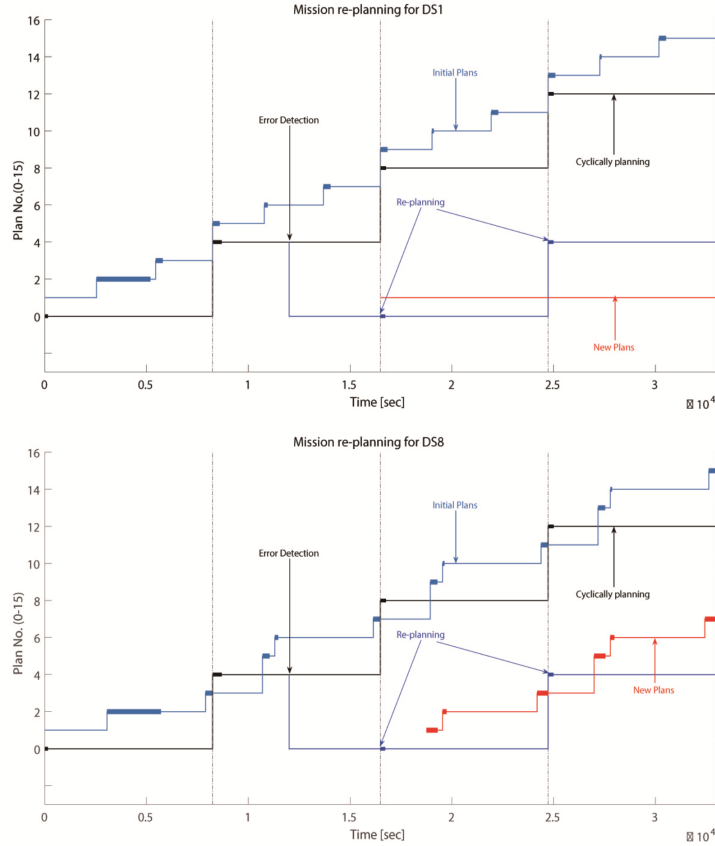


Figure 6: The CRM simulation results for Case A

DS needs CRM to provide plans during each cycle. (2) Based on case assumptions, the emergency occurred at 12000 s since the mission start. This time point has been marked on the black line. However, due to the concept of the CRM, the re-planning procedure after this emergency is triggered at the beginning of next cycle, represents the blue line at the bottom. (3) This case assumes that there are three DSs are damaged, the set of the damaged satellite is  $n_m = [1, 3, 5]$ . Since these three satellites share the same condition, we only present DS1 as a sample in Fig.6. This figure shows that after the emergence occurred, all the plans for DS1 have been deleted, which is same for DS3 and DS5. (4) Since the operable satellite number is decreased due to the damage, therefore, for each operable DS (DS2, DS4, DS6, DS7 and DS8), it has longer communication time with the MS. We take DS8 as a sample to represent rest operable DS in the figure. The communication time increasing also brings the extra storage capacity for a longer observation time. The new plans in DS8 figure show that both communication behaviors and observation behaviors are increased.

- Results of case B

Following the assumption about the case B, the simulation results are shown in Fig.7. The meaning of each line is the same as case A, along with the explanation of X

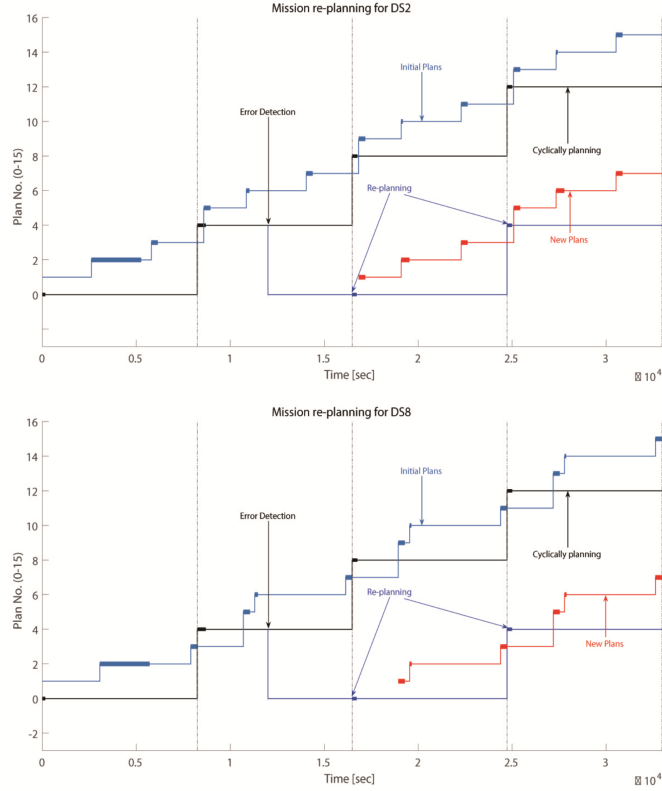


Figure 7: The CRM simulation results for Case B

& Y axis. The observation equipment partially damaged influence the observation duration, other healthy DSs are not influenced. Therefore, this figure contains the re-planning information about two partial-failure satellites (DS2 and DS8) as samples. The following aspects explained simulation results shown in this figure. Since the observation equipment has been harmed and can only operate partially, which has a direct impact on the data observe rate. With the same amount of onboard storage capacity, lower observe rate leads to longer observation time. In this figure, the block in the middle of each cycle represents the observation behavior. Comparing the red new plans line with the blue initial plans line in each sub-figures, the re-planned observation behavior block is longer than the initial block. For DS2, the percentage is 20% means that the observe rate can only work 20% than usual. The observation blocks of the DS2 are the longest among all four damaged DSs, and corresponding blocks for the DS8 is the shortest due to its smallest damage.

- Results of case C

In this case, the damage on four DSs cannot affect the rest DSs, so we only focus on the damaged four DSs, the results are shown in Fig.8, which contains two DSs (DS1 and DS7) as samples. Based on the mission requirement, the communication window for the MS has to equally distributed to every DS. With the same amount of

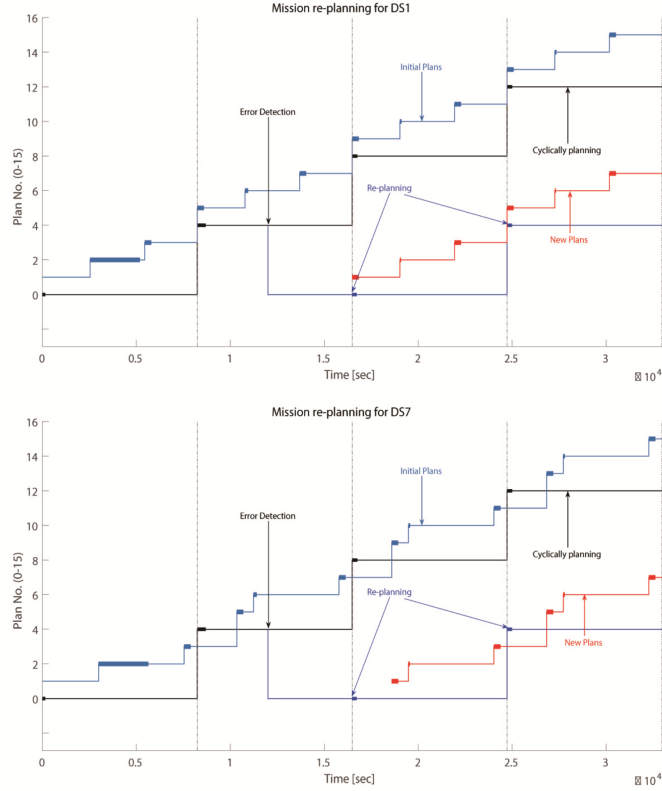


Figure 8: The CRM simulation results for Case C

DSs, the communication time for the damaged DS cannot change. The result shown in each sub-figure illustrates that communication behavior blocks in the new plans line are the same length with blocks in the initial plans line. Due to the damage on the communication rate, with the same communication time, the damaged DS can transmit less data than the normal situation, which leads to less storage recovery for next observation. Comparing new plans with initial plans, observation blocks in each DS are much shorter than initial blocks, which indicate the less observation time due to the communication damage.

To summarize this method, it is verified that the concept of this cyclically re-planning method works for every scenario we announced before and can provide valid plans for further mission operation. Meanwhile, with constant or even fewer variables for different cases, the CRM can re-plan the mission cyclically with a short computation time.

### 5.3. NRRM simulation results

In this part, we employ the NRRM to solve all the simulation cases. To compare the performance of the CRM and NRRM, we use same case assumptions to simulate. Every figure shown in this part share the same basic setting including the coordinate system and explanation of some lines. The different information within the figure will be indicated accordingly.

- Results of case A

The NRRM has different re-planning strategy compare with the CRM strategy. The simulation result for case A is shown in Fig.9. In each sub-figures, the NRRM initial planning procedure is represented by black line at the beginning, and the dashed line stands for the system standby. Once the emergency is detected, the NRRM need to make the decision about the activity time point of re-planning procedure, which is the pink line in each sub-figures. The time spends on decision-making process is related to the damaged satellite's position within the fleet. After determined the re-planning time, the blue block stands for one time re-planning procedure and the dashed line after that represents the system standby as well. The rest of the line shares the same understanding with previous figures. To fully explain this figure, we list following aspects. (1) Due to the case assumption, DS1, DS3, and DS5 are eliminated from the fleet after the emergency, therefore, in this figure, we only present ree-planning results about three healthy DSs as samples; (2) In first sub-figure shows the result about DS2. The third behavior of initial plans in the second cycle is a conflict with re-planning procedure period. Based on the NRRM concept, all the behaviors after the emergency should be suspended and reevaluated. At the time the NRRM finished the re-planning, the time window for this behavior is passed. However, after eliminated damaged satellites, DS2 is re-ranked to the first position within the fleet. Therefore, after the re-planning, this behavior has been replaced and recalculated according to the number of operable DS. (3) For the DS4, this same behavior operation period in the initial plan is behind the re-planning period, which supposes to be acceptable. However, the total number of the fleet is decreased and the communication time for each operable DS is correspondingly increased. The new plan of this behavior has to wait for the DS2 to finish its behavior first, then the DS4 can start this behavior. In this sub-figure, the red block represents this behavior is later than the blue block in initial plans. (4) For DS6, Ds7, and DS8, since the fleet is smaller than before, all the behaviors shown in initial plans have been move ahead accordingly, here only presents DS6 to show the results. (5) For all operable DSs, due to the increasing of the communication time, the observation time for each cycle after the emergency is also increased. This is as same as what happened when using the CRM.

- Results of case B

The simulation result is shown in Fig.10. Considering the influence made by the NRRM during the re-planning procedure, we present four DSs instead of two damaged DSs samples as shown in the Fig.7. This figure shows the following information.

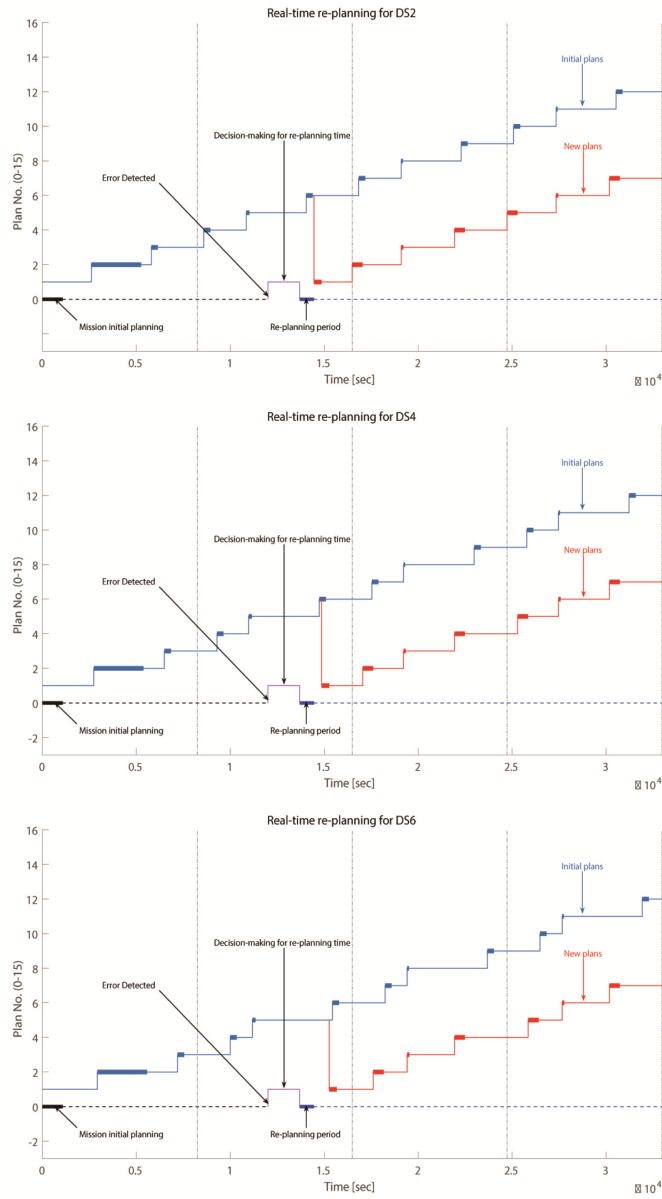
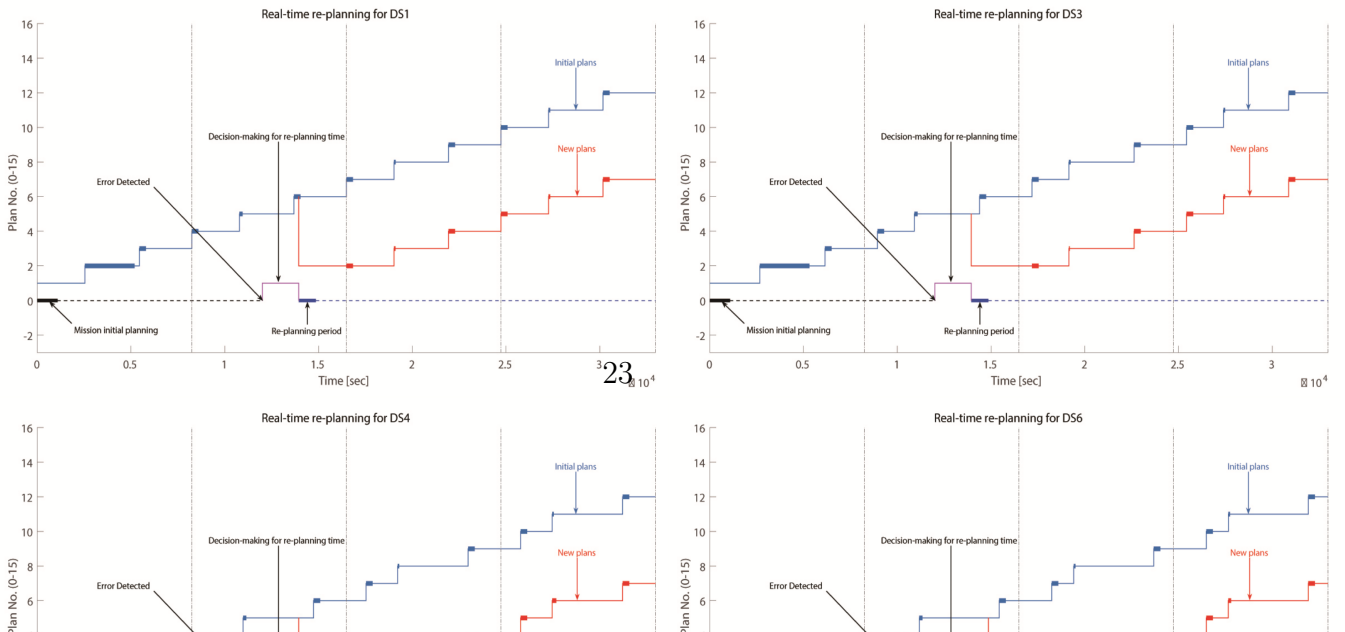


Figure 9: The NRRM simulation results for Case A





(1) Although the DS1 and DS3 are unharmed in this case, we can see from first two sub-figures that the re-planning procedure occupied the MS when two communication behaviors should happen. These communication behaviors need the DS and the MS to perform at the same time. Therefore, for DS1, the communication behavior cannot be fully finished due to the occupation of the MS. For DS3, the communication behavior which is happened after the re-planning procedure been activated need to be deleted. (2) Meanwhile, the communication time for the DS2 is also canceled for the same reason. For DS4, the initial plan about the communication behavior in this cycle is delayed and decreased due to the re-planning finish time point. The DS2 and the DS4 sub-figures show the corresponding actions in red line. (3) The reason for increasing the observation time for each damaged DS is as same as using the CRM. In this figure, new plans for DS2 and DS4 show the increase length of the observation block in new plan line, which for DS6 and DS8 is the same.

- Results of case C

In this case, for the same reason as in the case B, we present two samples in Fig.11. From this figure, several conclusions can be addressed. (1) Considering the same reason as mentioned in case B, due to the occupation of the re-planning procedure, the communication behavior in the second cycle of DS1, DS2, and DS3 need to be deleted or decreased. The new plans line in upper figure illustrates that the communication behavior block is stopped because of this reason. For DS2 and DS3, the results are similar and will not present here; (2) The observation time of partial-failure DS is shorter than initial plan because of the partial-failure to communication equipment. The reason cause this pheromone is the same as which been explained in the case C using the CRM. This is shown in lower figures about DS7, which is the same for DS3 and DS5.

The simulation results have verified that this method can manage the emergency scenario announced in Sec 2. For initial planning, the NRRM takes more time than the CRM. This is because the NRRM has to consider the whole mission period instead of one cycle, leading to more variables and bigger dimension of constraint matrix. Meanwhile, when an emergency occurred, the NRRM has to re-plan the rest of the mission at one time, which brings the uncertainty on the variable number and constraint matrix. This uncertainty result in more complex programming process and longer computation time. However, the NRRM has the unique ability that it can react to the emergency on near real-time. Besides, the NRRM can use the initial plans as the baseline to implement some re-plan techniques, which can help re-planner to eliminate some unnecessary work.

#### 5.4. Performance comparison

Based on the simulated time plans, we calculate the amount of data all DSs have observed, the amount of data MS has received, and the computation time for initial planning and re-planning. The performance comparison between the CRM and NRRM in terms of above three aspects will be shown in Fig.12,13,14, respectively.

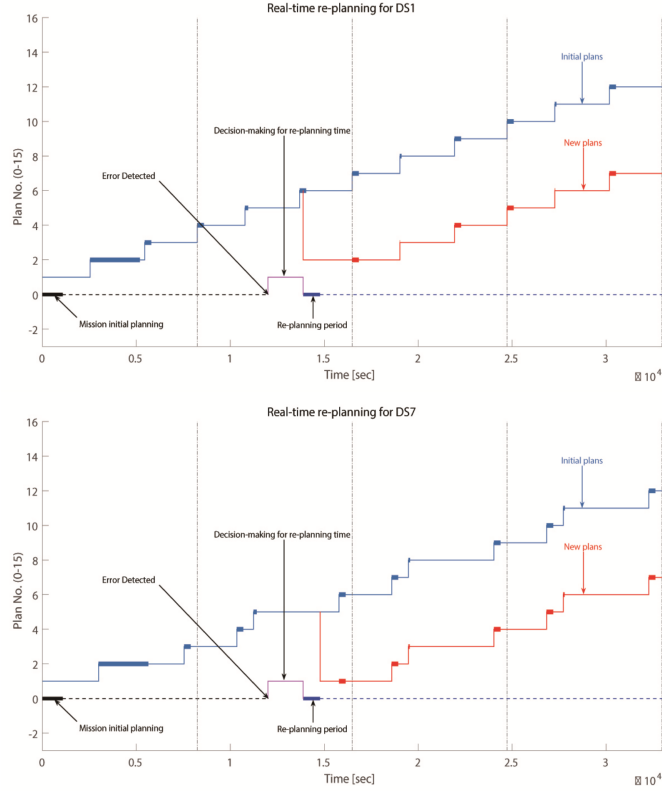


Figure 11: The NRRM simulation results for Case C

The histogram Fig.12 shows four categories, and the first one is the control group which represents the normal situation that no emergency has occurred during the mission operation period. The others are the proposed simulation cases. In the normal situation, the NRRM can obtain 0.53% more data than the CRM (1116 *Gbits*). Similarly, the percentage differences on case B & C are 0.72% and 0.74%, respectively. These are all because the CRM has to perform re-planning for each cycle, which will occupy the communication time between the MS and DSs. Compared with other cases, the percentage difference of case A (3.15%) is much higher. Because the NRRM can react to the emergency within this operation cycle, and re-allocate more communication time for operable DSs.

The Fig.13 illustrates the total data MS has received during the mission operation period. Due to the difference of the re-planning strategy on two methods, the NRRM can help the MS receive 3.91% more data than the CRM. The reason why for the normal case the NRRM can transmit more data than the CRM is as the same as which influenced the data observation. Each re-planning procedure in the CRM cost some communication time, which has an impact on storage capacity before the next observation. This effects all the simulation cases, each case shows that the NRRM can make the MS receive more data than the CRM. From three simulation cases, we can see that the difference of case B is 1.25%, which is lower than normal case. It is because the NRRM need some time from the MS to re-plan the mission, which will occupy some communication time. For case A, the difference on two

method shown in the observation has the same impact here, causing the difference percentage reaches 14.55%. For case C, the amount of data received drop significantly because of the damage on communication equipment. The increase of the difference percentage (16.58%) is caused by the NRRM re-allocates the communication time from unhealthy DSs to healthy DSs.

From Fig.14 we can directly see the difference between two methods on total time consumption for computation . For normal case, the NRRM has shorter computation time due to the one-time planning policy, which is 26.63% shorter than using the CRM. The CRM has to perform the re-planning procedure every cycle no matter there is emergency occurred or not. The NRRM only need to perform the initial planning at the beginning of the mission. However, besides the normal case, all other emergency cases show that the average computation time spends on the NRRM is longer than the CRM. The reason causes this is because when the NRRM is performing the re-planning procedure, it has larger variables and high dimension constraint matrix than the CRM. Although the CRM has to perform re-planning many times, for each time the number of variables and constraints are relatively small, which leads to a shorter computation time. From another perspective, the percentage differences show that for case B & C, the differences are in the same level (17.61% and 16.45%). For case A this difference is larger (21.25%) because the NRRM has less variables and constraints due to the three DSs loss.

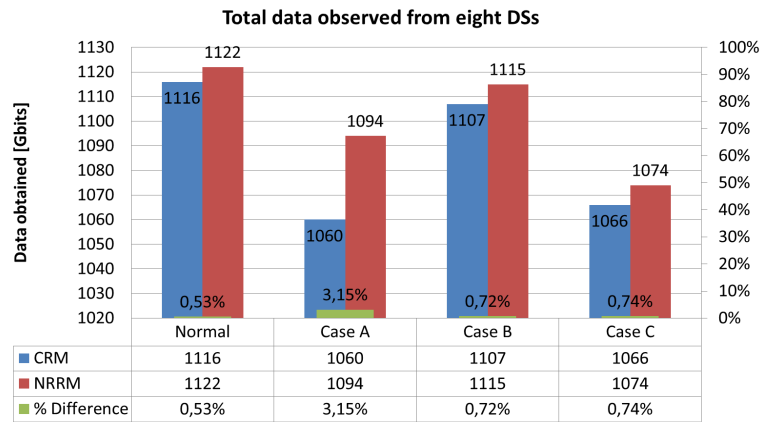


Figure 12: Data observed information in three cases

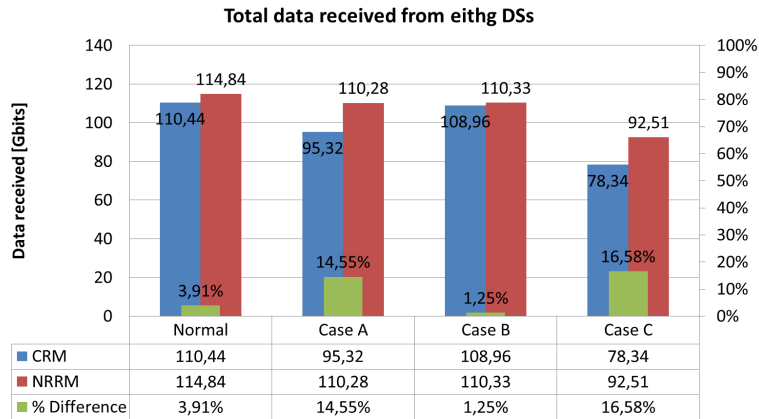


Figure 13: Data received information in three cases

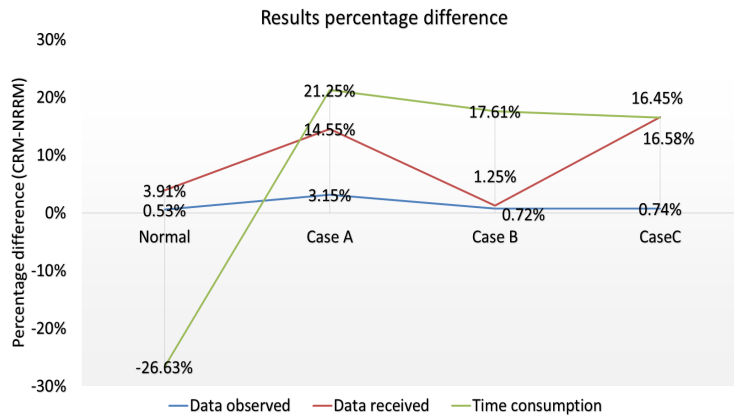


Figure 15: Percentage differences from three aspects

From the Fig. 15, we can draw some conclusions from performance differences. (1) Both

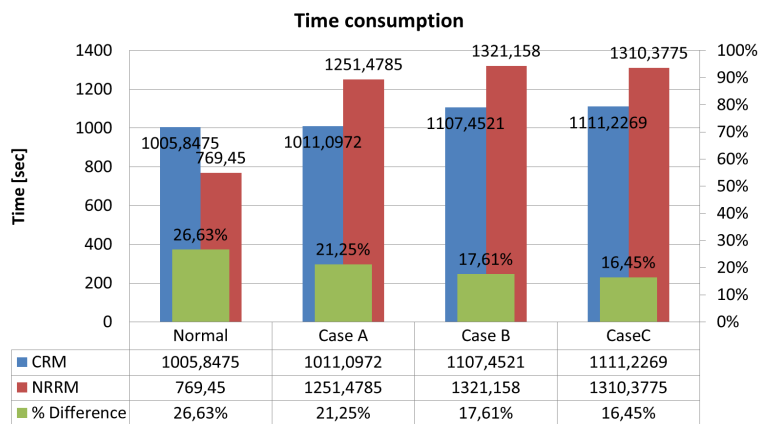


Figure 14: Time consumption information in three cases

on the amount of data observed and the amount of data MS received, the red line and blue line reveal that the NRRM can observe and sent more data than the CRM. For each specific emergency case, the difference on two methods follow the same understanding. Some big differences are caused by unique situations from the simulation cases, such as case A and C in red line. (2) For all the emergency cases, the computation time consumption differences reveal that the NRRM spend at least 16.45% time longer than the CRM. For normal cases, the NRRM costs 26.63% less time than the CRM. Therefore, for emergency situation, the CRM can provide re-planning sequences faster than the NRRM, and for normal case, the NRRM is much faster than the CRM for re-planning.

To simplify summarized the performance comparison, the NRRM shows better performance on data observation and transmission, and the CRM has better performance on re-planning procedure computation time consumption for emergency cases.

## 6. Conclusion

In this paper, we first proposed three scenarios based on the possible emergency situations during the mission operation period. Then we proposed a model for the multi-satellite system onboard mission planning & re-planning problem. We introduced the architecture of our system to realize mission decomposition, executing & monitoring, decision-making and re-planning. For solving the mission planning & re-planning problem, we proposed the CRM and the NRRM, explained the core algorithm, method strategy and re-plan techniques. The simulation results illustrated that both approaches could solve the emergency scenario successfully. The NRRM has better performance on data collecting compare to the CRM in same operation time, while the CRM consumes less computation time regarding to emergency situations. For future work, we will conduct further experiments in more realistic situations such as the damage on the MS. The mission planning & re-planning system will be extended to a distributed form where all the operable DSs will cooperate to virtually replace the MS for similar problems.

## References

- [1] M. D. Rayman, D. H. Lehman, Deep space one: Nasa's first deep-space technology validation mission, *Acta Astronautica* 41 (4) (1997) 289–299.
- [2] N. Muscettola, C. Fry, K. Rajan, B. Smith, S. Chien, G. Rabideau, D. Yan, On-board planning for new millennium deep space one autonomy, in: *Proceedings of the IEEE Aerospace Conference, 1997.*, Vol. 1, IEEE, 1997, pp. 303–318.
- [3] S. Chien, R. Sherwood, D. Tran, B. Cichy, G. Rabideau, R. Castano, A. Davies, R. Lee, D. Mandl, S. Frye, et al., The eo-1 autonomous science agent, in: *Proceedings of the Third International Joint Conference on Autonomous Agents and Multiagent Systems-Volume 1*, IEEE Computer Society, 2004, pp. 420–427.
- [4] B. Zhukov, E. Lorenz, D. Oertel, M. Wooster, G. Roberts, Spaceborne detection and characterization of fires during the bi-spectral infrared detection (bird) experimental small satellite mission (2001–2004), *Remote Sensing of Environment* 100 (1) (2006) 29–51.
- [5] M. J. Barnsley, J. J. Settle, M. A. Cutter, D. R. Lobb, F. Teston, The proba/chris mission: A low-cost smallsat for hyperspectral multiangle observations of the earth surface and atmosphere, *IEEE Transactions on Geoscience and Remote Sensing* 42 (7) (2004) 1512–1520.

- [6] S. Chien, R. Sherwood, M. Burl, R. Knight, G. Rabideau, B. Engelhardt, A. Davies, P. Zetocha, R. Wainright, P. Klupar, et al., The techsat-21 autonomous sciencecraft constellation demonstration, in: Proceedings of the International Symposium on Artificial Intelligence and Robotics & Automation in Space, 2001.
- [7] M. Martin, S. Kilberg, J. Winter, Techsat 21and revolutionizing space missions using microsatellites, in: Proceedings of the 15th AIAA/USU Conference on Small Satellites, Logan, Utah, Vol. 7, 2001.
- [8] S. Horan, L. Alvarez, M. Schoenoff, L. Egan, A. Friedman, M. Motola, J. Carlson, D. Allison, E. Henrikson, D. Horner, et al., The three corner satellite mission, in: Prodeedings of the International Symposium Formation Flying: Missions & Technologies, 2002.
- [9] S. Chien, S. Wichman, B. Engelhart, R. Knight, G. Rabideau, R. Sherwood, D. Tran, E. Hansen, A. Otiviz, C. Wilklow, Onboard autonomy software on the three corner sat mission, in: Prodeedings of SpaceOps 2002 Conference, 2002, p. 39.
- [10] A. S. Sharma, S. A. Curtis, Magnetospheric multiscale mission, in: Collections of Nonequilibrium Phenomena in Plasmas, Springer, 2005, pp. 179–195.
- [11] D. Suri, A. Howell, N. Shankaran, J. Kinnebrew, W. Otte, D. Schmidt, G. Biswas, Onboard processing using the adaptive network architecture, in: Proceedings of the Sixth Annual NASA Earth Science Technology Conference, Citeseer, 2006.
- [12] N. Shankaran, J. Balasubramanian, D. Schmidt, G. Biswas, P. Lardieri, E. Mulholland, T. Damiano, A framework for (re) deploying components in distributed real-time and embedded systems, in: Proceedings of the 2006 ACM symposium on Applied computing, ACM, 2006, pp. 737–738.
- [13] N. Arshad, D. Heimbigner, A. L. Wolf, Deployment and dynamic reconfiguration planning for distributed software systems, in: Proceedings of the 15th IEEE International Conference on: Tools with Artificial Intelligence, IEEE, 2003, pp. 39–46.
- [14] E. Bensana, G. Verfaillie, J. Agnese, N. Bataille, D. Blumstein, Exact & inexact methods for daily management of earth observation satellite, in: Proceedings of the SpaceOps 1996 Conference on: Space Mission Operations and Ground Data Systems, Vol. 394, 1996, p. 507.
- [15] V. Gabrel, A. Moulet, C. Murat, V. T. Paschos, A new single model and derived algorithms for the satellite shot planning problem using graph theory concepts, *Annals of Operations Research* 69 (1997) 115–134.
- [16] W. Potter, J. Gasch, C. Bauer, A photo album of earth scheduling landsat 7 mission daily activities.
- [17] M. Vasquez, J.-K. Hao, Upper bounds for the spot 5 daily photograph scheduling problem, *Journal of Combinatorial Optimization* 7 (1) (2003) 87–103.
- [18] W.-C. Lin, D.-Y. Liao, C.-Y. Liu, Y.-Y. Lee, Daily imaging scheduling of an earth observation satellite, *IEEE Transactions on Systems, Man, and Cybernetics-Part A: Systems and Humans* 35 (2) (2005) 213–223.
- [19] J. Frank, A. Jonsson, R. Morris, D. E. Smith, P. Norvig, Planning and scheduling for fleets of earth observing satellites, in: Proceedings of the International Symposium on Artificial Intelligence, Robotics, Automation and Space; Jun. 2001; Montreal; Canada, 2001.
- [20] M. Lemaître, G. Verfaillie, F. Jouhaud, J.-M. Lachiver, N. Bataille, How to manage the new generation of agile earth observation satellites, in: Proceedings of the International Symposium on Artificial Intelligence, Robotics and Automation in Space, Citeseer, 2000, pp. 1–10.
- [21] M. Abramson, D. Carter, S. Kolitz, J. McConnell, M. Ricard, C. Sanders, The design and implementation of drapers earth phenomena observing system (epos), in: Proceedings of the AIAA Space 2001 Conference, Aug, 2001, Albuquerque, NM, USA, 2001.
- [22] J. Dungan, J. Frank, A. Jónsson, R. Morris, D. Smith, Advances in planning and scheduling of remote sensing instruments for fleets of earth orbiting satellites, in: Proceedings of the Earth Science Technology Conference, June, 2002, Pasadena, CA, 2002.
- [23] A. Globus, J. Crawford, J. Lohn, R. Morris, Scheduling earth observing fleets using evolutionary algorithms: Problem description and approach, in: Proceedings of the 3rd International NASA Workshop on Planetary and Scheduling for Space, 2002.
- [24] A. Globus, J. Crawford, J. Lohn, A. Pryor, Scheduling earth observing satellites with evolutionary

- algorithms, in: Proceedings of the Conference on Space Mission Challenges for Information Technology, July, 2003, California, USA, 2003.
- [25] S. Chien, B. Cichy, A. Davies, D. Tran, G. Rabideau, R. Castano, R. Sherwood, D. Mandl, S. Frye, S. Shulman, et al., An autonomous earth-observing sensorweb, *IEEE Intelligent Systems* 20 (3) (2005) 16–24.
  - [26] S. Chien, A. Davies, D. Tran, B. Cichy, G. Rabideau, R. Castano, R. Sherwood, J. Jones, S. Grosvenor, D. Mandl, et al., Using automated planning for sensorweb response, in: Proceedings of the Fourth International Workshop on Planning and Scheduling for Space, NASA, Darmstadt, Germany, June, 2004.
  - [27] J. Wang, N. Jing, J. Li, Z. H. Chen, A multi-objective imaging scheduling approach for earth observing satellites, in: Proceedings of the 9th annual conference on Genetic and evolutionary computation, ACM, 2007, pp. 2211–2218.
  - [28] N. Bianchessi, J.-F. Cordeau, J. Desrosiers, G. Laporte, V. Raymond, A heuristic for the multi-satellite, multi-orbit and multi-user management of earth observation satellites, *European Journal of Operational Research* 177 (2) (2007) 750–762.
  - [29] M. A. Mansour, M. M. Dessouky, A genetic algorithm approach for solving the daily photograph selection problem of the spot5 satellite, *Computers & Industrial Engineering* 58 (3) (2010) 509–520.
  - [30] P. Wang, G. Reinelt, P. Gao, Y. Tan, A model, a heuristic and a decision support system to solve the scheduling problem of an earth observing satellite constellation, *Computers & Industrial Engineering* 61 (2) (2011) 322–335.
  - [31] G. Wu, M. Ma, J. Zhu, D. Qiu, Multi-satellite observation integrated scheduling method oriented to emergency tasks and common tasks, *Journal of Systems Engineering and Electronics* 23 (5) (2012) 723–733.
  - [32] Z. Zheng, J. Guo, E. Gill, Swarm satellite mission scheduling & planning using hybrid dynamic mutation genetic algorithm, *Acta Astronautica* 137 (2017) 243–253.
  - [33] A. Budianu, A. Meijerink, M. Bentum, Swarm-to-earth communication in olfar, *Acta Astronautica* 107 (2015) 14–19.
  - [34] A.-J. Boonstra, M. Garrett, G. Kruithof, M. Wise, A. van Ardenne, J. Yan, J. Wu, J. Zheng, E. K. Gill, J. Guo, et al., Discovering the sky at the longest wavelengths (dsl), in: Proceedings of the IEEE 2016 Aerospace Conference, IEEE, 2016, pp. 1–20.
  - [35] M. Bentum, C. Verhoeven, A. Boonstra, E. Gill, A. Veen, A novel astronomical application for formation flying small satellites, in: Proceedings of the 60th International Astronautical Congress, Oct, 2009, Daejeon, South Korea, 2009.
  - [36] R. T. Rajan, S. Engelen, M. Bentum, C. Verhoeven, Orbiting low frequency array for radio astronomy, in: Proceedings of the IEEE 2011 Aerospace Conference, IEEE, 2011, pp. 1–11.
  - [37] S. Engelen, C. J. Verhoeven, M. J. Bentum, Olfar a radio telescope based on nano satellites in moon orbit, in: Proceedings of the 24th Annual AIAA/USU Conference on Small Satellite, Logan, UT, 2010.