Intelligent system for real-time adaptive management of groups of small satellites: design and experimenting

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Abstract. The paper considers development of an intelligent system for real-time management of groups of small satellites, as well as an approach to its implementation built on the basis of multi-agent technology. It discusses the main disadvantages of traditional planning systems currently used to manage various space missions, which complicate their application with new-generation multi-satellite orbital groups. A brief problem statement for planning the operation of a space observation system is given. The architecture of the developed system is proposed, describing the functions of the main modules and screens, which make it possible to process applications for imaging of observation objects entering the system in real time. Results of experimental studies are also presented. They demonstrate applicability of the proposed approach to solving problems of managing groups of small satellites to increase efficiency of using resources of the space system. Finally, the prospects for development and application of the system are discussed.

1. Introduction
Development of an intelligent system for real-time management of groups of small satellites is highly relevant primarily due to immediate prospects for creation of space systems (SS) of a new generation, including a heterogeneous multi-satellite swarm of low-orbit small satellites and a distributed network of ground stations for receiving information (GS).

Examples of such space systems are the projects of Planet Labs (200 operating Dove (Flock) satellites and 13 SkySat sub-meter satellites) [1] and BlackSky Global (60 satellites and 17 receiving and control stations) [2]. Their productivity is hundreds of thousands of imaging sessions of unique observation objects (OO) per month.

The purpose of creating such SS is to meet the existing needs for data obtained from space, which are used in various fields: in the military, forestry and agriculture, cartography, oil and gas industries, elimination of consequences of natural disasters and in many other areas [3].

The increase in dimension and productivity of space systems leads to the growth of requirements for algorithms and planning systems. Existing planning systems used to manage various missions, such as CPAW [4], flexplan [5], SOC [6] and others, were originally built as centralized, hierarchical,
closed, monolithic and sequential solutions. These systems are aimed primarily at the batch mode of use, in which applications for imaging are pre-accumulated, and then distributed between groups of small satellites using traditional combinatorial methods, such as linear and dynamic programming, programming in constraints, various heuristics and metaheuristics. [7]. As a result, building a plan using such systems can sometimes take quite a long time (up to 8-12 hours). After that, the program does not take into account new information coming after the end of the last planning session.

However, in this case, the existing plan may already be impracticable. Thus, it needs to be corrected by experts and specialists, as a rule, in “manual mode”, which is an extremely labor-intensive process.

This paper is devoted to development of an intelligent system for managing groups of small satellites, designed to overcome the disadvantages of traditional planning systems. This system is built on the basis of multi-agent technology [8], according to the principles that were described earlier in [9-11].

The paper is structured as follows. Section 2 gives a brief problem statement for planning the operation of a space system; Section 3 discusses the current state of research and development on this issue. Section 4 provides the architecture of the developed system with a description of functions of the main modules. Section 5 briefly describes processing of applications for imaging of OOs entering the system. Section 6 covers the main system screens. Section 7 provides a description of the carried out experimental studies, and Section 8 summarizes the main results obtained and discusses the prospects for development and application of the system.

2. Problem Statement

Let us consider the main components of the developed space system. It is a combination of two segments: the space complex and the ground-based special complex. The space complex performs the functions of receiving and transmitting information. In its turn, the ground-based special complex performs the functions of receiving and processing the transmitted information.

The space complex consists of an orbital group of small satellites with the target ERS equipment on them and onboard means of transmitting information to the Earth via a radio channel. Each satellite is characterized by a set of orbital elements, a complete mathematical model of disturbing effects, limiting roll and pitch angles, as well as parameters of its onboard equipment, such as data transfer rate, retargeting time, memory capacity, linear resolution and available spectral ranges of imaging equipment.

The ground complex is represented by a distributed network of GSs, each of which is characterized by its geographic location and parameters of antenna, such as transmission rate and the opening angle. For ground stations, work schedules, unavailability intervals, and the average time of station preparation for receiving information can also be indicated.

From the point of view of planning the operation of target equipment of the orbital group of satellites, observation objects can be divided into point and area objects. A point object is small in size, and its image can be obtained in one flight. Whereas for imaging the area OO, it is necessary to make several flights, during which a lot of images will be obtained, completely covering the given observation area. For an imaging application, the following characteristics can be provided: its priority, frequency of imaging and many restrictions, such as the deadline for obtaining images, conditions, requirements for characteristics of imaging equipment and spatial resolution, restrictions on acceptable satellites and ground stations.

The described model of the space system presents two operations performed by the satellite: imaging of OO and communication session of the satellite with GS for transmitting the received data to the Earth, and one operation performed by the GS - receiving data from the satellite.

For implementation of remote sensing on the basis of applications from consumers, it is required to form a comprehensive plan in accordance with the criterion of minimizing delivery time of images to consumers, as well as maximizing their quality. The objective function of the system is as follows:

\[
OF = \frac{1}{M} \sum_{k=1}^{N} OF_k \rightarrow \text{max} ,
\]  

(1)
where $OF$ is the objective function of the system, $OF_k$ is the objective function of the $k$-th task, $M$ is the total number of tasks, $N$ is the number of scheduled tasks, $c_k$ is the balance coefficient between operational efficiency and quality of information received for the $k$-th task $F_1^k$ is evaluation of efficiency criterion of obtaining information for the $k$-th task, $F_2^k$ is evaluation of the quality criterion of the resulting image for the $k$-th task, $\tau_{dropEnd}$ is the time of completion of communication session between the satellite and GS for the $k$-th task, $t_{start}^k, t_{end}^k$ is the planning horizon for the $k$-th task, $\text{minRes}_k$ and $\text{maxRes}_k$ respectively, are the minimum and desired linear resolution of the resulting image for the $k$-th task, $r_k$ is the actual linear resolution of the resulting image for the $k$-th problem.

3. State of the Art

The currently existing solutions to the problem of scheduling the operation of the space system are based mainly on classical methods of linear programming or various kinds of heuristics, previously tested on classical problems of planning and resource allocation. Thus, in [12], to solve the problem of planning the target functioning of the SS, it is proposed to use a numerical method and an algorithm for generating optimal plans using the routing procedure when interpreting the process of target functioning of the SS in the form of a graph of operations. In [13] and [14], to find a solution to this problem, it is proposed to use a modified ant algorithm, and in [15], an application of the linear integer programming method is considered for planning the imaging of OOs by a satellite group, taking into account possible cloudiness.

In addition to studies devoted to development of methods for solving the problem of planning the target functioning of satellite groups in general, there is a fairly large number of studies aimed at solving its individual subtasks. Thus, [16] is devoted to solution of the subproblem of planning the operation of a satellite with several degrees of freedom using the method of local search in an expandable neighborhood, and [17] is devoted to optimizing communication sessions between the satellite and the GS based on the methods of simulating annealing and searching for options with restrictions. The use of genetic algorithm for planning imaging of area objects is considered in [18].

A review of the above mentioned papers has shown that the currently available methods for planning the work of orbital groups are mainly of a centralized, hierarchical and monolithic nature. Their main disadvantages are determinism and complexity of taking into account the rapidly changing conditions, lack of reliable information about the current situation, and the loss of adequacy of schedules over time. This greatly complicates their use in practice when creating a system for managing large-scale orbital groups of small satellites.

The solution proposed in this paper is based on the principles of self-organization and multi-agent technology, which have gone from the first experiments to full-fledged industrial implementations [8]. Their use makes it possible to flexibly and adaptively synthesize the schedule taking into account
events in real time, which makes it possible to more efficiently manage the SS resources in comparison with traditional methods.

4. System Architecture
The developed intelligent system for managing groups of small satellites has a network client-server architecture (Figure 1).

The automated workstation of the information center operator is a user interface for entering applications, managing planning progress, monitoring resources, viewing reports and planning results. The database is a subject-oriented information database that provides long-term storage of initial data and planning results. The interaction control module provides routing and transformation of information flows between the system and the external environment. The accounting system module is intended for interaction of other parts of the system with the database server. It includes a service for processing applications for reading and changing data, the purpose of which is to make queries to a relational database, as well as a service for providing data to the scheduler, designed to transform and provide data stored in the database into a data format understandable by the scheduler. In addition, the service providing data to the scheduler tracks changes in the source data at the request of the planning module.

The planning module is designed for adaptive scheduling and its rebuilding in case of external changes in the source data. The planning module, implemented on the basis of multi-agent technology, includes the following main elements:

- The scheduler, which includes a repository of agents - a system module that accumulates created agents, and planning algorithms - a set of algorithms that are responsible for managing the planning progress and behavior of agents depending on the current context.
- The event processing service is responsible for interaction of the scheduler with the rest of the system through performing appropriate actions in response to emerging external and internal events.
- The service for calculating placement options provides generation of a space of possible search options at the request of the scheduler. In the course of these calculations, it turns to the ballistics module to obtain cyclograms of visibility between satellite and OO and between satellite and GS.
The schedule is an object structure containing initial data for planning and assigning certain resources to applications, obtained during planning.

5. Processing applications for imaging

Figure 2 shows the basic diagram of processing applications for imaging entering the system.

![Diagram of processing applications for imaging in the system](image)

**Fig. 2.** Processing applications for imaging in the system

After receipt of applications for imaging and a signal from the operator about the start of planning, tasks for imaging are generated in the system. For each application, one or several imaging tasks can be created, depending on the specified frequency and size of the OO.

When imaging tasks have been generated for all applications, the system proceeds to the next stage – calculation of placement options using the method of successive concessions between the criteria of efficiency and quality of information received. The result of the search algorithm is a list of possible placement options sorted in descending order of the value of objective function $OF_i$ (2) (the placement option at the global $OF_i$ optimum point comes in the first place). After the possible placement options are calculated for all tasks, the stage of conflict-free planning begins.

At the stage of conflict-free planning, an initial feasible schedule is constructed using a greedy optimization algorithm. Tasks are placed on the first available option that does not conflict with other tasks. These are taken from the list obtained in the previous step. The solution obtained at this stage will show the main bottlenecks of the schedule and will become a reference point for further improvements. The conflict-free phase ends after an attempt has been made to find placement for each task.

At the stage of proactive planning, each task is assigned an agent, which tries to improve the value of its objective function $OF_i$ and take a more advantageous option for it, offering the conflicting tasks to find other options for placement. Effectiveness of each permutation is estimated by changing the values of satisfaction functions of agents $SF_k$ (3) [19] participating in it, according to the formula (4).

The launch of agents for proactivity is carried out iteratively until, during the next planning iteration, none of the task agents can find a better position, which means reaching an equilibrium point in negotiations and the possibility of issuing a ready-made solution.

$$\Delta SF = \frac{1}{M} \sum_{j=1}^{M} SF(\tilde{sw}_j) - SF(sw_j)$$  \hspace{1cm} (4)$$

where $\Delta SF$ is the increment of the agent’s satisfaction function, $M$ is the number of agents participating in the permutation, $sw_j$ is the current imaging job, $\tilde{sw}_j$ is the new imaging job.

When the system receives events bringing changes in the initial data for planning, the proactive phase starts again.

6. User Interface

The system user interface is a single page web application. It makes it possible to remotely access system resources from any device that has is connected to the Internet (PCs, laptops, tablets, mobile phones). Figure 3 shows one of the screens with data for planning – the GS screen. The system
contains similar screens for satellites, applications for imaging, calendars and resource availability restrictions. Data for planning can be added, changed or deleted, and the schedule will be dynamically rebuilt taking into account the changes that have occurred.

Figure 4 shows the screen with results of operation planning for each satellite and GS, displayed on the timeline. In the upper part of the screen, there is a graph of the satellite memory filling, which demonstrates memory limitations.

Figure 5 shows the screen with the physical world model in which the space system operates: a three-dimensional model of the Earth, orbits, location of OOs and GSs. The processes of imaging and transferring its results are modeled. At the bottom of the screen there is a timeline, which displays the queue of the nearest scheduled operations, and the model time management widget.

The screen with analytical information (Figure 6) shows many graphs and diagrams, allowing users to assess the quality of the resulting schedule and analyze the progress of its construction:
• graphs with the history of changes in the values of the current and limiting objective functions of the system from the start of planning, with the help of which it is possible to estimate how much the current value of the system OF differs from its maximum possible value;
• a bar chart of distribution of the number of placement options that are better than the current one, which helps analyze the current position of the task in the schedule in regards to all the possible ones;
• a bar chart of distribution of the number of permutations of tasks at each planning iteration, with which it is possible to analyze convergence of the planning algorithm;
• a bar chart of distribution of the total number of permutations of tasks during planning, which helps analyze how much the schedule has changed during planning;
• a pie chart displaying the ratio of successful and unsuccessful proactivities of the task agent and proactivities that ended with a conflict, which makes it possible to evaluate the computational efficiency of the proactive scheduling algorithm.

Fig. 5. Screen with a physical world model

Fig. 6. Screen with analytical information
7. Experimental Research

To test applicability of the developed system for solving problems of managing groups of small satellites in real time, a series of experiments has been carried out. The main parameters of the space system model used in the experiments are shown in Table 1. In the course of the experiments, planning of applications for imaging was performed at first, the number of which, depending on the experiment, varied from 100 to 20,000. The time spent on constructing the plan was measured (Figure 7a), as well as the value of the system OF (1) (Figure 7b). After the end of planning, another 100 new applications for imaging were added to the system and the time spent on their placement in the schedule was measured. Experimental results are shown in Table 2.

Table 1. The main parameters of the SS model

| Parameter                                      | Value         |
|-----------------------------------------------|---------------|
| Number of satellites                          | 30            |
| Number of GSs                                 | 10            |
| Orbital altitude                              | 500 km        |
| The period of complete revolution around the Earth | 90 min       |
| Roll angle                                    | 0° – 45°      |
| Pitch angle                                   | 0° – 10°      |
| Memory capacity                               | 500 Gb        |
| Visibility bandwidth                          | 200 km        |
| Imaging bandwidth                             | 45 km         |
| Sun angles                                    | >10°          |
| GS receiving speed                            | 500 Mb/s      |
| Minimum elevation angle for GS                | >10°          |

Fig. 7. Graphs of dependence of the OF value (a) and planning times (b) on the number of applications
Table 2. Results of experimental studies

| #  | Number of applications | Planning time | Value of system OF | Time for allocation of the new batch of applications |
|----|------------------------|---------------|-------------------|-----------------------------------------------------|
| 1  | 100                    | 0:00:10       | 0.8498            | 0:00:11                                             |
| 2  | 500                    | 0:00:20       | 0.8496            | 0:00:12                                             |
| 3  | 1000                   | 0:00:37       | 0.8494            | 0:00:12                                             |
| 4  | 2000                   | 0:01:11       | 0.8427            | 0:00:17                                             |
| 5  | 3000                   | 0:02:17       | 0.8342            | 0:00:32                                             |
| 6  | 4000                   | 0:03:09       | 0.8179            | 0:00:47                                             |
| 7  | 5000                   | 0:04:40       | 0.8164            | 0:01:12                                             |
| 8  | 7500                   | 0:09:09       | 0.7823            | 0:02:14                                             |
| 9  | 10000                  | 0:15:16       | 0.7715            | 0:03:09                                             |
| 10 | 15000                  | 0:47:12       | 0.7625            | 0:06:37                                             |
| 11 | 20000                  | 2:48:20       | 0.7544            | 0:18:28                                             |

8. Conclusions
The developed prototype of intelligent system for managing groups of satellites in real time has demonstrated applicability of the proposed multi-agent approach to increase the efficiency of using the satellite resources.

Further research will focus on improving planning algorithms by introducing a virtual marketplace and adding deeper analysis of the current planning context to reduce enumeration of options. In addition, it is planned to introduce a space observation system into the intelligent ontology system in order to provide a more flexible and adaptive ability to customize the applied rules. All these actions will ultimately make it possible to move from a prototype to a real management system scalable for a large number of small satellites in groups, and in the future - to create smart constellations in space, where each device makes decisions on its own and coordinates them with other satellites and ground stations.

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