Design of an Autonomous Distributed Multi-agent Mission Control System for a Swarm of Satellites

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Abstract: The paper describes an autonomous distributed multi-agent system for mission control of a multi-satellite swarm, using direct data exchange between satellites in space via a radio channel to make coordinated collective decisions. The main advantage of autonomous control on board the vehicle is the ability to use the current data on its state to quickly respond to events in real time, without having to wait for a response or instructions from the Earth. The proposed approach develops the principles of creating self-organizing systems and is supposed to be implemented in several stages of the space mission. The first stage consists in conducting experiments on the use of inter-satellite interaction in order to assess and clarify the possibility of performing and correcting the plan of operations built on the ground with account of the current telemetry data obtained in real time. At the second stage, it is planned to use more powerful on-board computers and organize fully autonomous control in a mesh network formed by the satellites for a distributed solution of the observation problem, surveying a given area in the interests of ecology and solving other problems requiring coordinated interaction of devices. In this regard, this paper presents a refined brief problem statement for planning the work of a multi-satellite swarm in relation to the previously considered one. A brief description of the developed system is given, which makes it possible to implement processing applications for performing space experiments by means of the ground circuit and resources of the space constellation. The paper also presents the structure and functions of the autonomous multi-agent system and protocols of agent interaction, as well as models and methods of multi-agent group management. Prospects for further development and practical application of the approach are discussed.

1 INTRODUCTION

The current level of development of computing equipment and technologies for inter-satellite communication makes it possible to come close to the possibility of creating the so-called "Swarm of satellites". This self-organizing group is fundamentally different from the usual swarm because each satellite can make independent decisions and directly interact with others for development, assessment, approval, adoption and implementation control of decisions. To create the swarm of satellites, it is proposed to organize a

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common mesh network and use multi-agent technologies for intelligent interaction through exchange of messages via the Contract Net Protocol (Zhang, 2019).

The purpose of creating such intelligent orbital constellations is efficient and guaranteed provision of data obtained from space to the user. In particular, the Earth remote sensing (ERS) data which is used for environmental and agricultural monitoring (Shimoda, 2016). A consequence of the increased interest in space observations is a significant increase in the number of requests and requirements for efficiency of their servicing. This leads to the need for dynamic adaptive adjustments to the operating schedule of the swarm as new applications arrive, as well as in case of unpredictable events related to equipment failure or rapidly changing meteorological conditions. Application of traditional methods of control based only on the ground control loop and traditional planning methods turns out to be ineffective.

Attempts have already been made to implement the concept of autonomous planning and inter-satellite communication. For example, in 2015, Biros satellites were launched, on board of which images can be processed, which makes it possible to determine cloudiness, as well as identify certain types of objects and events, allowing users to adjust the plan of operations based on the current target situation (Lenzen, 2014). A year earlier, the DEIMOS-2 satellite was launched, on board of which a similar task can be solved (Tonetti, 2015). Another example is an attempt to implement the scenario of information interaction within a cluster of eight satellites within the EDSN mission (Hanson, 2014).

It is proposed to implement this approach in several stages of a space mission. At the first stage, planning of space experiments is carried out by a multi-agent system on Earth. Implementation of a prototype multi-agent system for this stage was described by the authors in the paper (Skobelev, 2021). At the same time, on board each satellite there is an autonomous intelligent control system (AIS) with auto-glider functions. The action plan built on the ground is transmitted to AIS as a proposal for consideration. Based on the analysis of the current situation, each satellite checks the plan feasibility based on available factual data. If it is impossible to fulfill it, it starts negotiations with other satellites of the group on transferring part of its tasks to them. Results of these negotiations are transmitted to the ground, where they are used to clarify the status and work plans of each satellite. As a result, a digital twin of the satellite swarm functions on the ground, which reflects the state of each satellite in space and its plan, and which can be used for advanced modeling of various unforeseen events.

At the second stage, adaptive scheduling of the flow of tasks directly on board is to be performed, followed by ground control of planning results.

The project is being implemented with the support of Roscosmos and commissioned by RSC Energia in a consortium of 18 leading Russian universities. The main contractor for the project is the Samara State Technical University. During the project, it is planned to launch from the International Space Station four 3U CubeSats to analyze neutron stars, and then six 6U CubeSats equipped with Earth remote sensing sensors. The timeframe of the project is 2021-2024.

The paper is structured as follows. In the second chapter, a brief problem statement for adaptive scheduling of operations for an autonomous multi-satellite orbital constellation is given. The third chapter describes the current state of research and development on this problem. The fourth chapter contains the architecture of the system with description of subsystems and functions of its main modules. In the fifth chapter, the proposed adaptive planning method based on multi-agent technology is described. The sixth chapter considers intermediate results obtained and discusses possible applications and development prospects.

2 PROBLEM STATEMENT

The generalized task of planning execution of operations in a multi-satellite swarm can be represented in the following way. Let there be a simplified model of the space system (SS), which is a combination of two segments: a space complex, the main task of which is to collect and transmit information, and a ground-based special complex, which receives and processes the transmitted data.

The space complex consists of a set of satellites $S = \{s_i\}, i=\overline{1, L}$. Each satellite s_i is characterized by a set of orbital elements and parameters of its onboard equipment (battery, memory, transmitting and receiving antennas, payload, etc.). The ground-based complex is represented by a plurality of information receiving stations (ground stations, GS) $G_R = \{g_r\}, r = \overline{1, R}$ and mission control centers (MCC)$C_v = \{c_v\}, v = \overline{1, V}$. Each station g_r and each MCC c_v are characterized by their geographic location and parameters of installed antenna. The main difference between GS and MCC is that usually ground stations are equipped with an antenna that receives data from payload, whereas a receiving-transmitting control antenna complex is installed in MCC. Restrictions may be indicated in the form of a work schedule and intervals of unavailability.

The space system must ensure fulfillment of a set of applications for collection of information about a certain object of observation (OO) $O = \{o_p\}, p = \overline{1, P}$), which can be located both on the Earth and in the space. For the application o_p, its cost ($cost_p$) and a set of restrictions are indicated: the time until which it is necessary to obtain data about the object t_p^{end}, and the minimum quality of the collected data $minQ_p$. The composition of the application set is not completely known in advance and changes during system operation. Depending on the type of application, several satellites can be involved in its execution at once. For example, for distributed observation of stars, two or three satellites must be aimed at one star at a given time.

In the considered model, the system of satellites performs the following operations:

- receiving the flight assignment from the MCC $sReceiv_j$.
- battery charging $charge_j$.
- OO surveying $imaging_j$,
- transfer of results to GS $drop_j$.

The scope of operations may vary depending on the task being performed and the equipment installed.

Ground stations perform one operation - receiving data from satellite $gReceiv_j$. The MCC also performs one operation - sending a flight mission to the satellites $dispatch_j$. Each of the presented operations op_j is characterized by an execution interval $t_j^{op} = [t_j^{opStart};\ t_j^{opEnd}]$.

To implement target functioning of the satellite swarm, it is necessary to provide adaptive scheduling of incoming applications by redistributing them between the devices in order to increase SS performance, obtain data on the maximum quality of OO, minimize the time required to complete individual applications and ensure fulfillment of other criteria. The objective function (OF) of the system has the following form:

$$OF = \frac{1}{S}\sum_{k=1}^{N} OF_k \to max, \quad (1)$$

$$OF_k = \sum_{m=1}^{M} c_m F_m^k \to max, \quad (2)$$

where OF is the system's objective function,
OF_k is the OF of the k-th application,
S is the total number of applications,
N is the number of placed applications,
M is the number of optimization criteria,
c_m is the weight coefficient of the m-th optimization criterion, such that $0 \le c_m \le 1,\ \sum_{m=1}^{M} c_m = 1$,
F_m^k is the estimate of the m-th optimization criterion for the k-th application.

Minimization of the imaging time F_1^k (3) and maximization of the quality of images F_2^k (4) have been chosen as optimization criteria in this work.

$$F_1^k = \frac{t_k^{end} - t_k^{dropEnd}}{t_k^{end} - t_k^{start}}, \quad (3)$$

$$F_2^k = \frac{maxQ_k - q_k}{maxQ_k - minQ_k} \quad (4)$$

3 REVIEW OF REFERENCES

To date, there has been a fairly large number of works devoted to solving the problem of planning the target application of multi-satellite SS. These papers usually describe the traditional ground-based option for drawing up the plan. However, recently there have begun to appear works in which planning is partially or completely carried out on board the satellite. The methods for solving this problem are mainly based on linear integer programming and various kinds of heuristics to reduce the enumeration. However, differences in description of the problem statements of the considered approaches are making it difficult to compare their performance and effectiveness.

In particular, linear programming methods as a way to solve this problem are considered in (Wang, 2016). Results of these experimental studies show the possibility of solving the problem in relation to a multi-satellite swarm. However, objective functions used in them imply optimization according to only one criterion, and the planning duration grows exponentially with an increase in the dimension of input data, i.e. the number of applications and the number of satellites.

A number of works consider the use of heuristic and metaheuristic algorithms previously tested on classical problems of planning and resource allocation, such as the ant algorithm (He, 2019), the local search method (He, 2018), and the genetic algorithm (Hosseinabadi, 2017). Although heuristic algorithms show better performance than linear programming methods, their centralized approach makes them impossible to apply for distributed computing in the satellite networks in real time.

Application of a multi-agent approach to planning the operation of a swarm of satellites is considered in (Bonnet, 2015) and (Phillips, 2019), but only within the framework of the ground contour. As prerequisites for application of the multi-agent approach, the advantages of self-adaptation and self-organization are given in relation to multi-criteria problems of large dimensions that require dynamic adaptation of the plan in case of abnormal events. In the works (Song, 2018), (Tonetti, 2015) and (Chu, 2017) approaches to fully autonomous planning are considered. However, the presented solutions are limited to one device, not solving the problem of organizing distributed computing and implementing messaging within the orbital constellation. The work (Picard, 2021) discusses the idea of fully autonomous multi-agent planning, however, specific algorithms and protocols for interaction of vehicles in orbit, as well as obtained results, are not provided.

This review of references has shown that the currently available methods of planning are mainly of a centralized, hierarchical and monolithic nature, and are designed to be used only in the ground-based planning method. Methods and algorithms for autonomous planning on board a satellite, with support for interaction between them, are just starting to appear. However, they are limited by only one satellite and cannot be upscaled for the orbital constellation. Thus, efficient and scalable solutions to the problem of autonomous planning for target application of multi-satellite swarms, suitable for practical digital implementation, are currently not presented in the scientific literature.

4 SYSTEM ARCHITECTURE

The architecture of the developed system is shown in Figure 1. It consists of a ground control subsystem, concentrated in the MCC, connected to the global GS network, as well as an orbital planning subsystem, represented by a set of AIS on board each satellite.

The ground control subsystem includes the following main software modules:

- *Planning module* - designed for adaptive scheduling and rebuilding of the schedule in response to external changes in the initial data by simulating the interaction of satellites in orbit. A detailed description of the multi-agent planning method implemented in this module is given in (Skobelev, 2021).
- *Ontology and knowledge base* - to accumulate and formalize current knowledge about the subject area, which is used in planning and management.
- *Database* is subject-oriented and provides long-term storage of initial data and planning results.
- *Digital twin of satellite* is a computer model, replenished with data on the real state of each device.
- *Service of accounting system* for interaction of other parts of the system with the database server.
- *User interface* provides the ability to enter applications, manage the progress of planning, monitor resources, view reports and planning results.

Whereas, the onboard AIS of each satellite must include the following main software modules:

- *Intelligent control module* allows users to process applications from the MCC and other satellites, plan operations, and coordinate decisions. The intelligent control module is implemented on the basis of multi-agent technologies and includes the following main elements:
  - *Scheduler* that includes an *agent repository* - a system module that accumulates the created agents, and *scheduling algorithms* – a set of algorithms responsible for managing the progress of planning and agent behavior in accordance with the current context.
  - *Event processing service* is responsible for interaction of the scheduler with other parts of the system by performing appropriate actions in response to emerging external and internal events.
  - *Placement calculation service* provides generation of the space of possible search options at the request of the scheduler.
- *Ontology and knowledge base* is a simplified version of the knowledge base from the ground control system, used to make control decisions, reschedule tasks and diagnose the state of onboard systems within the swarm of satellites.
- *Communication module* for negotiations with other satellites in the mesh network mode.
- *Satellite self-diagnostics module* makes it possible to evaluate and predict its condition.
  • *Image processing module* is designed to process and analyze information obtained during observation, in order to solve the target problem.

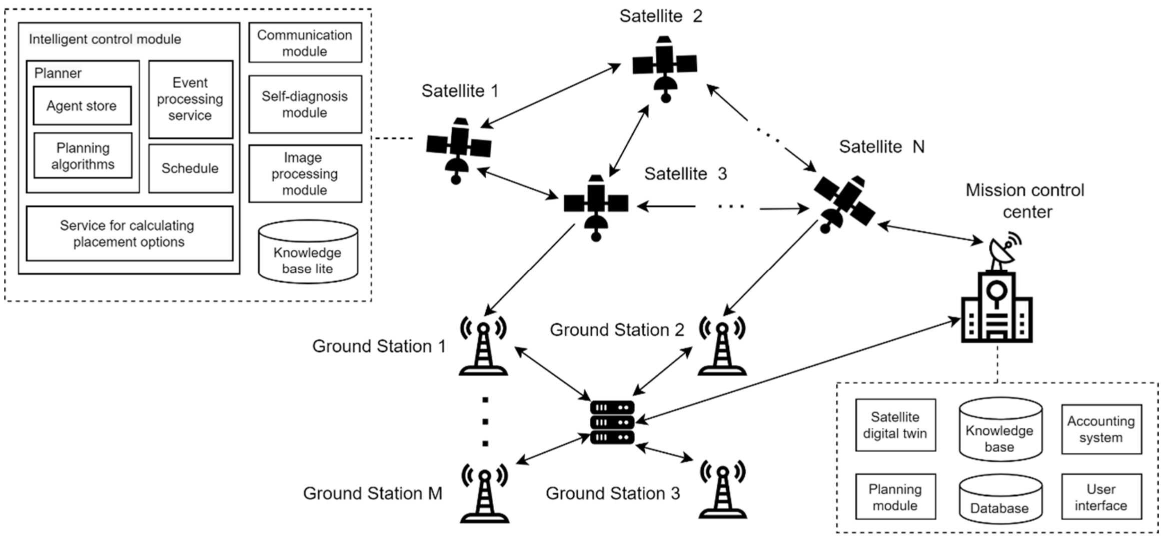

Figure 1: System architecture.

5 DEVELOPMENT OF A MULTI-AGENT PLANNING METHOD

5.1 Generalized Scheme of Processing Applications in the System

Figure 2 shows the application state diagram. After receiving a survey application, the satellite attempts to place it using a ground-based planning system to assess its feasibility at the given horizon.

Moreover, for each satellite, the current state and action plan are known. The possibility of including new applications in the current plans of satellites is assessed taking into account ballistics of each vehicle, battery reserves, time spent on orientation to the desired point, etc. At this stage, those applications that cannot be fulfilled by means of the orbital constellation are discarded. After processing the application in the multi-agent planning system on Earth and accumulating a certain set of received applications, a summary flight assignment is formed, which is sent to the nearest available satellite.

The flight assignment is the following set $FA = \{< A, O, V >\}$, where A is a short description of the application (OO coordinates, deadline, restrictions), O is a list of pre-planned operations (may be empty for fully autonomous planning), and V are periods of GS and MCC availability.

The multi-agent system deployed on the basis of the AIS of the orbital constellation is represented by two types of agents: the agent of the swarm of satellites as a whole and the agent of a satellite. The swarm agent is launched on board the satellite that received the flight assignment from MCC, its main goal is to fulfill it as fully as possible with available resources. The objective function of this agent coincides with the system's OF as a whole (1). The satellite agent is launched on board each vehicle and is the executor of the received applications.

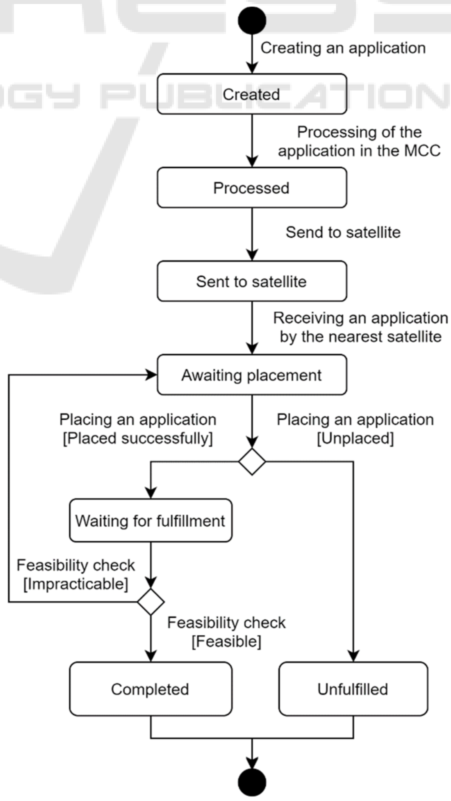

Figure 2: Application state diagram.

The system can perform several flight missions at once, and for each of them, its own instance of the swarm agent will be launched. However, the instances of satellite agents remain the same for different flight missions, this is necessary to coordinate their execution plans.

The logic of agents' work differs depending on the type of planning at different stages of experimental research. After receiving the flight assignment, within hybrid planning the swarm agent simply sends parts of it to the pre-assigned agents of the satellites-contractors. Otherwise, in case of autonomous planning, it initiates a more complex chain of negotiations with the aim of organizing a team of executors for each application. The logic of interaction between agents will be discussed in more detail later in this chapter.

After the application has reached the contractor, it waits for the moment of its fulfillment. Shortly before that, the possibility of executing this application by the appointed contractors is re-checked, and if for some reason it turns out to be impossible, an attempt is made to redistribute it to the available satellite.

Upon completion of the application, the results obtained are sent to Earth.

In addition, the results of each redistribution are also sent to Earth for synchronization with the satellite digital twin and updating the status of the flight mission.

5.2 Messages Sent during Negotiations

The negotiation protocol of agents is based on the Contract Net Protocol, chosen among other distributed protocols for agent negotiations, such as, for example, (Patrikar, 2015) and (Yu, 2017) due to its relative simplicity of implementation and reliability.

The swarm agent acts as the leader (manager), and satellite agents act as contractors. Table 1 lists the main messages sent by the swarm agent, with a brief description and expected response. Table 2 provides a similar list of messages for satellite agents.

Table 1: Messages sent by the swarm agent.

Message	Description	Expected Response
Call	Request to execute the application	Proposal | Reject
Accept	Accept the contractor's proposal	–
Reject	Refuse the contractor's proposal	–

Table 2: Messages sent by the satellite agent.

Message	Description	Expected Response
Proposal	Proposal to complete the application	Accept | Reject
Reject	Refusal to execute the application	–
Cancel	Refusal to execute the assigned application	–
Completed	Informing about the fact of application execution	–

5.3 Hybrid Planning Method

As mentioned above, the hybrid planning method will be applied at the first stage of experimental research on deployment of the Satellite Swarm. Hybrid planning consists of two stages: ground planning and subsequent adaptive adjustment of the constructed plan in orbit. The essence of the hybrid planning method lies in the fact that due to the limited computing power of the satellites, the initial plan for target application of the orbital constellation is built in the traditional way – on Earth, by means of a multi-agent planning system launched at the MCC. After that, the resulting solution is sent into orbit and forwarded there among the performers. At the same time, in case of impossibility of execution, its adaptive reconstruction is performed by the multi-agent planning system deployed in orbit. The main logic of the swarm and satellite agents is concentrated in the event handlers presented in Algorithm 1 and Algorithm 2, respectively.

Algorithm 1: Swarm Agent Event Handler.

```
Input: event
  swich(event)
    case: Flight assignment received;
        Send out messages with Assignments to
        agents of the appropriate satellites;
    case: Cancel message received
        Send a Call message to other satellite
        agents;
    case: Proposal message received
        Proposal receipt;
        if (all reply messages are received)
            Choose the best proposal;
            Reply with an Accept message to the
            selected contractor;
            Reply with a Reject message to other
            contractors;
    case: Reject message received
        Refusal receipt;
    case: Completed message received;
        Application completion;
```

Algorithm 2: Satellite Agent Event Handler.

```
Input: event
swich(event)
    case: Assignment message received
        Analysis of the appointment's feasibility;
        if (assignment is doable)
            Fix the appointment in the schedule;
        else Reply with a Reject message;
    case: Call message received
        Search for the application placement
        option;
        if (Accommodation found)
            Reply with a Proposal message;
        else Reply with a Reject message;
    case: Accept message received
        Fix the appointment in the schedule;
    case: Receiving self-diagnostics results |
    Approaching application execution
        Analysis of the appointment feasibility;
        if (assignment is not feasible)
            Send the Cancel message;
    case: Application completed
        Send the Completed message;
```

5.4 Autonomous Planning Algorithm

The autonomous planning algorithm assumes complication of the logic of system agents in order to increase intellectualization of the Satellite Swarm for solving a wider range of tasks, for example, joint observation of a certain object. For these purposes, satellite agents have a separate satisfaction function SF_i (5), and their actions become proactive in accordance with this function.

$$SF_i = \frac{profit_i - profit_i^{min}}{profit_i^{opt} - profit_i^{min}} \rightarrow max, \quad (5)$$

$$profit_i = \sum_{k=1}^{S} cost_k OF_k \quad (6)$$

where $profit_i$ is the current profit of the *i*-th satellite; $profit_i^{min}$ is the minimum profit of the *i*-th satellite; $profit_i^{opt}$ is the optimal profit of the *i*-th satellite; *S* is the number of assigned applications.

Processing of applications by the orbital constellation during autonomous planning is carried out according to the following algorithm:

1. After receiving the flight assignment with a list of applications, the swarm agent sequentially processes the received applications.
2. For each application, the swarm agent sends *Call* messages to all satellite agents - potential contractors.
3. Upon receipt of the *Call* message, satellite agents calculate options for possible placement of the application, which are free time slots for operations.
4. If accommodation options are found, satellite agent responds with a *Proposal* message indicating the calculated placement options. Otherwise, the satellite agent responds with a *Reject* message.
5. The swarm agent analyzes the received *Proposal* replies and appoints co-executors for the application. This takes into account time intersections in the proposed placement options for synchronization of distributed observation. Co-executors are chosen so that the combination of their proposals maximizes the application's OF (2).
6. An *Accept* message is sent to the selected performers, indicating the exact time of operations within the application. A *Reject* message is sent to other satellites with a list of assigned executors.
7. Satellite agents who receive the *Reject* message begin negotiations with the assigned contractors in order to receive the application.
   - 7.1 During negotiations, satellite agents send a message to the executing agent with a proposal to transfer them execution of the application.
   - 7.2 The Contractor, in turn, estimates the value of the required compensation *comp*=ΔSF and sends it in a response message.
   - 7.3 The satellite agent decides whether it is possible to provide this compensation *comp*, based on its increment in the satisfaction function $\Delta SF'$. If $\Delta SF' >$ *comp*, it agrees to provide this compensation and becomes the contractor.
8. After the end of negotiations between the rejected satellite agents and the appointed contractors, their results are reported to the swarm agent to adjust the plan and synchronize it with the MCC.
9. When the moment of order execution approaches, the agents of satellites-executors perform a repeated analysis of assignment feasibility. If they cannot complete the assignment, they send a Cancel message to the

swarm agent. Upon receipt of this message, the swarm agent tries to find a new executor in the same way as in steps 2-8.

5.5 The System Testing Plan

To assess the degree of suitability of the proposed method for solving the problems of autonomous control of the satellite constellation in space, before its deployment in orbit, it is planned to conduct a number of experimental studies by simulation modeling on Earth. These studies will include the following:

1. Testing basic scheduling functions.
2. Testing the quality of the solution – to what extent is the resulting solution close to the possible global optimum.
3. Testing adaptability of event planning - analysis of the system's ability to adjust the schedule according to events in real time.
4. Testing the stability of solutions and sensitivity to events.
5. Testing the impact of the order of arrival of applications. Here, the less the final result depends on the order sequence of events, the more stable the system finds the optimum and the higher the planning quality.
6. Performance testing - analysis of system performance on a large flow of applications.

Based on the results of these studies, a decision will be made on the possibility of introducing these methods into the on-board system of real satellites or the need for their refinement. Results of experimental studies of the multi-agent system used in the ground contour are presented in (Skobelev, 2021).

6 CONCLUSIONS

The paper proposes an approach to design of an autonomous distributed multi-agent mission control system for a satellite swarm. The existing approach to planning the work of such a group is considered, the system architecture and functions of the components are proposed, and a method for planning the group work is developed.

The proposed approach makes it possible to organize both hybrid and completely autonomous planning in the satellite mesh network. Technical tasks of building a stable communication system between satellites are not the topic of this paper, but effectiveness of the proposed approach in practice depends on their successful solution.

Further studies will be aimed at practical implementation of the proposed approach within the ground control loop and orbital constellation, as well as at carrying out experimental studies directly on board the satellites. The expected systemic effect of creating the Satellite Swarm should consist in greater openness, efficiency, flexibility in executing applications, reducing the cost of solving target tasks, increasing productivity, scalability, reliability and survivability of satellite swarms of the future, as well as improving the quality and efficiency of solving the target tasks by them.

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