The formation of the target function in the design of a small spacecraft for technological purposes

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Abstract. The paper deals with the issues of forming and minimizing the target function in the process of creating a small spacecraft for technological purposes. The main difference between such a spacecraft is the need to meet specific requirements for micro-accelerations. These requirements provide favorable conditions for the implementation of gravity-sensitive processes on board a small spacecraft. The constructed objective function allowed us to determine the design appearance of a small spacecraft for technological purposes. The results of the work can be used in the design of small spacecraft.

1. Introduction
New approaches are required to create modern space technology capable of solving the most advanced technological problems. Thus, small spacecraft have significantly reduced the implementation time of space projects and significantly reduced their cost [1-3]. However, there were also new problems. Providing favorable micro-acceleration conditions for the successful implementation of gravity-sensitive technological processes for small spacecraft is a more complex task than for spacecraft of other classes [4-6].

Firstly, a different orientation and motion control system is required for long-term gravity-sensitive processes. The main executive body of such system is the flywheel motors [2, 7]. However, they require regular reduction of the kinetic moment with the help of other executive bodies. Such executive bodies were low-thrust liquid rocket engines for medium-class spacecraft [8-10]. However, studies [2, 9, 11] show that the energy of low-thrust liquid rocket engines is excessive for small spacecraft. Therefore, it is proposed to use an electrothermal micro-motor for unloading flywheel motors in [2, 12, 13].

Secondly, some perturbations that were insignificant for medium-class spacecraft have a significant impact on the micro-accelerations level of the internal environment of a small spacecraft [14-16]. Flywheel motors cannot effectively compensate for this effect. Therefore, the orientation and motion control system should have more advanced functionality. So, there are proposed some algorithms of electrothermal motor to compensate for thermal shock in [15, 17], which allow to significantly reduce the amount of generated accelerations.

Thirdly, the miniaturization of space technology leads to the fact that some methods of estimating micro-accelerations have to be refined. For example, magnetic measuring instruments are influenced by the target and supporting equipment [18-20]. The impossibility of eliminating this influence to a negligible extent due to the small size of the small spacecraft leads to the need to develop new
methods for operating measuring instruments to obtain correct estimates of micro-accelerations. Thus, a procedure for continuous monitoring of magnetic measuring instruments is proposed in [19, 21].

Thus, it is necessary to develop a new concept for designing small spacecraft for technological purposes taking into account the above-mentioned and other problems. In this paper, we solve the problem of forming an objective function that includes the mass of a small spacecraft (its layout) and the parameters of the executive bodies. Minimizing this function will allow you to choose the optimal parameters of a small spacecraft for technological purposes.

2. Materials and methods.
The fundamental method of designing small spacecraft for technological purposes is a systematic approach. In this approach, the task of choosing the optimal design parameters of small spacecraft, including the parameters of the orientation system and traffic management, providing to meet the targets taking into accounts the specifics of a small spacecraft. The mathematical formalization of this process is the solution of an optimization problem on a conditional extremum. The target function to be minimized is the mass-dimensional parameters of a small spacecraft. However, the minimization itself must be carried out within the framework of an additional condition – the fulfillment of the requirements for micro-accelerations. These requirements, in turn, impose restrictions on the parameters and characteristics of the elements of the orientation and motion control system of a small spacecraft.

The series of small spacecraft "Aist" is considered as a prototype of a small spacecraft [13, 19, 21, 22]. This series includes small spacecraft of the "Aist–1" type: flight and prototype models of the small spacecraft "Aist" [13, 16, 19, 21]. They are identical in design and equipment composition (Figure 1) and represent a small spacecraft weighing about 40 kg. The Aist series includes the Aist-2D Earth remote sensing spacecraft (figure 2) [2, 17, 22].

![Figure 1. There is an appearance of the flight sample of the small spacecraft «Aist»](image-url)
The design and layout scheme of a small spacecraft should contain solar panels since the implementation of most gravity-sensitive processes requires significant electrical power. In this case, the small spacecraft should be operated in a controlled mode [17, 22]. The main executive bodies of the orientation and motion control system of a small spacecraft are the flywheel engines (Figure 3) [2, 6, 7, 9, 22]. The electrothermal micro-motors are used in the work (Figure 4) to compensate for the kinetic moment of the flywheels, as well as to reduce the effects of temperature shock [2, 9, 12, 15].

Figure 2. There is an appearance of the small spacecraft «Aist-2D»

Figure 3. These are flywheel motors

Figure 4. There is an appearance of an electrothermal micro-motor
Thus, the formation of the target function is required to determine the design appearance of a small spacecraft for technological purposes. Minimizing this objective function under additional conditions (requirements for micro-accelerations) will allow us to determine the optimal parameters of a small spacecraft.

3. The formation of the target function.

The classical objective function is its total mass for a small spacecraft:

\[ m_0 = m_1 + m_2 + m_3 + m_4 + m_5 \rightarrow \min, \]  

where \( m_0 \) is the total mass of small spacecraft; \( m_1 \) – is the weight of corpus; \( m_2 \) – is the mass of the solar panels; \( m_3 \) is the system mass of orientation and movement control, including the mass of the working body; \( m_4 \) is the mass of the target hardware, including a lot of raw materials for the gravity-sensitive processes; \( m_5 \) is the mass of providing equipment.

A special feature of this work is the presence of additional conditions:

\[ m_2 \rightarrow \min_{P=P_{\min}}, \]  

where \( P \) is the daily electrical power generated by the solar panels of the small spacecraft, and \( P_{\min} \) is the minimum value of the daily power required for the normal operation of the small spacecraft including the operation of the target equipment.

\[ m_3 \rightarrow \min_{|\vec{w}| \leq |\vec{w}|_{\max, t \in [t_0, t_1]}}, \]  

where \( |\vec{w}| \) – is the module of micro-accelerations occurring in the internal environment of a small spacecraft in the area of technological equipment placement; \( |\vec{w}|_{\max} \) – is the maximum allowable module microgravity environment favorable for the realization of the gravity-sensitive processes; \( t \in [t_0, t_1] \) – is the period of conducting gravity-sensitive processes.

The conditions (2) and (3) are formally additional while solving the optimization problem. However, they are more important than condition (1) while designing a small spacecraft for technological purposes. It is the fulfillment of additional conditions (2) and (3) that determine the possibility and feasibility of implementing certain gravity-sensitive processes on board the designed small spacecraft [5, 9, 23].

Thus, the problem to be solved belongs to the class of variational problems for finding the conditional extremum of a function of several variables.

4. The numerical simulation.

Let us consider as a prototype a small spacecraft of the "Aist–2D" type (Figure 2). Let's simulate a situation that allows for sequential optimization of the terms of the objective function (1). Let's assume that some gravitationally sensitive process can be implemented on the target \( m_A \) mass equipment. At the same time, the initial material of the \( m_m \) mass will be required for a full-fledged technological cycle. Then \( m_4 \) from the expression (1) is defined as:

\[ m_4 = m_A + m_m. \]  

We will select the supporting equipment based on the technical characteristics of the target equipment and the features of the implemented gravity-sensitive processes. On the one hand, its
composition and weight should be minimal \((m_3 \rightarrow \text{min})\). On the other hand, it should guarantee the regular operation of the target equipment.

Further let us design power frame and the body of small spacecraft providing the location of the equipment, systems orientation, motion control a small spacecraft and terms of strength and stability. At the same time: \(m_1 \rightarrow \text{min}\). We choose the minimum mass of solar panels considering the condition \((2)\).

Thus, we will further assume that:

\[
m_1 \approx \text{const}
\]

In this case, the objective function turns into a linear function: \(m_0 = m_0(m_3)\). However, minimizing is not an easy task even in this case. It is due to the additional condition \((3)\). For example, we have the dependence shown in Figure 5 depending on the number of solar panels while maintaining the condition \(m_3 = \text{const}\).

\[
m_3 = m_1 + m_2 + m_4 + m_5 \approx \text{const}
\]

\[
m_3 + m_2 + m_4 + m_5 \approx \text{const}
\]

Figure 5. There is a dependence of the mass of the orientation and motion control system \((m_3)\) on the number of solar panels \((N)\).

The dependence shown in Figure 5 is essentially nonlinear. It is easier to provide micro-acceleration conditions with an even number of solar panels. The perturbations associated with their own oscillations are more mutually compensated with a symmetrical arrangement of solar panels. Therefore, five panels require a larger mass \(m_3\) than four.

The same situation occurs when selecting the number of executive bodies included in the orientation and motion control system (Figure 6).

Figure 6. There is a dependence of the mass of the orientation and motion control system \((m_3)\) on the number of executive bodies \((N)\).
It is possible to solve the problem of providing micro-acceleration conditions in the case of permanently fixed executive bodies on a small spacecraft if there are more than three executive bodies. The addition of the fourth and fifth only makes the orientation and movement control system heavier without increasing the efficiency of its work. If you put two executive bodies on each control channel, then the total weight can be reduced by increasing the efficiency of work. However, dependence 6 assumes perfect synchronicity of the two executive bodies. It should be considered when designing. It should also be noted that when using several executive bodies on the same control channel, most likely, the mass of m1 can no longer be considered constant. Since the placement of a larger number of executive bodies will increase the volume occupied by the orientation and motion control system of a small spacecraft.

5. Summary and conclusions.
Thus, in the first approximation, we can use the approach considered in this article when determining the design appearance of a small spacecraft for technological purposes. It consists in solving the variational problem of finding the conditional extremum of a function of several variables under additional constraints (2) and (3). In this case, the problem is significantly simplified if it is possible to consistently optimize the terms of the objective function (1) which leads to the validity of the condition (5).

The parameters of the orientation and motion control system should be selected based on the most stringent requirements for micro-accelerations in the case of implementing several processes on the target equipment.

The obtained results can be used in the design of a small spacecraft for technological purposes.

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