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THE CHOICE OF NANOSATELLITE GROUP SEPARATION PROGRAM: PROVIDING THE REQUIRED INITIAL NANOSATELLITES MOTION BY PIGGYBACK LAUNCHING

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This paper proposes the method of selection of the nanosatellites separation program from an undirected space platform at the stage of a flight task formulation. The method is based on statistical researches and provides a predetermined character relative motion of nanosatellites. The method of choosing of nanosatellites separation parameters is based on the criterion of minimizing a maximum distance between nanosatellites and with the exception of the possibility of dangerous approach. The method considered by the example of nanosatellites group separation from the orbital stage of the carrier rocket "Soyuz".

INTRODUCTION

Nowadays the number of clustered launches grows with the increasing trend of using small spacecraft, including nanosatellites (NS) of CubeSat standard. These satellites have gained popularity because their development does not require significant financial means, but allows to conduct flight tests of miniature sensors and on-board systems' elements in space conditions before applying them to expensive space missions. The launch of several NS, which jointly perform the common task, greatly extends their field of application. Orbiting of NS cluster is a complex problem that usually solves by piggyback launch from a space platform after the main payload (PL).

However, when deploying of NS clusters causes a lot of difficult scientific and technical problems. The most important problems are safe separation from the space platform, mutual collisions avoiding, holding of the NS group in a given region of space at the initial flight stage in order to minimize maneuvering during the formation of the desired configuration group.

Since there is no specialized economically beneficial light rockets for nanosatellites, it is advisable to use existing launch vehicles. The location of additional payload and its deploying should not interfere with the primary mission.

As a platform for piggyback launch of NS can be used, for example, orbital stage (OS) of launch vehicles (LV), for example, "Soyuz" or "Proton" rocket series. Usually every LV has a reserved mass of PL. There are different options of NS location in LV, for example, a transfer compartment between main PL and an OS[1].

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Orbital stages of LV usually have a low nearcircular orbit with an average height in the range of 200 to 240 km. A NS in such orbits has a short lifetime (a few days). For conducting short-term low-orbit experiments this is enough. In addition, if a NS has a propulsion system, the active life may be increased due to the implementation of the maneuver for raising the height of the orbit.

NS have limitations on mass and dimensions. That is why there is no possibility to have a large volume of fuel on board for maneuvering. As a result, for the NS cluster orbiting, which is required to keep a given configuration when they perform a joint mission, it is needed to choose such parameters of separation, which can provide required conditions of not exceeding the limit of certain distance between nanosatellites. This condition should be fulfilled on initial stages of flight (before activating of onboard systems and before maneuvering for formation of the specified relative configuration). During a few turns after NS separation, they will make the movement that is generated by initial separation conditions. So the separation parameters of the NS group (separation velocity and time) must satisfy not only the conditions to prevent collision with the platform and with each other (terms of safety), but also the limitations on mutual distance.

A MATHEMATICAL MODEL FOR FORMATION OF THE NANOSATELLITES SEPARATION PROGRAM

For formation of the nanosatellites separation program it was used a mathematical model of relative motion in orbital coordinates[2]. It describes the motion of one NS relatively to OS, moving in an elliptical orbit, in the orbital coordinates (*Oxyz*), the center of which is located in the mass center of the OS. The *Ox* axis is directed along the vector of orbital velocity, the axis *Oy* is directed along the radius-vector of the OS, the *Oz* axis complements the right coordinates. This model describes the movement of NS in the Central gravitational field with the influence of aerodynamic drag.

$$\begin{cases} \ddot{x} + 2\dot{\theta}\dot{y} + \ddot{\theta}y - \dot{\theta}^2 x + \dfrac{\mu}{R_0^{\ 3}} x = P_x \\ \ddot{y} - 2\dot{\theta}\dot{x} - \ddot{\theta}x - \dot{\theta}^2 y - \dfrac{\mu}{R^2} + \dfrac{\mu}{R_0^{\ 3}}\left(y + R\right) = 0, \\ \ddot{z} + \dfrac{\mu}{R_0^{\ 3}} z = 0 \end{cases} \tag{1}$$

where $\dot{\theta} = \dfrac{\sqrt{\mu p}}{R^2}$, $\ddot{\theta} = -2e\sqrt{\dfrac{\mu}{p^3}} \cdot \dot{\theta}\sin\theta$ – expressions for the derivatives of the angle of true anomaly; $P_x=\rho V^2 \cdot \Delta Q$ – the projection of relative aerodynamic acceleration in the transversal direction; $\Delta Q = S_b^{SP} - S_b^{NS}$ – the difference between ballistic coefficients of space platform and NS.

The orbital parameters of a space platform (θ, R, p, e), change over time and determined by simulation of the motion of its mass center in the orbit.

EVALUATION OF MAXIMUM DISTANCE BETWEEN NANOSATELLITES

In previous papers[3, 4] were obtained the parameters of nanosatellites separation, which provide safe motion with a certain probability. The separation of NS performs in a random direction from a space platform, which has a non-orientated motion around its mass center with random parameters.

However, for missions that require to launch a nanosatellites cluster to perform a joint mission, it is not always enough to provide only safety in orbit. For example, if it is needed to exchange data from one NS to another, it is required to keep a distance between them. This distance should be less than a given one and it requires a lot of energy, which typically nanosatellites do not have. In addition, after NS separation, all onboard systems cannot be activated immediately and the initial flight of nanosatellites generated by the conditions of its separation. In this case, from a set of NS separation parameters that provide a safe motion it is necessary to choose such parameters, which would not allow nanosatellites to fly from each other at relative distances longer than certain one for a desired time interval.

For this purpose, it was investigated the probability of exceeding the certain relative distance between NS for a certain time interval for different separation parameters.

The investigation was carried out with reference to the separation of nanosatellites from the orbital stage of the Soyuz LV (orbit 190 km x 240 km). The condition for exceeding the certain relative distance was checked:

$$P(r_{ij}(\Delta V_i, \Delta t_i, \Delta V_j, \Delta t_j, t) \leq r^*) \geq P^*,$$

where r_{ij} – distance between satellites; r^* – maximum distance between satellites; ΔV_i, Δt_i, ΔV_j, Δt_j – separation velocity and time of each satellite; $i=1,...n-1$, $j=1,...n$, $i>j$, n – NS quantity; $t \in [0;\infty]$ – current time; P^* – the required probability of the fulfillment of the certain motion conditions.

Dependencies of the maximum distances (d_{max}) between two NS on the separation time delay between nanosatellite are constructed. The results are given for the case of the equality of the NS's ballistic coefficients and show that with a probability of 0.997 the distance between the NSs in two turns of the flight will be less than indicated (figure 1).

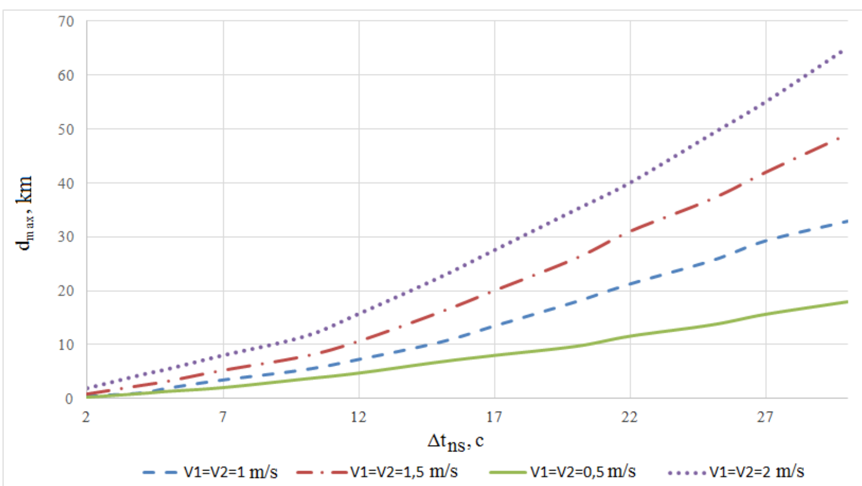

Figure 1. Dependence of the maximum distance between two NS on the separation time delay.

It can be seen from figure 1 that, for example, when two NS separate with velocity 1 m/s and with a delay 12 s, the distance between them for two turns does not exceed 10 km with a probability of 0.997.

During the research, it was found out that if two NS have different separation velocities, their spread significantly increases. As an example, Figure 2 shows the dependence of the minimum distance between NS, which will be achieved in two turns for the case of their simultaneous separation (Δt_{ns} = 0), with equal ballistic coefficients (ΔQ_{ns} = 0). The simulation results for the case of different ballistic coefficients of nanosatellites are given in paper[3].

If the difference in the ballistic coefficients and/or the separation time delay between nanosatellites increases, than increases the distance between them.

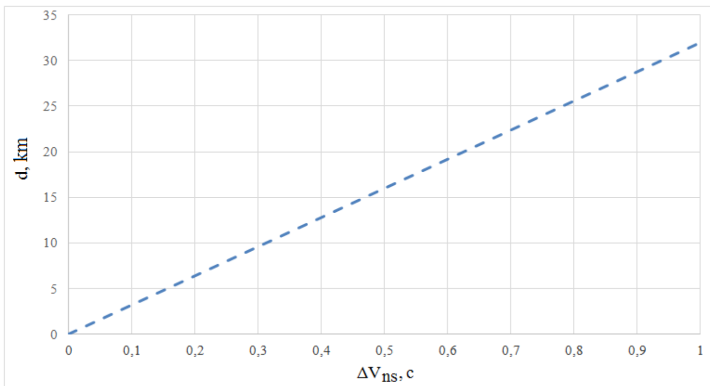

Figure 2. The dependence of the minimum distance between NS on the difference between the separation velocities of each nanosatellite.

Thus, if it is required for a mission to hold a certain distance between NS, than to save some fuel for the recovery of a certain distance it is necessary to separate nanosatellites with the same velocities and to choose such a time delay, which will provide the desired probability of a certain distance between them.

THE METHOD AND ALGORITHM OF CHOOSING A SEPARATION PROGRAM FOR NANOSATELLITES

It was developed a method for determination of separation parameters from the condition for providing the required initial nanosatellites motion. This method is intended for the formation of the program for a nanosatellites cluster separation. The method is based on a statistical study of each NS motion relative to the space platform they are separated from. The developed method consists of the following stages:

1. Determination of the set of each NS separation parameters from condition of safe motion relatively to a space platform (for example, OS) which was used for deploying.
2. Determination of the set of NS group separation parameters from the condition of safe motion relatively to each other.
3. Determination of the set of each NS separation parameters by combining of two sets obtained in 1st and 2nd paragraphs, which makes it possible to obtain a set of NS separation parameters that ensure the safety of their motion.
4. Determination of the set of each NS separation parameters from the condition of required maximum distance between NS.
5. Determination of the set of each NS separation parameters by combining of two sets obtained in 3rd and 4th paragraphs. When there is no intersections of sets (the contradiction between the requirement of flight safety and limitation on maximum relative distance), it is needed to change the limitation on maximum relative distance between NS (reduce the time interval for fulfilling the condition, or increase the maximum distance).

During the preliminary mission analysis to compose a NS group separation program, after determination of the set of separation parameters, it is suggested that the final parameters should be selected according to the algorithm given in Figure 3. It is assumed that some of the nanosatellites are part of a group, and the rest ones have independent missions.

The algorithm is based on the selection of such NS separation, which provide their minimum removal relative to each other. This is done by selecting the minimum possible delays between the separation of each NS, which can provide the safety of motion in orbit.

To finalize the NS group separation parameters from the found set, it is proposed to use the minimax criterion for the distance between nanosatellites:

$$\min_{\Delta t_i} \max_{i,j,t} r_{i-j} \left| P\left(r_{i-j}(t) \le r^*\right) \ge P^*, t \subset T, \; i>j, \; i = 1..k_n, \; j = 1..k_n, \right. \quad (2)$$

where T – certain time interval, i and j – number of each NS; k_n – NS quantity.

The application of the criterion: after determining the set of nanosatellites separation sequences (for those which are included in a group) that satisfy all necessary conditions, the maximum distances between NS are determined. As a result, it is selected a separation sequence which provide the maximum value of the distance between any pair of NS to be minimum.

As an example, it is consider the application of the developed algorithm in the case of four NS separation from the orbital stage of the LV "Soyuz". In this case, the first three of them form a cluster performing a common task, and for them it is required to provide a distance no more than 10 km in the time interval of two turns, and the fourth NS has its own mission. The nanosatellites from the cluster are separated using a typical separation device, hence the velocity of their separation is fixed.

As known from paper[5], the orbital stage after separation of the main payload performs an unoriented motion around the mass center with random initial parameters. In this regard, it is assumed that the required probability of fulfilling the claimed requirements is 0.997.

The values of the difference in the ballistic coefficients are assumed: $\Delta Q_{ns2\text{-}1}$ = 0,001 m^2/kg; $\Delta Q_{ns3\text{-}1}$ = 0,002 m^2/kg; $\Delta Q_{ns3\text{-}2}$ = 0,001 m^2/kg; $\Delta Q_{ns4\text{-}1}$ = –0,002 m^2/kg; $\Delta Q_{ns4\text{-}2}$ = –0,003 m^2/kg; $\Delta Q_{ns4\text{-}3}$ = –0,004 m^2/kg; $\Delta Q_{os\text{-}1}$ = –0,006 m^2/kg, $\Delta Q_{os\text{-}2}$ = –0,007 m^2/kg, $\Delta Q_{os\text{-}3}$ = –0,008 m^2/kg, $\Delta Q_{os\text{-}4}$ = –0,004 m^2/kg, where the indices mean the numbers of each NS.

Selected separation device provides the same separation velocity for each of the three NS forming the cluster: $\Delta V_1 = \Delta V_2 = \Delta V_3$ = 2 m/s. For the 4th NS, which is deployed separately, it was select the separation velocity of typical device ΔV_4 = 1 m/s, which provides the safe motion.

To determine the safe separation parameters, it were used the results obtained in paper[3].

Table 1. NS separation conditions.

The separation conditions, providing the safe motion of each NS in relation to the OS	The separation conditions, providing the safe motion of each NS in relation to each other	The separation conditions, providing distance between NS no more than 10 km
$\begin{cases} 5\,s \le \Delta t_1 < 60\,s \\ 5\,s \le \Delta t_2 < 60\,s \\ 5\,s \le \Delta t_3 < 60\,s \\ 5\,s \le \Delta t_4 < 45\,s \end{cases}$	$\begin{cases} \Delta t_2 - \Delta t_1 \ge 6\,s \\ \Delta t_3 - \Delta t_1 \ge 5\,s \\ \Delta t_3 - \Delta t_2 \ge 6\,s \end{cases}$	$\begin{cases} \Delta t_2 - \Delta t_1 \le 12\,s \\ \Delta t_3 - \Delta t_1 \le 11\,s \\ \Delta t_3 - \Delta t_2 \le 12\,s \end{cases}$

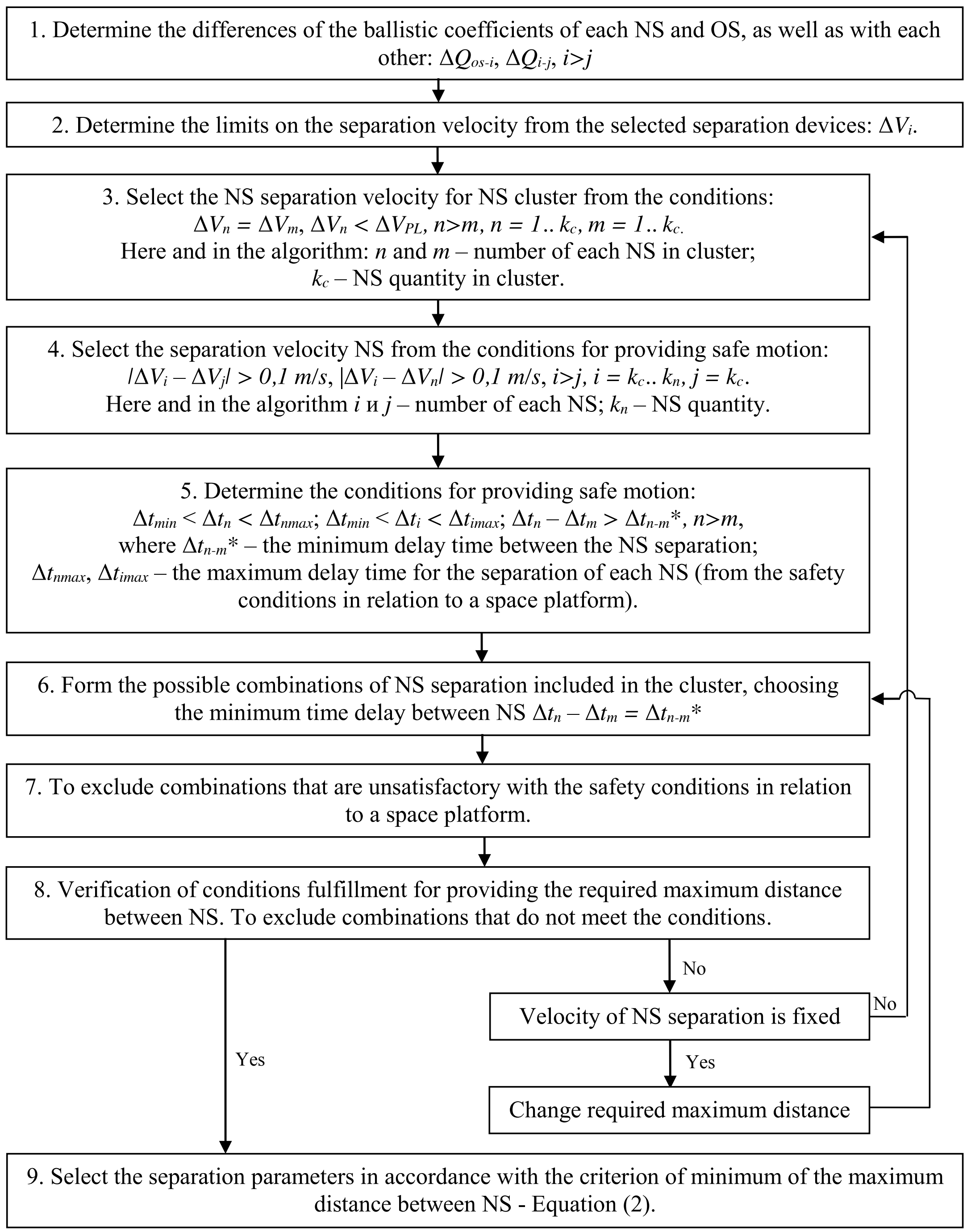

Figure 3. Scheme of the algorithm for selecting parameters for NS separation.

Applying the minimax criterion of the distance between the NS (in this case the minimum value of the maximum distance is provided with the minimum delay time of separation between each NS), we obtain: Δt_1 = 5 s, Δt_3 = 10 s, Δt_2 = 16 s.

For the fourth NS, which is not part of the cluster, the time delay must satisfy only the separation condition, which provides the safe motion of each NS in relation to the OS, so it can be deployed immediately after the cluster is separated, for example, with a delay Δt_4 = 17 s.

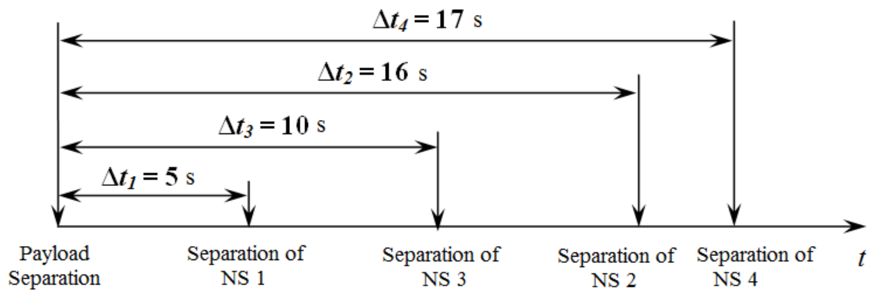

Figure 4. Example of a separation program.

The selected separation program provides safe NS motion in relation to each other and to the OS with a probability of 0.997. Also it provides the distance between three NS (that must implement a formation flight) at a distance no more than 10 km for two turns of flight.

CONCLUSION

Thus, a method has been developed for obtaining of a set of NS separation parameters, excluding the possibility of a dangerous approach of nanosatellites, taking into account the limitation on their maximum mutual distance. An algorithm is developed for selecting a program for separating the NS group from an unoriented space platform that provides a given character of the relative motion. An example of the application of the developed algorithm for the case of separation of four NS from the orbital stage of the Soyuz LV is given.

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NOTATION

x, y, z	coordinates of a NS relative to the OS in the orbital coordinate system
μ	Earth's gravitational parameter
θ	the angle of the true anomaly of space platform (current position in orbit)
R_0, R	the radius vector of the NS and the space platform
p	focal parameter of orbit
e	eccentricity of orbit

S_b^{SP}, S_b^{NS} the ballistic coefficients of a space platform and a NS

ρ atmospheric density

V upstream velocity

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