Simulation of process of small satellites separation from deployer installed on cargo spacecraft

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Abstract. A possible way to launch CubeSats is to place them in deployers installed on Progress MS cargo spacecraft. Launching satellites into orbit is potentially feasible both during Progress MS autonomous flight and during its stay in the International Space Station. In order for the CubeSats to achieve their mission targets, the separation process requires that they obtain the necessary linear velocities, the angular disturbances obtained be minimized and that the satellites continue to move without collisions. Addressing these issues involves the development of a dynamic model based on the numerical integration of motion equations. Once the model has been verified, taking into account, in addition to the permissible mass-centric and inertial characteristics of the objects, the contact interactions of satellites with the deployer guide rails and the door, a series of statistical calculations are carried out for different launch scenarios, based on the results of which a conclusion about the possibility of implementing the schemes considered is drawn and recommendations are made (in terms of dynamics) on the choice of the most appropriate layout.

1. Introduction

When planning and carrying out each space mission, special attention should be paid to the dynamics of transient processes (e.g., landing of spacecraft [1, 2, 3, 4], disclosure of elements of their construction [5, 6], separation of space rocket systems and complexes objects [7, 8, 9]).

Currently, many organizations, private companies and educational institutions are engaged in the development of small satellites (SS) such as CubeSat to address various target tasks. For many years there has been a steady demand for small satellite launch services. Frequently, SS are derived as a concomitant payload for the launch of medium and heavy class launch vehicles (LV). Every year, the number of light class LV manufacturers for launching micro- and nanosatellites grows. Nevertheless, despite the popularity of small satellites launching with the help of a LV, there are other popular ways of launching small satellites - for example, from the International Space Station (ISS) with the help of the JEM RMS manipulator and the NanoRacks launch platform. The satellites themselves are delivered to the station inside cargo spacecraft (CS). The SS can also be launched directly from the CS, which makes it possible to launch satellites into a higher or lower orbit than the ISS. Such a scheme is implemented on Cygnus cargo spacecraft.
Progress spacecraft offers an excellent opportunity to launch SS [10, 11]. One of the promising proposals is to place deployers for CubeSats on the outer surface of Progress MS spacecraft (figure 1).

![Figure 1. Possible layout scheme of deployers on external surface of Progress MS spacecraft: 1, 2, 3, 4, 5 - deployer locations.](image)

In order to control the fulfillment of the requirements on angular (less than 5.0 deg/s) and linear relative (from 0.5 to 2.0 m/s) velocities of CubeSats after separation, it was necessary to develop a dynamic model of the SS separation process from each possible variant of the deployer and conduct appropriate studies.

2. Study aims and objectives
The aim of the study was to develop an approach, dynamic model and computational algorithms to determine the values of parameters that ensure the separation of CubeSats from the deployers installed on Progress MS spacecraft with a given linear and angular velocity. In case of launch from a spacecraft docked to the ISS and not being in autonomous flight, the mandatory condition is also the absence of collisions between the separated objects and the station.

Due to the variety of possible launch scenarios, deployer versions, their location on the spacecraft and filling in different CubeSat form-factors, the main tasks were to develop a methodology for calculations and analysis of the results, to build a dynamic model of the SS separation process that correctly takes into account their interaction with the elements of the deployer, to give recommendations on the values of the parameters of the objects under study and layout.

3. Description of deployer design
The deployer is a rectangular construction, the main elements of which are a body with mechanisms, electronic switches, electric heaters, guillotines, end probes, thermometer, screen vacuum insulation and cables. Separation of the main payload from the deployer is carried out due to the mechanism of ejection consisting of a pusher plate and one or two (in case of 6U CubeSat) springs. The SS starts from the moment the command to the compartment is given. When the guillotine is triggered, the door is opened (this is the responsibility of the two springs in the hinges attached to the deployer body by means of the pivot pins). When the door is at the desired opening angle, it is fixed in place to prevent it from rebounding back. By triggering the ejection mechanism, the SS exit(s) the deployer.

4. Distinctive features of study
Although it is prohibited for the main payload to collide with CS or station (for the corresponding launch option) after leaving the deployer, satellites may come into contact with both the guide rails and the door when moving inside the deployer. This has become a key feature in comparison with the authors’ previous studies in this area.
Compared to the known works carried out earlier in this field by other researchers, a characteristic feature of the analysis described, in addition to the lack of additional means of retaining the main payload in the deployer, is the variety of design cases. CubeSats can be launched from Progress MS spacecraft, which is either in autonomous flight or docked to the ISS. There are several possible options for placing deployers onboard, types of deployers, versions of their layout. Since these deployers are not designed for a specific group of CubeSats with well-known mass-centric and inertial characteristics, it is necessary to take into account possible variations of masses, center-of-mass coordinates, and satellite inertia tensor components in the ranges set by the CubeSat standard for each size. In addition, in order to separate the satellites with a given linear velocities and the lowest possible angular velocities, it is necessary to select the most appropriate characteristics of the pusher springs (stiffness factor, free length, working stroke), torsion springs for the deployer doors, to determine the possible values of gaps between the deployer guide rails and satellites, taking into account the possible transverse displacements of the latter at the beginning of separation. These parameters are also within a certain tolerance.

5. Dynamic process modeling of CubeSat separation from deployer

To carry out the research, a model was used in which the deployer, the pusher plate of the ejection mechanism, the satellite (or a group of 1U + 2U or 1U + 1U + 1U CubeSats) and the door are represented by rigid bodies. Their movement is described by well-known motion equations

\[
\frac{d\mathbf{r}_i}{dt} = \mathbf{V}_i \\
\frac{d\mathbf{V}_i}{dt} = \sum \frac{\mathbf{F}^{(e)}_{ki}}{m_i} \\
\frac{d\mathbf{I}_i}{dt} = I_i^{-1} \left[ \sum \mathbf{M}^{(e)}_i + \sum \mathbf{M}_i \left( \mathbf{F}^{(e)}_{ki} \right) - \mathbf{\omega}_i \times (I_i \mathbf{\omega}_i) \right],
\]

where \( \mathbf{r}_i \) is the i-th body radius-vector of the mass center in the inertial reference frame, \( \mathbf{V}_i \) is linear speed of mass center, \( \mathbf{\omega}_i \) is angular speed, \( m_i \) is mass , \( I_i \) is inertia tensor, \( \mathbf{F}^{(e)}_{ki} \) - external forces, \( \mathbf{M}^{(e)}_i \) - external moments, \( \mathbf{M}_i \left( \mathbf{F}^{(e)}_{ki} \right) \) - moments from external forces acting on the body.

All the bodies of the system in question are affected by gravity force. CS (or CS + ISS bundle) may be affected by external controlled forces and moments. The door has one degree of freedom and from the beginning of the separation process until a certain angle of rotation is reached, it is opened by torsional moments and then fixed. The spring force (each of the two springs in the case of 6U CubeSat) of the ejection mechanism is calculated by the formula

\[
F_{spr} = k_{spr} (s - s_0) + f_{spr} ds,
\]

where \( k_{spr} \) is stiffness coefficient, \( s \) is current spring length, \( s_0 \) is free spring length, \( f_{spr} \) is damping coefficient, \( ds \) is spring length change rate.

If damping is not taken into account, in the first approximation, the following ratio can be used to select suitable springs that provide the main payload separation with the required relative speed \( V_r \):

\[
c \cdot k_{spr} \frac{\Delta s^2}{2} = (m + m_{plate}) \frac{V_r^2}{2},
\]

where \( m_{plate} \) is pusher plate mass, \( m \) is the main payload mass, \( \Delta s \) is full stroke of the spring, \( c \) is number of springs in the ejection mechanism.

In case of combined CubeSats separation (schemes 1U + 2U or 1U + 1U + 1U), in accordance with the standard, additional spring pushers are installed between the satellites, the spring force of which is also according to the formula (4).
There are a large number of models for the contact interaction of objects with each other. In this paper, the contact between the pusher plate of the ejection mechanism and the satellite, as well as the satellite and the door, is determined by the insertion of points on one body into the surface of the other and is considered to be a collision of objects. The contact force is represented by the sum of three components:

\[ F_{\text{contact}} = F_n + F_d + F_{fr} \]

where \( F_n \) is the force of elastic normal reaction, \( F_d \) is the force of normal damping, \( F_{fr} \) is the friction force.

Force of elastic normal reaction

\[ F_n = k_c l_c \]

where \( k_c \) is the normal contact stiffness of the interaction, \( l_c \) is the depth of contact.

Body impact consists of two phases: compression (characterized by increased contact depth) and recovery. During the compression phase, the kinetic energy of the interacting bodies passes into the potential energy of the elastic normal reaction force. During the recovery phase, the kinetic energy is partially recovered. The loss of energy is due to friction and normal damping:

\[ F_d = \chi_d(V_n) F_n \]

where \( V_n \) is projection of the rate of penetration of the point relative to the penetration surface on the normal to this surface, \( \chi_d(V_n) \) is function of the relative strength of normal damping

\[ \chi_d(V_n) = \begin{cases} \chi_1 & \text{if } k_d V_n > \chi_1 \\ \chi_2 & \text{if } k_d V_n < \chi_2 \\ k_d V_n & \text{otherwise} \end{cases} \]

where

\[ \chi_1 = \frac{(1 - c_r^2) k_e}{1 - k_e + c_r^2 k_e}, \quad \chi_2 = \frac{(c_r^2 - 1) (1 - k_e)}{1 - k_e + c_r^2 k_e} \]

are values of the relative limiting force of normal damping in the compression and recovery phases, \( c_r \) is rate recovery coefficient \((0 \leq c_r \leq 1)\), \( k_e \) is coefficient of relative energy absorption in the compression phase \((0 \leq k_e \leq 1)\), \( k_d \) is coefficient of linear transition between damping modes.

The vector of friction force \( F_{fr} \) is oppositely directed \( V_t \) - projection of the velocity of the embedded point relative to the penetration surface on a plane perpendicular to the normal to this surface.

\[ F_{fr} = k_{fr} N \chi_{fr} (V_t) \]

where \( N \) is full force of normal reaction \((N = |F_n + F_d|)\), \( k_{fr} \) is friction coefficient, \( \chi_{fr} (V_t) \) is friction force function:

\[ \chi_{fr} = \begin{cases} 1 & \text{if } k_l V_t > 1 \\ k_l V_t & \text{otherwise} \end{cases} \]

where \( k_l \) is the coefficient of linear transition between rest (friction force is equal to zero) and full inclusion of force.

As a result of taking into account all force factors in (1, 2, 3) and setting initial conditions, a system of homogeneous differential equation is formed, which can be solved by numerical integration, thus determining the position, orientation, velocities and accelerations of the bodies at any time.
6. Conducting research and analysis of obtained results

The study consisted of two stages. Initially, for various separation scenarios, a series of calculations by Monte Carlo method were carried out using the dynamic model described earlier (numerical integration was carried out by Runge-Kutta method of 4 order with a step of 0.001 s). Inside each series for 10000 calculation cases the masses of the spacecraft \( (10.0...12.0 \text{ kg for 6U; } 3.0...4.0 \text{ kg for 3U; } 2.0...2.66 \text{ kg for 2U; } 1.0...1.33 \text{ kg for 1U}) \), displacements of satellite mass centers coordinates from their geometrical centers (congruent to CubeSat standards) varied according to the uniform distribution law, and, in the range from -10% to +10% of the nominal values, the spring stiffness coefficients of the ejection mechanisms and additional pushers (for the cases with separation of 1U + 2U and 1U + 1U + 1U). Within the range 0...25% of the nominal value of the gap \( \Delta \) between the satellites and deployer guide rails, the transverse displacement of CubeSats inside the deployer also changed.

Determination of inertia tensor components for each calculation case in the series was carried out as follows. First, the inertia moments were calculated assuming that SS are homogeneous parallelepipeds of corresponding masses and dimensions

\[
I_{xx} = \frac{1}{12} k_I m (l_y l_y + l_z l_z), \quad I_{yy} = \frac{1}{12} k_I m (l_x l_x + l_z l_z), \quad I_{zz} = \frac{1}{12} k_I m (l_x l_x + l_y l_y),
\]

where \( m \) is SS mass at the current run, \( l_x, l_y, l_z \) are length, width and height of the satellite, \( k_I \) is multiplier of the inertia moments, varying by a uniform law in the range from 1.0 to 1.2.

Then the inertia tensor was recalculated from the geometric center of the SS to its center of mass by the formula

\[
I_C = I - m (r_C^2 E - r_C r_C^T),
\]

where \( I \) is initial inertia tensor, \( I_C \) is recalculated inertia tensor, \( r_C \) is radius-vector from the center of mass of the satellite to its geometric center for the current calculated case, \( E \) is unit tensor.

The uniform law was chosen in order to get more “extreme” values, as the variants with the most unfavorable possible conditions of separation were of the greatest interest. For the same reason, damping of the springs of the ejection mechanisms and additional pushers was introduced into the model.

The result of a series of such calculations was a set of files with initial values of variable parameters for each calculation case and implemented trajectories of the CubeSats relative motion, their angular and relative linear velocities at the time of exit from the deployer. These sets were used at the second stage of the study, which consisted in statistical processing of the obtained data and construction of tubes of trajectories of the separated objects.

As an example of the results obtained in the course of the second stage of the study, figure 2 shows graphs of 6U CubeSat angular and relative linear velocity distribution functions for one of the possible cases of the deployer on Progress MS spacecraft, which is in autonomous flight, after leaving the deployer.

7. Conclusion

The research made it possible to determine the suitable characteristics of the deployer design elements and layout of the CubeSats in it. In particular, to avoid collisions between satellites when separating in combinations of 1U + 2U, 1U + 1U + 1U, it is necessary to place the CubeSats in the deployer in ascending order of mass so that the most massive satellite was the first to leave the deployer. The value of gaps between the deployer guide rails and satellites with the working stroke of the springs of the ejection mechanisms have strong influence on the realized angular velocities of the CubeSats.
The analysis of the results also showed that in the whole range of initial conditions the SS exit from the zone of CS and ISS structural elements (under the corresponding scenario) occurs without impact with a relative linear velocity, located within the required range.

For the initially designed gaps between the deployer guide rails and satellites, 3U and 6U angular velocities do not exceed the maximum permissible values at the moment of exit, but for smaller standard sizes this condition is not met in all cases, and therefore it may be necessary to reduce the gaps, introduce more stringent restrictions on the SS data alignment or soften the requirements for angular velocity.

The model developed will be useful for the CubeSat developers. For example, it could be supplemented by aerodynamic forces and moments and the inclusion of the SS control systems, which would allow the movement of specific satellites to be investigated after separation to meet orientation, stabilization and communication objectives.

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