DCAP: ASSESSMENT OF A MULTI-PAYLOAD INSERTION PROBLEM BY MEANS OF MULTIBODY DYNAMICS

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ABSTRACT

The demand for a competitive swift deployment of future large constellation of satellites is driving the space industry to find attractive solutions to move from a single customer – single payload proposal toward a versatile single launch of larger number of satellites.
Deploying multiple small satellites and cubesats on multi-manifest missions requires unprecedented attention to mission design by the spacecrafts' and launchers' industries.
Since 2001, the European Space Agency (ESA) has been developing specific multibody flight dynamics simulation features, able to address a wide variety of satellites and launchers coupled interaction and control problems at system level. These features are made available in the Agency's Dynamic and Control Analysis Package software (DCAP).
This paper offers a showcase analysis, supporting the early definition of a multi-payload orbital insertion problem.

1. BACKGROUND

Deploying multiple satellites and cubesats from a single payload dispenser offers unprecedented challenges to the whole mission design, spanning a large spectrum of disciplines:

- detailed mission design and flight software development;
- technical, performance and operational constraints for the launch vehicle and the satellites commissioning;
- integration management, logistics, and facilities support infrastructure;
- multi-customer contracting;
- regulatory approvals.

While the contractual and business management aspects are beyond the scope of this work, the paper will focus on the more mechanical technical aspects typical of a preliminary study:

- investigate the sensitivity of the dispenser's constrained layout with respect to the disengagement phase of the spacecrafts;
- evaluate the suitability of commercially available separation mechanism systems to the new application;
- analyse the separation dynamics identifying the minimal clearance during the disengagement and the system critical requirements for the dispenser configuration;
- propagate the deployed satellites orbits and define collision avoidance scenarios;
- assess the suitability of the current on-board software capability and anticipate the need for evolutions.

2. DCAP SOFTWARE

2.1. Heritage

Since the early 1980s, DCAP has been progressively developed by the European Space Research and Technology Centre (ESTEC) through several industrial contracts with Thales Alenia Space Italy (TAS-I) in Torino. Since 2014, ASTOS Solution GmbH has taken the lead on the software development and commercialization, with partial contribution from ESA, as summarised in Fig. 1.

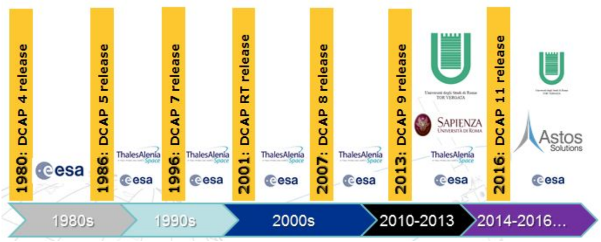


Figure 1. DCAP development: major milestones

With almost 40 years of space heritage, DCAP is regarded by the European space community as an independently-coded, alternative benchmark for highly reliable cross-validation of space dynamics simulations.
DCAP, which originates from NASA's DISCOS code, has become a no-frills, rational, fast multibody program designed for the dynamic simulation and stability analysis of passive and actively controlled space systems and devices.
This software [3] is a suite of fast, effective computer programs that provides the user with capabilities to model, simulate and analyse the dynamics and control performances of coupled rigid and flexible structural systems subjected to possibly time varying structural characteristics and space environmental loads.
By means of dedicated interfaces to other specialised

software, it enables reproducing most of the key subsystems and disciplines (such as configuration, structures, mechanisms, aerodynamics, propulsion, GNC, trajectory, scenarios,...) of the launcher in a seamless simulation environment [2].
The simulator has been also tuned for tackling specific complex events [6], such as multi-payload separation dynamics, thrust vector control subsystem studies, lift-off analysis, general loads, as shown in Fig. 2.

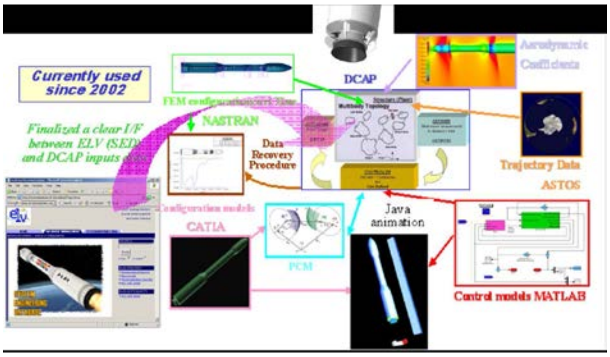


Figure 2. ESA launcher multibody dynamics simulator: general overview

2.2. Dedicated features

When it comes to design and simulate a multi-payload separation scenario with a complex configuration of moving parts, maximising user-friendliness becomes a mandatory key aspect in selecting a software tool.
Lesson learnt from previous programs identified the ability for different experts to separately collaborate inside a consistent model framework and the possibility to parametrise the system's critical design features, as the most important missing features in DCAP. In the software GUI, these two features are called:

- Sub-modelling;
- static variables.

The capability to import a slave model into a master scenario is called sub-modelling. This feature introduces a new concept of designing a multibody system. A detailed self-standing model of a mechanism can then be designed once, and used in several master projects by importing it as a slave model, as shown in Fig. 3.

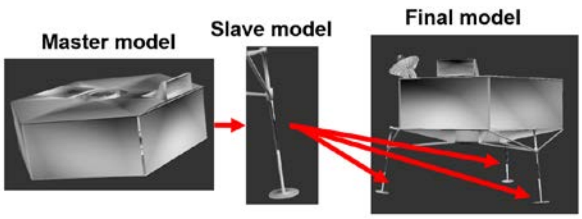


Figure 3. Master and slave models

Once the sub-model feature is activated in the DCAP GUI, the slave model definitions are copied in the DCAP master model files. The link is indeed completely static which ensure that the resulting model does not depending on any external dependency.
Since the release of DCAP 11.3, the user is allowed to create and link variables in the GUI. This property is called static variables and allows to associate several input fields of different model properties to the same numerical value.
In such a way by changing only one parameter, the GUI automatically spreads the modification to any feature which makes use of that static variable.
By using the main static variables panel, the user can easily manage the linked properties and the actual numerical values. This feature drastically reduces redundant inputs and collects the most important number in an easy-to-access summary panel.

DCAP is also able to account for the component flexibility. Even if the Finite Element Models (FEM) produce high accurate results, they are time consuming to build and to customize. A fast and simple solution is usually the best way to go, especially in the first project phases.
DCAP embeds a linear Euler-Bernoulli flexible beam model which can be used without the need of any external FEM software. Since DCAP release 11.3, the user can consider bending, axial and torsional flexible modes. Fig. 4 reports the axial and torsional mode frequencies computed by DCAP and by NASTRAN NX.

Modes	DCAP [Hz]	Reference Value [Hz]	NX Nastran [Hz]
#1 Torsional	77.244	77.540	77.840
#2 Axial	125.000	125.000	125.500
#3 Torsional	231.730	233.100	241.200

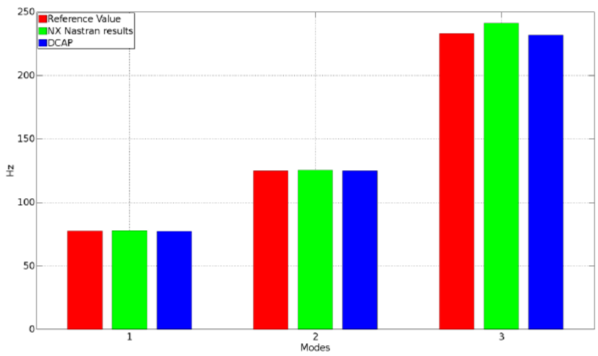


Figure 4. Benchmark of the torsional and axial modes between DCAP, NASTRA NX and reference computations

3. PAYLOAD INSERTION SHOWCASE

3.1. Heritage

DCAP has extensive heritage in supporting ESA projects [5]. Regarding payload separation and satellites orbit insertion predictions, the simulations for the

SWARM Project and the GALILEO Project included the long term trajectory propagation in order to verify the risk of collision before commissioning.
Swarm is a ESA mission launched in 2013, with the aim to study the Earth's magnetic field. The Swarm constellation consists of three satellites, placed in different polar orbits, two flying side by side at an altitude of 450 km and a third at an altitude of 530 km, see Fig. 5. The SWARM deployment mechanism is rather complex, involving pyronuts, push-and-roll hinges. DCAP analysis have been used to design the deployment mechanism and to simulate the trajectories of the three satellites after the separation in order to avoid any collision.

Figure 5. SWARM satellites impression. Credits: ESA/CNES/ARIANESPACE

GALILEO is the European constellation of satellites providing an alternative global navigation system.
The programmatic and economic necessity to deploy multiple spacecrafts in a single launch triggered the use of DCAP in assessing a number of feasible launch configurations. Fig. 6 exhibits to of the effectively executed scenarios.

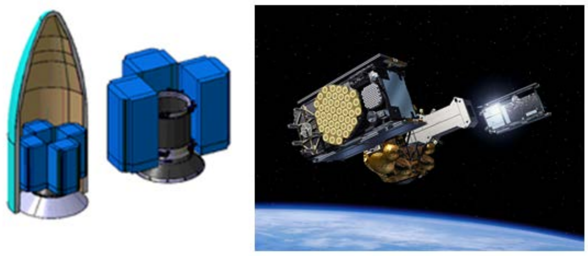


Figure 6. Galileo satellites mated in Ariane5 and Soyuz configurations. Credits: ESA/CNES/ARIANESPACE

3.2. Small Satellites Mission Service dispenser analysis

The new versatile Small Satellites Mission Service (SSMS) dispenser allows VEGA launcher to deploy multiple light satellites. It is composed by a lower module suited to accommodate 6 Smallsats up to 70 Kg and/or Cubesat deployers, typically 12 units able to carry 12U Cubesats each and a versatile upper part (composed by a platform and 3 or 4 lateral towers and a central column) available in several modular configurations. In its configuration tagged FLEXI-4 (featuring 4 lateral towers), the SSMS dispenser can host 9 Smallsats.

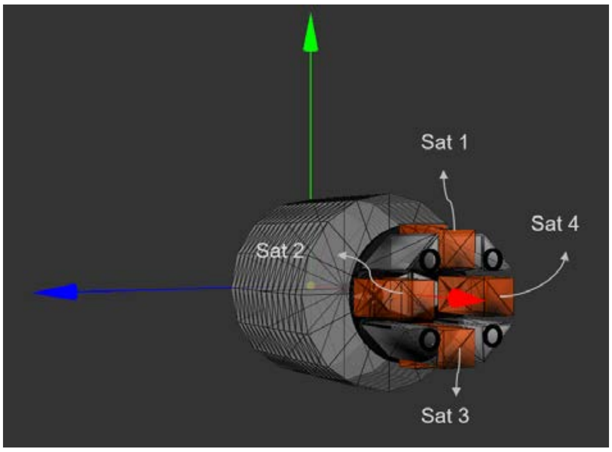


Figure 7. Four satellites mounted on the SSMS structure

The SSMS dispenser provides launch opportunities for light satellites with an overall mass ranging from 1 kg CubeSats up to 400 kg minisats. The SSMS modular design allows different alternative configurations and combinations of various payloads.

DCAP is employed to perform a clearance analysis during satellite deployment. The separation of each satellite affects the overall system attitude and generates centrifugal forces. This investigation has the objective to check for undesired contacts between the satellites and the dispenser body.
For analysis purposes four satellites are considered as payload of the SSMS.
The dispenser consist of a lower module, fixed directly to the Payload Adaptor (PA), and 4 tower modules. The VEGA upper stage AVUM is also part of the model due to its inertial influence during the separation.

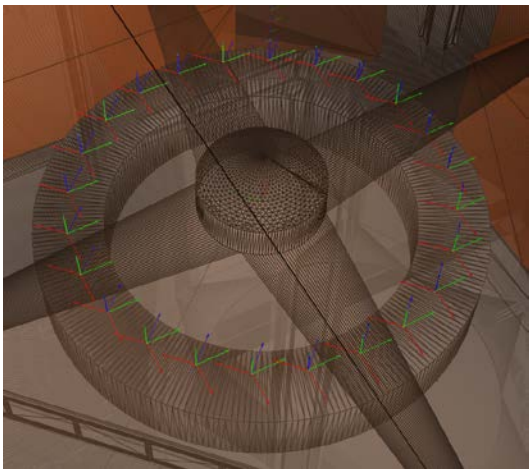


Figure 8. Springs located on the clamp band diameter

The satellites are attached to the lower module among the towers, as shown in Fig. 7, via light clamp band devices. These devices consist of several springs placed along a circumference [4], see Fig. 8. Once the satellite is released, the springs push the payload away from the dispenser.

The new DCAP 11.3 features allow a fast system modelling:

- global stiffness and damping values are defined as static variables for all the springs in every clamp band;
- since the clamp band device is a self-standing model, the user can model it separately as slave model, and then import it as many times as needed in the final SSMS assembly scenarios.

The separation timing and the number of springs for each satellite clamp band are chosen in order to minimize the movement of the dispenser and to increase the clearance between the satellites and SSMS structure during the separation. Tab. 1 reports the number of separation springs and delay time for each satellite.

Table 1. Number of clamp band springs and separation delay for each satellite

Satellite	Number of springs	Separation delay [s]
1	24	1
2	16	5
3	12	3
4	6	7

In order to check that no collision occurs during the separation, 8 sensors are defined to measure the distance between the SSMS dispenser body and the satellite envelope lower corners. The most critical part of the dispenser body is indeed the rod connector, which is located in the top part of each tower module, as shown in Fig. 9.

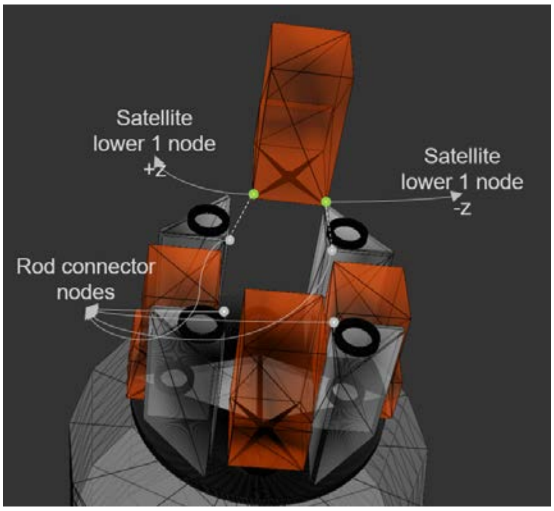
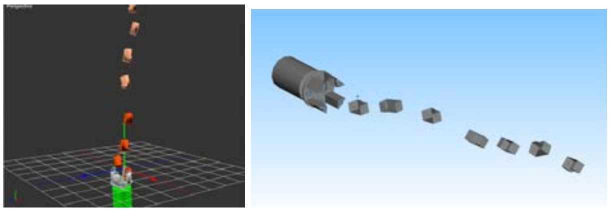


Figure 9. Clearance between the lower satellite envelope corners and the SSMS rod connectors

The final multibody model consists of 7 bodies (AVUM, PA, SSMS and 4 satellites), 58 elastic elements and 4 transition time logic triggers to release the payload.

3.3. Model validation and benchmarking

Due to the obvious absence, this early in the Project development phase, of hardware test data against which validating the DCAP predictions, an initial benchmark case is created, where the same model is constructed in DCAP as well as in another independent commercial software (SIMPACK is selected). In this case, it was decided to simulate the highest payload capacity case, where the Smallsats rigid bodies are accommodated on two decks (Fig 10) and sequentially deployed.



(a) (b)

Figure 10. Multi-satellite benchmark model: (a) DCAP, (b) SIMPACK

The trajectories of each body are registered in the global inertial frame and compared between the two software tools. As expected, the DCAP results (Fig. 11) well match the SIMPACK predictions (Fig.12).

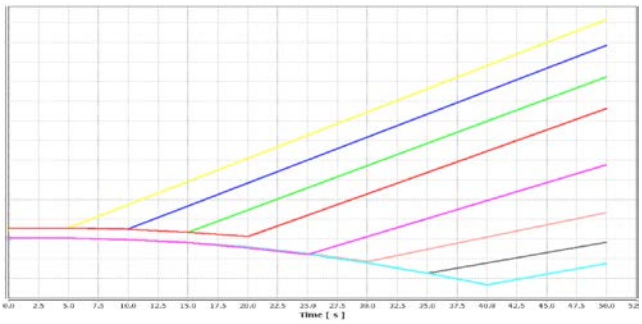


Figure 11. Multi-satellite benchmark model: DCAP results

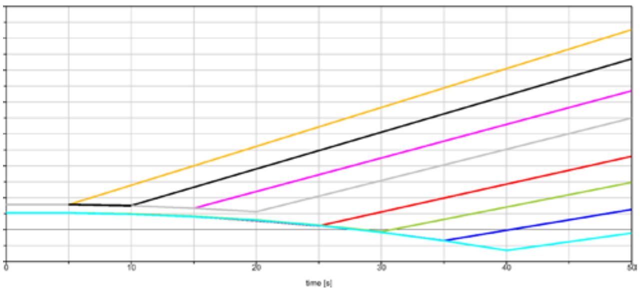


Figure 12. Multi-satellite benchmark model: SIMPACK results

The only main difference is detected in the trajectories of the lower deck satellites. After further investigation, the root cause was identified in a small difference in the coding of the release spring forces: DCAP force vector is coded to push perpendicular to clamp band plane, while the SIMPACK standard spring acts as a point-to-point force. When the mass ratio between the dispenser and the released payload reduces, the relative rotation experienced by the dispenser as result of the acting separation force increases, emphasising the trajectory discrepancy. This root cause was finally confirmed by creating a simple 2 bodies model connected by point-to-point spring forces and the results were matched with the analytical solution.
Because the DCAP clamp band representation corresponds exactly to the physical scenario, no modifications to the model is introduced before progressing with the final simulation campaign

3.4. Simulation campaign results

The DCAP multibody simulation has proved that no collision occurs during the satellites separation and a safe clearance of minimum 10 cm is guaranteed between the satellite envelopes and the SSMS dispenser body.
Fig. 13 shows the distance between the two lower satellite envelope corners and the corresponding rod connector nodes on the dispenser side.

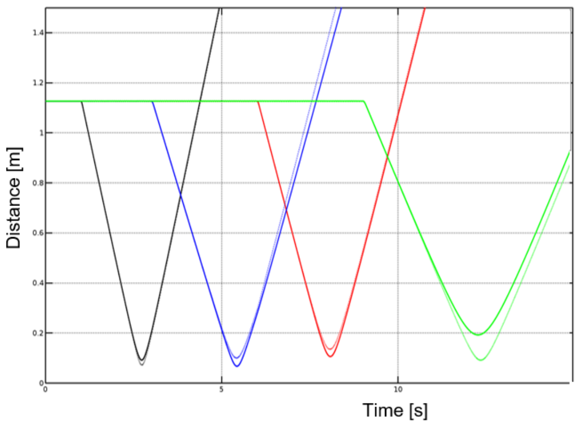


Figure 13. Clearance between the rod connectors and the lower corners of every satellite

Each colour in the graph corresponds to a different satellite. After the separation, the payload and the dispenser gets closer but within a safe clearance. When the entire satellite envelope overcomes the dispenser tower module, there is no possibility for any other collision.

4. CONCLUSIONS

DCAP is a multibody software specifically design to tackle space applications such as ascent launcher scenarios, payload separations and space mechanisms design, with extensive heritage in supporting ESA Projects.

The improved user-friendliness enabled to swiftly model the SSMS dispenser, thanks to the new features of the DCAP 11.3 release. The technical performances and prediction accuracy capabilities of the software have been validated against an independent commercial tool (SIMPACK): DCAP confirms to be an efficient and practical technical support tool for the simulation of complex system dynamics problems as well as in the preliminary phases of space mechanisms design.

5. REFERENCES

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