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# Flexibility issues in discrete on–off actuated spacecraft: Numerical and experimental tests ☆

Paolo Gasbarri [a], Marco Sabatini [b,*], Nazareno Leonangeli [b], Giovanni B. Palmerini [b]

[a] DIMA, University of Rome "La Sapienza", Italy
[b] DIAEE, University of Rome "La Sapienza", Italy

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ABSTRACT

Spacecraft are often characterized by the presence of large appendages with very low natural frequencies. Control strategies of such systems must necessarily take the rigid–flexible dynamics interaction into account. In particular, an unstable behavior can occur when important characteristics of a real control system, such as the time delay affecting the navigation and control loop, are considered. In fact, it is possible to show that the stability delay margins can become insufficient, and the maneuver, that can be aimed to change the platform attitude or just to damp the elastic oscillations, fails. In the present work, this problem is solved by compensating the time delay by means of a model-based prediction algorithm. A free floating platform is used to test the navigation, control and delay compensation algorithms, confirming the soundness and the robustness of the approach.


## 1. Introduction

The light-weight requirement of space structures, necessary to save mass at launch, together with the need of very large surfaces (for example for solar arrays or telecommunication antennas), can lead to highly flexible systems. This characteristic causes a serious challenge when a control must be applied in order to re-orient the platform, or to compensate the effects of orbital perturbations (see Refs. [1,2]). In fact, flexibility brings unwanted oscillations that may lead to resonance conditions if they interact with control actions; this is especially true when dealing with space systems (see Refs. [3,4]).

Many researchers have been facing this problem, and different solutions have been proposed. Active structural damping, performed by piezo-electric sensors and actuators (PZT), is certainly an interesting approach, that has been studied both for simple structures [5] and for complex multibodies [6]. In Ref. [7] a positive position feedback controller is implemented for regulating via PZT the first mode of vibration of a two-link multi-body experiment; also in Ref. [8] a positive position feedback is considered for the control of PZT in the case of a spacecraft formed by a hub with a cantilever flexible beam appendage.

However this approach, though effective, has some drawbacks. First of all, it is necessary to distribute a net of PZT with relevant harness, and to power them. More importantly, these actuators are not efficient when very low natural frequencies are involved [9].

A different strategy consists in modifying the reference trajectory that the control should track, in order to reduce its influence on the elastic dynamics. A well-known technique in this sense is the command shaping technique [10], which

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* Corresponding author.
*E-mail addresses:* paolo.gasbarri@uniroma1.it (P. Gasbarri), marco.sabatini@uniroma1.it (M. Sabatini), nazareno.leonangeli@gmail.com (N. Leonangeli), giovanni.palmerini@uniroma1.it (G.B. Palmerini).

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is based on the fact that the vibrations exhibited by most systems can be characterized by one or more frequencies excited by the motion transient. Using this information, it is possible to generate a modified command signal that will move the system at the maximum rate possible, without exciting vibrations. In Ref. [11] a fast attitude maneuver has been simulated in the case of a flexible spacecraft, and the results show that the introduction of a proper shaping of the input trajectory greatly reduces the elastic oscillations.

A combined strategy can also be adopted, i.e. actively increasing the structural damping via PZT devices, and shaping the command to reduce the flexible dynamics excitation [12]. Ref. [13] presents a vibration control strategy for a flexible manipulator with a collocated piezoelectric sensor/actuator pair. The proposed vibration controller combines the input shaping technique with a multimode adaptive positive position feedback.

In these cases, however, the problem that real systems suffer from a time discretization and a time delay in the control application is not directly faced. In actual applications, in fact, the sensors and the actuators are characterized by a maximum working frequency, and therefore the measurements and the control commands are updated at a given sample time. This time discretization lowers the stability delay margins of the system. This means that if the system is characterized by a non-negligible time delay between the control evaluation and the control actuation, the controlled flexible platform can become unstable; the amplitude of the elastic vibrations grows and the desired attitude is not acquired.

This is the case we want to study in this paper, first theoretically, and then experimentally, by means of a free floating platform with flexible appendages. Since elastic oscillations of the panels play an important role, a device for measuring these oscillations is included. As already proposed in previous works, a video system is a good tool for measuring the flexible behavior of a structure. In Ref. [14], this contactless measurement system is deemed to provide displacement data for a beam with a single transducer. In Ref. [15] a similar device is used to control the flexible displacement of a beam tip; in order to obtain more precise information of the tip point location, a camera is used to get a vision feedback where the delayed vision signal is compensated by the state estimator and predictor. In these works, however, (a) the structure is considered as an independent body, and (b) the delay compensation is used to improve the performance (i.e. reducing the overshoot), and not for recovering the system from an unstable condition. The scope of the present work is instead to focus on the stability recovery of a “space-like” free floating multibody system, composed by rigid and flexible parts, giving experimental evidence for the performance of the proposed delay compensation technique. The technique will be applied to attitude control and elastic vibrations damping, in a condition in which the system would be unstable if no delay compensation was implemented. In Section 2 the experimental setup is presented and in Section 3 two mathematical models (a nonlinear one and a linear one) are derived for the flexible multibody platform. The accuracy of the models is tested in Section 4. In Section 5 the control torque is used to damp the flexible vibrations, while in Section 6 the scope is to re-orient the platform attitude. In both cases, simulation results are validated by an experimental campaign, where the soundness of the delay compensation approach is confirmed.

## 2. The PINOCCHIO platform

In this paper the flexible multibody system to be controlled is represented by a free floating platform, Platform Integrating Navigation and Orbital Control Capabilities Hosting Intelligence Onboard [16] (PINOCCHIO), designed and built at the GNC Lab in University of Rome “La Sapienza”. The platform replicates the behavior of a spacecraft with attached flexible appendages, even if limited to the case of a single axis rotation. This is possible thanks to an air bearing which almost completely cancels the sliding friction out, so that the platform has actually three rigid degrees of freedom (two translations and one rotation) augmented by the (theoretically infinite) elastic degrees of freedom. In this paper we will focus on the interaction between *attitude* and *flexible* dynamics due to the control actuation, that is performed by means of on–off thrusters. At the scope, the platform is equipped with sensors dedicated to the rigid attitude motion (attitude and angular velocity) and to the flexible displacements, via a vision based technique that will be explained in Section 3.

Fig. 1 shows a picture of the experimental setup, with the central bus on the flat working plane and the two flexible appendages. These structures have been designed so that their natural frequencies are very low, in order to simulate the behavior of large space structures, such as solar wings. Of course there are scaling problems to face, since too large panels would not fit the PINOCCHIO platform. The design of the panels has been performed taking these requirements (low natural frequencies and reduced dimensions) into account. The aluminum rectangular panels (500 mm long, 100 mm wide and 1 mm thick) are lightened by means of rectangular holes with rounded corners, whose dimensions can be seen in Fig. 2. By removing the mass of the holes, we have achieved a reduction on the structural rigidity of the plates and, as a consequence, a reduction on their natural frequencies of vibration. The eigenfrequencies

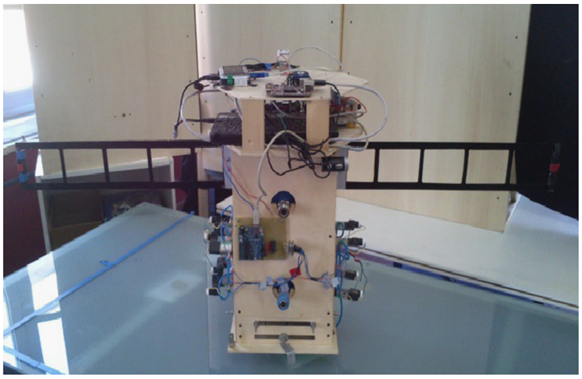

**Fig. 1.** Picture of the free-floating platform, with the central rigid bus and the two symmetric elastic panels.