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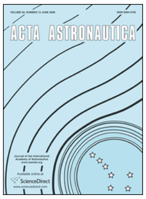

Analysis and experiments for delay compensation in attitude control of flexible spacecraft[☆]

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ABSTRACT

Space vehicles are often characterized by highly flexible appendages, with low natural frequencies which can generate coupling phenomena during orbital maneuvering. The stability and delay margins of the controlled system are deeply affected by the presence of bodies with different elastic properties, assembled to form a complex multibody system. As a consequence, unstable behavior can arise. In this paper the problem is first faced from a numerical point of view, developing accurate multibody mathematical models, as well as relevant navigation and control algorithms. One of the main causes of instability is identified with the unavoidable presence of time delays in the GNC loop. A strategy to compensate for these delays is elaborated and tested using the simulation tool, and finally validated by means of a free floating platform, replicating the flexible spacecraft attitude dynamics (single axis rotation). The platform is equipped with thrusters commanded according to the on–off modulation of the Linear Quadratic Regulator (LQR) control law. The LQR is based on the estimate of the full state vector, i.e. including both rigid – attitude – and elastic variables, that is possible thanks to the on line measurement of the flexible displacements, realized by processing the images acquired by a dedicated camera. The accurate mathematical model of the system and the rigid and elastic measurements enable a prediction of the state, so that the control is evaluated taking the predicted state relevant to a delayed time into account. Both the simulations and the experimental campaign demonstrate that by compensating in this way the time delay, the instability is eliminated, and the maneuver is performed accurately.

1. Introduction

Large space structures are often characterized by high flexibility and very low natural frequencies, generating serious problems for controlled systems, in terms of accuracy or even in terms of stability. For example, rapid attitude maneuvers of a large spacecraft can cause large oscillations of its flexible appendages. To reduce such vibrations, different approaches can be followed, namely changing the elastic properties of the structure (increasing the stiffness or the damping coefficient), adjusting the reference signal to track, or accurately tuning the controller gains.

If the flexible deformation is considered not just as a disturbance, but as part of the state to be controlled, then we are in presence of an underactuated system, i.e. a system with fewer inputs (in our case: the control

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torques) than degrees of freedom (attitude and flexible displacement). A theoretical framework for the dynamics and control of underactuated mechanical systems can be found in Ref. [1]. A possible solution [2] considers the partition of the dynamics equation into slow and fast modes, based upon the singular perturbation theory. However, the decomposition into slow (rigid) and fast (flexible) dynamics cannot be a reasonable hypothesis in some cases, and moreover the controller could not be able to act sufficiently fast.

In fact, control systems often operate in the presence of delays, primarily due to the time it takes to acquire the information needed for decision-making, to create control decisions, and to execute these decisions [3]. These delays deteriorate the regulation, thereby causing a performance decrease. A theoretical and experimental work [4] demonstrated that time delays are a major cause of instability in such highly flexible systems. An extensive literature exists on the compensation of time delayed processes [5].

In this paper, we use a model-based predictor to compensate for the time delay and return to a stable system. In fact, if the aim is to improve the control accuracy while minimizing residual vibrations of the system, the so called command shaping method is a meaningful choice, as shown by many authors [6–9]. However, this technique does not seem to be decisive in the case in which the time delays are so high that the delay margin of the system is not respected. This is actually the case that this work aims to analyze, both theoretically and experimentally. At the scope, a free floating platform, equipped with very flexible appendages, is used to perform a fast attitude re-orientation maneuver. The control parameters are selected so that the system is theoretically (and practically) unstable, due to the on–off thrusters interaction with flexible dynamics of the panels, leading to a failing maneuver.

The flexible panels vibrations are observed in real time thanks to a dedicated camera, fixed on the platform bus. An imaging device is indeed an interesting tool for measuring the flexible deformation [10]. This contactless measurement system is able to provide the digitalized displacement, in particular of the panel tip.

These data are used not only to sense the effects of the control on the structure, but also to compensate the system time delays. In fact, once an accurate model of the flexible floating platform has been realized, the measurements (relevant to the attitude, to the angular rate and to the flexible displacement) allow to estimate the system state vector at the current time, and to predict the state at a certain following time (according to the expected system time delay). If the control is evaluated taking this predicted state into account, it will be applied in a delayed time on the basis of the corresponding delayed state, thus solving the instability problem.

This paper shows that, beginning with a reasonable estimate of the system characteristic delay and developing an accurate mathematical multibody model, it is possible to perform a successful attitude re-orientation, without changing the controller gains or the reference trajectory, by just including a state prediction for compensating the time delays. These results have been found numerically and confirmed by the experimental campaign. A limit that is often underlined about model-based predictors, i.e. the sensitivity to model inaccuracies, has also been analyzed, showing the robustness of the approach with respect to poor knowledge of the system time delay.

2. The PINOCCHIO hardware and software architecture

Platform Integrating Navigation and Orbital Control Capabilities Hosting Intelligence Onboard (PINOCCHIO), represented in Fig. 1, consists of a 10 kg central bus, accommodating different subsystems and the pressured air tanks, plus a couple of symmetric panels, purposely designed for reproducing a light weight flexible structure, such as solar wings (see Ref. [11] for more details). The air bearing, which allows the frictionless motion over the flat surface, and thrusters' nozzles are connected to the tanks by rubber pipelines. In particular, the airflow of the bearing is continuous and regulated at 2 bar pressure, while the airflow from the thrusters is controlled by on–off electrovalves, at a pressure of 3 bar.

All the maneuvers of the platform are performed thanks to these on–off actuators, which supply the required forces and torques, according to the commands sent by the Central Process Unit (CPU). This 1.6 GHz main processor, belonging to the class Atom Intel, manages the communication with all the sensors and actuators, and computes the reference trajectories and the required actions to be performed. As shown in Fig. 2, sensors' set includes an Inertial Measurement Unit (only the gyro will be actually used in this work), and two cameras. One of the cameras, called “attitude camera”, supplies attitude measurements by processing particular features on the laboratory ceiling (such as a coarse star tracker), completing the set of gyro measurements; the second camera, called “flexibility camera”, is instead pointed at the panels, for detecting and measuring their elastic displacements.

The vision based technique for identifying the elastic characteristics of a structure calls for the determination of the time behavior of special points (features) that can be easily tracked by optical devices. In the present case these features are represented by a red colored mark (about 1 cm^2 area) on the middle of the panel tip, as visible in Fig. 3. More details about the vision based technique can

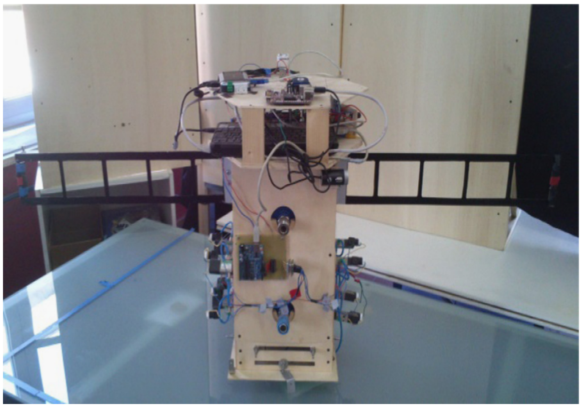

Fig. 1. Picture of the PINOCCHIO bus completed with flexible appendages.