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Delay compensation for controlling flexible space multibodies: Dynamic modeling and experiments

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ABSTRACT

The problem of controlling a spacecraft with large flexible appendages, such as solar wings or antennas, can be further complicated by the presence of time delays in the navigation and control loop, that can cause an increase in the elastic oscillations. If the delay margins are insufficient, the system is unstable, and a dangerous interaction between flexible dynamics of the appendages and rigid dynamics of the bus can arise. This paper proposes a model-based compensation of the time delay for the control of such systems. At the scope, the dynamic equations of a flexible multibody system are derived, and tested against a commercial code. The proposed algorithm for avoiding the unstable behavior is first numerically tested, then experimentally verified by means of a free floating platform equipped with highly flexible appendages. One of the most critical aspects of this kind of approaches, i.e. the robustness with respect to uncertainties on the system characteristics and on the knowledge of the actual time delay, is finally tested by μ-analysis and verified by means of a Monte Carlo approach.

1. Introduction

The control of large space structures can be seriously affected in terms of accuracy or even of stability, because of the high flexibility and the very low natural frequencies of the involved structures. Different solutions have been proposed to face the problem, ranging from the active structural damping to the design of ad hoc guidance trajectories. Piezo-electric (PZT) sensors and actuators have been suggested for vibration suppression of many different structures, from the cantilever beam to complex multibody systems (Li & Bainum, 1994; Denoyer & Kwak, 1996); the main drawback of this approach is the need to include additional electronic devices, with relevant power consumption and risk of failures; moreover, the performance of PZT devices decreases with the natural frequency of the structure, while space structures are often characterized by very low frequencies (Balas, 1979). A different strategy, that does not require the inclusion of specific hardware, consists in shaping the nominal trajectory to be tracked in such a way that the command signal moves the system at the maximum possible rate, without exciting vibrations (e.g. input shaping technique (Hong, Huh & Hong, 2003; Singhose, 2009; Singhose, 1996).

The real applications should also tackle hardware implementation problems, that could decrease or destruct the expected performance. A key-point in the implementation is the fact that 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 (Sipahi, Niculescu, Abdallah, Michiels & Keqin, 2011). This characteristic is not taken into account in these cited works and it is the focus of the present one. A theoretical and experimental work (Sabatini, Palmerini, Leonangeli & Gasbarri, 2014) demonstrated that time delays can be a major cause of instability in highly flexible systems. Also (Alazard, Loquen, de Plinval & Cumer, 2013) highlights that the transmission delay of the avionics can raise some parametric robustness problems. An extensive literature exists on the compensation of time delayed processes (O'Dwyer, 2005). The existence of a delay in the states or in the inputs of a system may induce instability or poor performance for the closed-loop schemes (Niculescu & Annaswamy, 2003). One of the first original approaches for controlling systems with known time-delay was originated by Smith (1959). According to this technique, the effect of the delay can be compensated estimating the plant output using a model of the plant. Bresch-Pietri and Krstic (2010) deal with the problem of stabilization of an unstable system with an unknown actuator delay of substantial length by mean of a Lyapunov-based adaptive control design. In Gaudette and Miller (2014) the problem of stabilizing any single-input single-output linear time-invariant controllable/

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Nomenclature

$A_{k,i}$	amplitude of oscillation of the k^{th} mode of the i^{th} body ($\sqrt{kg}\cdot m$)
δt	time delay (s)
$\mathbf{H}$	measurement matrix of the Kalman filter
$\mathbf{J}$	Jacobian matrix
$\mathbf{M}_i$ ($\mathbf{M}$)	mass matrix of the i^{th} body (of the overall system)
N	number of bodies
N_m	number of modes
Q	vector of the joint variables
u	control vector (N and Nm)
θ	attitude about the vertical axis (rad)
$X_i(X)$	state vector of the i^{th} body (of the overall system)
x, y	position of the bus center of mass with respect to the inertial frame (m)
$\mathbf{\Omega}_i$	angular velocity of the i^{th} body (rad/s)
$\omega_{k,i}$	pulsation of the k^{th} mode of the i^{th} body (rad/s)
$\gamma_{k,i}^{t}$ ($\gamma_{k,i}^{r}$)	modal participation factors with respect to translation (rotation) relevant to the k^{th} mode of the i^{th} body ($\sqrt{kg}$ and $\sqrt{kg}\cdot m$)

observable plant with gain and time delay margins as large as desired is tackled by means of a non-linear time varying controller. In many of these works, single-input single-output systems are analyzed, while the objective of the present paper is to apply delay compensation techniques to nonlinear flexible multibodies with multiple inputs and outputs. The test case adopted for this study is a typical spacecraft structure, with a central rigid bus equipped with flexible panels. In a previous work of Gasbarri, Sabatini, Leonangeli & Palmerini (2014), a model-based predictor to compensate for the time delay and stabilize a similar space system has been proposed. The basic idea in Gasbarri et al. (2014) is simple and not original: the problem of a delayed system consists in the fact that the control, evaluated on the basis of the measurements taken at a given time, is applied after a certain time interval (the delay). On account of this, the approach in Gasbarri et al. (2014) requires the prediction of the system state vector at the time of the actual application of the control, and evaluate the control taking this prediction into account. It was shown that an accurate attitude re-orientation could be achieved if the delay compensation algorithm was implemented, while an unstable behavior would have been obtained if it was not.

Of course such a time-delay compensation is possible if an accurate model of the system dynamics is developed. The case study in Gasbarri et al. (2014) was limited to a symmetric multibody system, with only one degree of freedom (single axis rotation). Starting from these early achievements, the present work extends the approach to the case of a generic non-symmetric flexible multibody space system, with the possibility to be controlled in attitude and position. This extension involves important qualitative changes in the problem characteristics: the dynamic plant becomes highly nonlinear, the number of observables increases (e.g. the modal amplitudes of each flexible part must be individually measured), the linear and angular dynamics are coupled. Thus, the application to a much more general case can be considered an important benchmark to verify the applicability of the method to a wider range of problems.

In order to compensate the delay by predicting the system state vector, the multibody dynamic equations are first derived for the general case, then rewritten for the specific case study. The model, tested against a commercial multibody code, is used as building block for the Kalman filter and for the prediction algorithm of delay compensation. The control parameters are selected on purpose so that the system is theoretically (and practically) unstable. The aim is to show that with a limited set of measurements, relevant just to the rigid dynamics of the bus, it is possible to estimate the complete multibody kinematic state (rigid and flexible), and to propagate over the time delay this estimate to predict the state and finally evaluate the control actions that are now delay free – at least in an ideal simulation environment.

The developed algorithms for navigation, control and delay compensation must be experimentally verified, by means of a testbed in which the space conditions can be replicated. At the scope, a free floating platform, equipped with very flexible appendages, is used to perform the required translational and rotational maneuvers. The testbed is equipped with an air suspension to remove the friction and on–off thrusters for controlling the position and the attitude. Clearly, the free floating approach limits the study to the 2D scenario, yet the dynamic equations and the relevant delay compensation algorithms hold when extended to the 3D case.

In addition to inertial measurement sensors, a device for measuring these oscillations is included, since elastic oscillations of the panels play an important role. Even though accelerometers can be considered as the most common choice for measuring elastic vibrations, in this paper a video system is used for measuring the flexible displacement of the panels. The measurement is of course limited to the low frequencies, because of the low frame rate of the cameras and because of the remarkable computing time required for image processing; however this technique has the great advantage that it does not require the introduction of distributed sensors with relevant harness and power. This approach has been already investigated (for example in Tang, Wang & Lu (1990) and Xu & Ritz (2009)) but in these works the system was not considered as a complex multibody; additionally, in the present paper the real time video system is used only as a benchmark for the Kalman filter estimates, while it does not enter the Guidance, Navigation and Control (GNC) loop, since the experiments will prove that an accurate modeling of the system dynamics is sufficient for compensating the delay.

One of the most evident drawbacks of a model-based delay compensation is that its performance depends on the accuracy of the dynamic model used for the prediction, and on the estimation of the delay itself. A robustness analysis must be therefore accomplished, which would be very time consuming if performed by means of the experimental testbed. On the other hand, the good match between the experimental and simulation results allows to consider the numerical model as a valid tool for fulfilling the goals of this last part of the study. A μ-analysis will be performed to test the robustness of the algorithm with respect to uncertainties affecting the system characteristics (in particular the flexible ones, which are likely to be the hardest to be exactly known), and the estimated delay. The results will be furthermore verified thanks to a Monte Carlo simulation including all the characteristics (sensor noisy, actuators inaccuracy and so on) of the fully nonlinear system.

The paper is organized as follows: in Section 2 the dynamic equations of a flexible multibody systems are derived for a general case, and they are rewritten for the specific case study in Section 3. The experimental testbed is described in Section 4, while the delay compensation algorithm, the Kalman filter and the control laws are described in Section 5. The results relevant to the complete control maneuver in terms of simulation and in terms of