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Adaptive Variable Structure Control System for Attitude Spacecraft Applications

By

Mauro Mancini

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Supervisor(s):
Prof. Elisa Capello, Supervisor
Dr. Dimitri Peaucelle, Co-Supervisor
Prof. Luca Zaccarian, Co-Supervisor

Doctoral Examination Committee:
Prof. A.B. , Referee, University of...
Prof. C.D, Referee, University of...
Prof. E.F, University of...
Prof. G.H, University of...
Prof. I.J, University of...

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Mauro Mancini
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Whatever the mission tasked to a satellite (observation of the universe, Earth monitoring, rendezvous and docking), it is crucial for its success that the satellite has the proper attitude, i.e. the proper orientation in space. So, satellites have a dedicated on-board system that is responsible for generating the desired attitude, estimating the true attitude and controlling the actuators, to change the orientation in the desired direction. This role is assigned to the Guidance, Navigation, and Control (GNC) system, and it is clear from the description that the overall attitude error of a spacecraft consists of both the estimation and control errors.

The main focus of this thesis is the design of an Attitude Control System (ACS), whose requirements certainly depend on the space mission, but which usually provides a tree-axis stabilisation. Therefore, an ACS is usually required for both manoeuvring from one desired orientation to another and maintaining the desired orientation. Indeed, a space mission often involves multiple pointing modes.Moreover, the space environment should be counteracted, to avoid deviation of the satellite attitude during manoeuvres. For this reason, the attitude control algorithms developed in this thesis were designed to ensure both fast spacecraft manoeuvrability and fine pointing accuracy. Since attitude dynamics is inherently non-linear and characterised by uncertain parameters and unmodelled dynamics, robust non-linear control techniques based on Variable Structure Control (VSC) with sliding mode are considered for the ACS. Sliding Mode Control (SMC) offers high robustness against external disturbances and parametric uncertainties, but it suffers from chattering, i.e. high-frequency oscillations in the closed-loop dynamics. Therefore, techniques to eliminate chattering are addressed in the controller design. In addition, real actuators, i.e. reaction wheels, with limited actuating power are taken into account for the application of the control torques calculated by the ACS. Therefore, the attitude control algorithms are designed in such a way that the output of the control law does not overload the actuators, thus actuator saturations are avoided even considering parametric uncertainties.

A further difficulty in tackling the design of the ACS is the flexibility of the satellite's structures. Indeed, modern spacecraft often have appendages with low stiffness, so they do not behave like a rigid body. The coupling between the flexibility of the structure and the attitude dynamics causes (I) vibrations of the flexible bodies and (II) internal torques disturbing the attitude dynamics. To study these effects, a three degree-of-freedom attitude dynamics simulator is constructed, with a mathematical model that includes uncertainties on the inertia tensor and a coupling matrix between the satellite's attitude dynamics and the flexible dynamics of the appendages. In addition, this simulator also includes the dynamics and saturations of the actuators and is used to validate the control algorithms designed in the thesis through numerical simulations.

Finally, the main outcome of this thesis is the development of an innovative control algorithm by combining adaptive control techniques and SMC. First the stability of the novel adaptive SMC algorithm is proven using Lyapunov functions, and then it is tested within the attitude dynamics simulator through extensive numerical simulations. The comparison between the results obtained with adaptive SMC and classical SMC shows that the combined use of adaptive control and SMC improves the robustness of the closed-loop system, the convergence speed and the pointing accuracy. In addition, both classical SMC and adaptive SMC are applied to a high fidelity simulator of the DEMETER spacecraft from CNES. In this case, the algorithms are designed to replicate the switching control law implemented on the real satellite, and the results show that the adaptive SMC developed in this thesis project succeeds in avoiding actuator saturations and thus steering to zero the attitude error of the DEMETER, while the classical SMC fails in this task.