Book Review: Spacecraft Modeling, Attitude Determination and Control: Quaternion-Based Approach

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Spacecraft Modeling, attitude, determination and control
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This book provides a good and comprehensive overview of spacecraft attitude dynamics, determination and control, including advances in the quaternion-based approach, with application to practical problems such as coupled attitude and orbit control and model predictive optimal control with realistic actuators constraints. Different options for spacecraft actuation are considered including the use of momentum exchange devices such as control moment gyros for attitude control, thrusters based reaction control systems and magnetic torques for the desaturation of momentum exchange devices.
Chapters 2 and 3 respectively provide the necessary background to orbital dynamics and attitude parameterisations. The orbital dynamics background is necessary to the later sections where the attitude is referenced with respect to a local orbit frame, particularly when applied to orbit raising manoeuvres, as in section 12. The attitude parameterisations covered include the Euler angles based rotational sequences with respect to fixed or rotating frames and the quaternion attitude parameterisation. The rotation matrix concept and quaternion properties are very clearly presented. The Euler rotational sequences could have been presented in a more comprehensive way to cover all 12 possible rotational sequences, but the focus was understandably on quaternions, which are the focus of the book.
In chapter 4, the equations of attitude dynamics and kinematics are derived from the differential equation relating angular momentum to external torques. It would have been helpful to start with the simpler case of torque free motion where momentum is conserved, but the focus of the book is understandably on the effect of control and disturbance torques. The dynamical models represent the nonlinear and linearized models, with respect to the inertial and nadir pointing frames. The linearized models traditionally derived using Euler angles are presented using quaternion modelling, which is an interesting feature of the book. External disturbance torques are accurately modelled in chapter 5, including gravity gradient torques, aerodynamic torques, magnetic torques and the torques due to solar radiation pressure.
In chapter 6, sensor fusion methods allowing the determination of spaceraft attitude from a minimum of two vector observations are proposed, starting from the formulation of the Wahba problem with two vector observations that can be solved using the triad method before Davenport's q-method is presented together with computationally efficient approaches to the problem such as QUEST method. The author then proposes his own innovative research based approaches to this problem using an analytic method in the case of two observations (section 6.4) using a minimum angle quaternion approach and multiple observations (section 6.5), using a characteristic polynomial approach. The superiority of the analytic method is demonstrated by numerical tests.

In chapter 8, spacecraft attitude estimation uses the widely used extended Kalman filter

(EKF) approach, which approaches the optimal estimates using a local linearization. In this book, the EKF uses quaternions for the attitude kinematics and assumes a Gaussian process noise and a drift in the gyro angular rate measurements. A good engineering based explanation is given about the way the Kalman gain is optimized. A reduced order quaternion model is then introduced by the author and allows for the use of the standard linear Kalman filter, which simplifies estimator tuning. Given that the author covers the most advanced optimal control methods such as model predictive control, this discussion could have been extended to mention how some advances in nonlinear optimal estimators such as particle filters may be required to address the estimation accuracy and robustness requirements of future space missions.

The spacecraft attitude control problem is first formulated using a linear quadratic regulator (LQR) approach, for which the analytic solution is analysed and linked to a robust closed loop pole assignment problem. In page 111, the analysis is correct but it is unclear why the author refers to the Karush Kuhn Tucker conditions as the problem only has equality and no inequality constraints, so the conditions used correspond in reality to the simpler Lagrange conditions. Interesting examples show how control requirements on settling time and overshoot can be met using the robust pole assignment method based on linear control theory, even in the presence of small nonlinearities (10 degrees on all 3 axes) and model uncertainty on the cross diagonal elements of the moment of inertia matrix.

After a brief introduction of actuator models in chapter 10, chapter 11 addresses the conditions on spacecraft controllability using only magnetic torques before deriving the periodic Riccati equation because of the periodic nature of the magnetic field vector variations. The effectiveness of the magnetic control algorithms as a means of slow attitude control is demonstrated by numerical simulation analysis. Magnetic torquers are then applied to momentum desaturation using a quaternion based LQR approach, which is then extended to discrete time periodic LQR. An interesting analysis of computation time using the proposed LQR implementations, both analytically and numerically, is then presented in 11.5.3.

The quaternion based attitude control approach used throughout the book is then compared to the Euler based approach for an orbit raising maneuver using thrusters.

model predictive control (MPC) is then introduced as one of the promising methods for attitude control following advances in the computational capabilities of spacecraft. MPC is applied in chapter 13 to the spacecraft attitude control problem subject to actuator constraints. The MPC algorithm uses a box constrainted convex quadratic programming (QP) approach, which is solved using an efficient interior point method that solves the KKT conditions and ensures convergence to the optimal solutions. The approach is applied to the thruster based control problem of section 12.

The additional practical consideration when attitude control is performed using control moment gyros (CMGs) due to ensure agile manoeuvring are covered in section 14, where an MPC approach is also proposed to optimise performance under robustness constraints.

Finally, the proposed quaternion based MPC approach is applied in chapter 15 to the coupled attitude and orbit control problem for a soft spacecraft docking application. This research area has received increased attention in recent years. Useful appendices are provided, particularly for the fundamentals of optimal control and robust pole assignment.

In conclusion, the book is a good and useful resource for researchers and research minded engineers wishing to develop a more detailed understanding of some of the latest advances in robust pole placement and model predictive control to spacecraft attitude control. The quaternion based approach is applied to practical attitude estimation and attitude control problems ranging from nadir pointing using reaction wheels or CMGs to momentum dumping using magnetic torquers and coupled attitude and orbit control for spacecraft docking. Rigorous proofs of stability and optimality are provided by the author for the quaternion based robust pole placement, LQR, MPC and other control methods used throughout the book. The proposed methods are methodically analysed and numerically simulated, evaluated and compared against published research in the field.

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