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Integrated attitude determination and control system via magnetic measurements and actuation

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ABSTRACT

A nonlinear control scheme using a Modified State-Dependent Riccati Equation (MSDRE) is developed through a pseudo-linearization of spacecraft augmented nonlinear dynamics and kinematics. The full-state knowledge required for the control loop is provided through a generalized algorithm for spacecraft three-axis attitude and rate estimation based on the utilization of magnetometer measurements and their time derivatives, while the control torque is generated via magnetorquers. The stability of the controller is investigated through Lyapunov function analysis and the local observability of the estimator is verified. The resulted attitude determination and control system has shown the capability of estimating the attitude better than 5 deg and rate of order 0.03 deg/s in addition to maintain the pointing accuracy within 5 deg in each axis with pointing stability of less than 0.05 deg/s. Monte-Carlo simulations are used to demonstrate the global asymptotic stability of the controller and the estimator for various initial conditions.

1. Introduction

The aim of this paper is to develop a low cost three-axis Attitude Determination and Control System (ADCS) to fulfill spacecraft mission requirements during low accuracy modes which are the most frequent modes during mission life time. Many previous efforts extensively handled the problem of attitude determination and stabilization based on using magnetometer measurements and electromagnetic torquing separately. Previous researches on the State-Dependent Riccati Equation (SDRE) were done by Pearson [1], Garrard et al. [2], Burghart [3], and Wernli and Cook [4]. Recently, the SDRE control has been studied by Krikelis and Kiriakidis [5], and Cloutier et al. [6,7] with the application of the SDRE to a nonlinear benchmark problem in Mracek and Cloutier [8] and Chang et al. [9,10]. Hammett et al. introduced controllability issues for the SDRE in Ref. [11]. A comparison study involving the SDRE among other nonlinear control method was done in Ref. [12], and tracking control and state estimation methods using the SDRE were developed in Ref. [13]. Periodic Linear Quadratic Regulators (LQR) already has been developed for slightly perturbed spacecraft stabilization about nominal attitude via magnetic torquers. The linearized spacecraft dynamics is treated as a periodic system since such system is controllable if the orbit is inclined because the Earth's magnetic field vector rotates in space as the spacecraft moves around its orbit. Then the controller is obtained based on a transient or steady-state solution of the Riccati equation while the magnetic field is modeled as dipole or averaged over a time interval corresponding to a common period for the satellite revolution about the Earth and the Earth's own rotation [14, 15]. Also, Marco Lovera et al. [16] proposed a solution to spacecraft attitude control using magnetic actuation in terms of classical LQ periodic optimal control and extensions thereof, aiming at achieving efficient rejection of periodic disturbance torques was presented. The approach introduced by Challa et al. [17, 18], for attitude and rate estimation using only magnetometer measurements, uses a

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deterministic batch algorithm in conjunction with extended Kalman filtering. Crassidis and Markley [19] derived a real-time predictive filter for spacecraft attitude estimation without utilizing gyro measurements. The filter is based on a predictive tracking algorithm developed by Lu [20], which basically deals with control problems. Psiaki [21] developed a self-initializing filter to estimate three-axis attitude and rate from magnetometer data only. It uses a new attitude parameterization that is based on perturbations to the minimum quaternion that aligns the magnetic field in reference coordinates with the field in spacecraft coordinates. The filter model includes Euler dynamics and attitude kinematics, and its least-squares cost function penalizes magnetometer measurement errors and torque process noise.

The current work introduces a generalized nonlinear control scheme using a Modified State-Dependent Riccati Equation (MSDRE). The system dynamics equation is represented by the spacecraft nonlinear dynamics with momentum bias including gravity gradient, aerodynamic, and magnetic residual torques. Then, the quaternion kinematics is augmented with spacecraft dynamics to represent the overall process dynamics. A pseudo-linear formulation of the augmented system is developed while a MSDRE controller derived to solve a trajectory-tracking/model-following problem. The derivatives of the state dependent matrix w.r.t the states are taken into account through the development of the final MSDRE controller such that an optimal control signal is obtained rather than producing a suboptimal controller when these derivates are ignored. To obtain the optimum control signal full-state knowledge is required, so attitude and rate filter is integrated to the control loop. The proposed filter is previously developed by the authors for spacecraft three-axis attitude and rate estimation utilizing magnetometer measurements only [22]. The architecture of the filter follows the extended Kalman filter EKF algorithm. Its structure is built up using spacecraft nonlinear dynamics and kinematics augmentation as in the MSDRE controller. Due to the interference between the magnetometer and magnetorquers which are used as main actuators, satellite dipole moment is added to the state vector. Also, the aerodynamic drag coefficient is included in the state vector for more filter robustness. Magnetometer measurements and its corresponding time derivatives are used to represent the filter measurement model. Except for the local linearization of the EKF scheme, the filter avoids any additional approximations regarding the attitude parameters and dynamics. Hence, analytical closed form solutions for the derivatives necessary to calculate the Jacobian matrix through the EKF algorithm is derived. The global asymptotic stability of the controller is investigated by applying Lyapunov theorem, and concluded by introducing stability regimes for the overall system which verify the stability conditions of the controller and the required accuracy of the filter. To test the developed ADCS, EgyptSat-1, launched in the last April, is used as a real test case where a magnetometer and fiber optic gyros are used for attitude/rate determination and magnetorquers/reaction wheels for stabilization. Basically, the ADCS has been tested to control the satellite and estimate the attitude and rates during detumbling and standby modes where the magnetometer measurements and magnetorquers only can fulfill the mission attitude and rate accuracy requirements for these two modes. Except for the imaging (high accuracy) mode, the developed ADCS works as the main controller and attitude/rate estimator algorithm and not as a contingency algorithm in case of actuator/sensor failure which was the essential focus of many former research works. Finally, magnetometer measurements and magnetorquers are used through this paper only due to the hardware configuration of the test case in hand, but any other actuators or reference vector measurements such as Sun vector can be used.

The main contributions of this paper can be summarized first, in the development of a Modified State-Dependent Riccati Equation (MSDRE) controller which includes the derivatives of the state matrix such that an optimal control signal is obtained rather than producing suboptimal control signal when these derivatives are ignored. Second the derivation of a new pseudo-linear formulation of the augmented spacecraft non-linear dynamics and kinematics. The formulation includes the gravity gradient, aerodynamics, and magnetic residual torques in a moment biased system. The MSDRE controller is adopted to solve a trajectory-tracking/model-following problem and not only to solve a regulation problem. Third, a new previously developed filter for attitude and rate estimation using magnetic field measurements and their derivatives only is introduced and integrated with the MSDRE controller to represent a new developed ADCS based on using magnetic field measurements and actuation only. Fourth, the global asymptotic stability of the controller is investigated by applying Lyapunov function analysis and the local observability of the estimator is verified. Finally, the developed ADCS is applied to a real test case.

The next section describes briefly the statement of the problem, and then the MSDRE controller is developed and adopted for tracking problem. Through the fourth section the pseudo-linear representation of the system is derived and the stability issues are introduced. Before the simulation section, the state estimator design appears and is discussed. Then, the paper is concluded by testing the proposed ADCS via simulations and real flight data.

2. Statement of the problem

Consider the nonlinear system

$$\dot{x} = f(x,t) + v_x(t) \tag{1}$$

we will try to control this system such that its output is expressed as

$$y = cx \tag{2}$$

with the availability of a set of measurements

$$z = h(x,t) + v_z(t) \tag{3}$$

where $\nu_x(t)$ and $\nu_z(t)$ are random zero-mean Gaussian white-noise processes described

$$E\{v_x(t)v_x^T(t)\} = Q_f\delta(t-\tau) \tag{4}$$