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A suboptimal excitation torque for parameter estimation of a 5-DOF spacecraft simulator

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Abstract

Five degrees of freedom spacecraft simulators are designed to verify spacecraft control strategies, rendezvous and docking techniques. The accurate knowledge of simulator inertia parameters which can be calculated by parameter estimation is of vital importance in these experiments. However, the rotation limits of the simulator must be considered during estimation process. This paper presents an approach to determine a suboptimal excitation torque for the system identification of the inertia parameters. The continuous optimization problem is transcribed into a discrete nonlinear programming problem by integral gauss pseudospectral method. To reduce the effect of noise, the states and inertia parameters are estimated simultaneously by joint filter within Extended Kalman Filter (EKF) or Unscented Kalman Filter (UKF). The proposed method is validated by simulations and the results indicate that this method not only satisfies the constraints of simulator rotation angles, but also improves the efficiency of parameter estimation.

Keywords: Parameter estimation; Spacecraft simulator; Excitation torque

1. Introduction

Spacecraft simulators based on air bearings which provide frictionless and microgravity environment can simulate spacecraft dynamics, navigation, control, rendezvous and docking on the ground (Schwartz et al., 2003; Mittelsteadt and Mehiel, 2007; Cho et al., 2009; Scharf et al., 2010; Scharf et al., 2010). Experiments on spacecraft simulators greatly reduce the costs and risks of spacecraft project on the orbit. However, one of the major disturbance torques on simulators is gravity torque. To reduce this disturbance, the distance between the simulator center of mass and the center of rotation needs to be calculated accurately. In addition, the inertia parameters are important for simulator control experiments. But there are many flexible cables on the simulator. These cables are complex and have irregular shape. So, it is difficult to accurately model the simulator and the inertia parameters of simulator calculated by CAD software are not accurate enough.

To attain the accurate inertia parameters, including the moment of inertia and the center of mass, parameter estimation technique is applied to spacecraft simulators. Kim et al. (2001), Peck and Cavender (2003), Jung and Tsiotras (2003), Kim and Agrawal (2006), and Keim et al. (2006) adopt least squares estimation methods for system identification of spacecraft simulators. Sensor noise is one of the main factors that affect the accuracy of estimation. To reduce the effect of noise; integrated forms of

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spacecraft simulator dynamics is presented (Schwartz and Hall, 2004; Schwartz, 2004). For the same purpose, joint filtering and dual filtering of Kalman filter are applied to system identification. The states and inertia parameters are estimated simultaneously by joint filtering or dual filtering. The joint method is that the parameter vector is appended onto the true state vector, while the dual filtering utilizes a pair of distinct sequential filters, one estimating the true states and the other estimating the parameters. Extended Kalman Filter (EKF) and Unscented Kalman Filter (UKF) are widely used for parameter estimation of nonlinear system. EKF linearizes the nonlinear model, while UKF uses unscented transformation (UT) of a deterministic sampling of points to obtain an approximation of the mean and covariance of the state distribution. For example, using a simplified equation of spacecraft simulator motion, Schwartz and Hall (2004) estimates the states and inertia parameters simultaneously by dual EKF. Also, dual UKF is applied to the state and inertia parameter estimation for spacecraft (VanDyke et al., 2004). Wright (2006) estimated the states and the center of mass by joint EKF. The vertical offsets between the center of rotation and the center of mass, and the angular velocities are estimated by joint UKF (Chesi et al., 2013). But in these articles, the excitation torque in estimation process is not given. The upper attitude stage of simulator rotates on air bearings, so the rotation has a limit, i.e. ±30°about the horizontal axes and a full rotation about the vertical axis. During the estimation process, the simulator should move freely within the rotating range.

In Kim and Agrawal (2009), an attitude control system is designed for the simulator to follow a sinusoidal reference trajectory during the estimation process. This method needs complex control system and capable actuators. Moreover, the center of mass usually needs to be manually located far below the center of rotation to provide a stable equilibrium point that generates a balancing torque. In this paper, we present a method which calculates excitation torque directly without attitude control system and the simulator rotates within the rotation range under this excitation torque.

Condition number is widely used as the cost for excitation torque optimization problems of robot parameter estimation (Presse and Gautier, 1993). Calafiore et al. (2001) and Swevers et al. (1997) generate optimal robot excitation trajectories for parameter estimation using condition number as cost function. Optimal excitation trajectories acquired by using condition number may decrease disturbances and noise impact of the estimation (Rackl and Lampariello, 2012). Therefore, we consider condition number as the cost for excitation optimization problems of spacecraft simulator parameter estimation. In simple words, the problem of optimizing excitation torque, using condition number as the cost and satisfying the constraints of simulator rotation angles, is a constrained nonlinear optimization problem.

The paper is organized as follows. The spacecraft simulator and its dynamics equation are described firstly. Then to get the condition number, the dynamics equation is rewritten and observation matrix is given. Cost function, equality constraints and inequality constraints are discretized by integral gauss pseudospectral method. The Lagrange interpolating polynomials of the optimized variables are added to constraint equation to satisfy the constraints of simulator rotation angles and the reaction wheel performance limits. To decrease the noise impact, joint UKF and joint EKF is applied to estimate the state and inertia parameter simultaneously. Finally, the optimized excitation torque trajectory is generated and a series of simulation results using sinusoidal excitation and optimized excitation are presented.

2. Spacecraft simulator and dynamic model

2.1. The 5-DOF spacecraft simulator

The five degrees of freedom (DOF) spacecraft simulator consists of translational stage and attitude stage supported by a spherical air bearing. The simulator in this paper can rotate around the center of air bearing ±30 deg in the two horizontal axes and 360° in the vertical axis. Various actuators, sensors, on-board computers and an automatic mass balancing system are installed on the attitude stage as shown in Fig. 1. The automatic mass balancing system consist of three balance masses, which can be moved along the three axes of the simulator body frame. The body frame is shown in Fig. 1. The origin is located at the center of rotation, z axis is perpendicular to attitude stage. The actuators include cold-gas thrusters and three reaction wheels which provide the excitation torque for parameter estimation. The output torques of these three reaction wheels are along the three axes of the simulator body frame. The maximum output torque of each reaction wheel is 0.1Nm and maximum angular momentum is 6Nms. Sensors include a rate

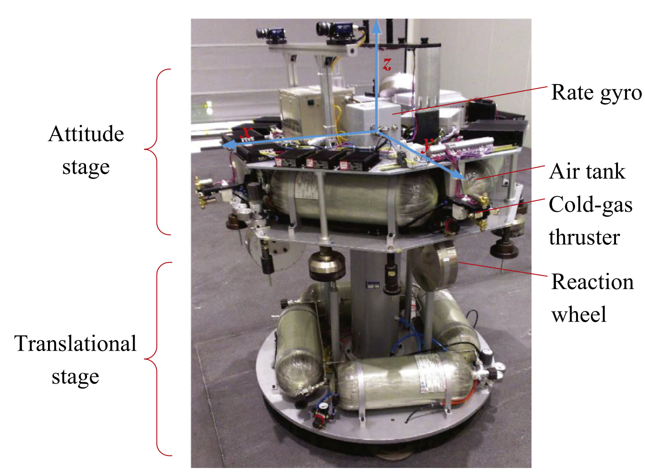

Fig. 1. A 5 DOF simulator.