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Parameter estimation of a three-axis spacecraft simulator using recursive least-squares approach with tracking differentiator and Extended Kalman Filter

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ABSTRACT

Spacecraft simulators are widely used to study the dynamics, guidance, navigation, and control of a spacecraft on the ground. A spacecraft simulator can have three rotational degrees of freedom by using a spherical air-bearing to simulate a frictionless and micro-gravity space environment. The moment of inertia and center of mass are essential for control system design of ground-based three-axis spacecraft simulators. Unfortunately, they cannot be known precisely. This paper presents two approaches, i.e. a recursive least-squares (RLS) approach with tracking differentiator (TD) and Extended Kalman Filter (EKF) method, to estimate inertia parameters. The tracking differentiator (TD) filter the noise coupled with the measured signals and generate derivate of the measured signals. Combination of two TD filters in series obtains the angular accelerations that are required in RLS (TD-TD-RLS). Another method that does not need to estimate the angular accelerations is using the integrated form of dynamics equation. An extended TD (ETD) filter which can also generate the integration of the function of signals is presented for RLS (denoted as ETD-RLS). States and inertia parameters are estimated simultaneously using EKF. The observability is analyzed. All proposed methods are illustrated by simulations and experiments.

1. Introduction

Spacecraft simulators provide a frictionless and micro-gravity space environment and are widely used to develop control algorithm on the ground. Several academic institutions have developed various air-bearing spacecraft simulators in the past [1–8]. The moment of inertia and the center of mass location of spacecraft simulator play a significant role in control design. In addition, to eliminate gravitational disturbance, the center of mass must be exactly aligned with the center of rotation of the spacecraft simulator. So, knowledge of the center of mass is directly used for mass balancing. Due to the uniform density of the components and the complex wiring harness on the simulator, the mass properties estimate from a CAD model is not accurate enough. So system identification for the moments of inertia and the center of mass of spacecraft simulator is necessary.

References [9–16] present different least-squares estimation methods for system identification of spacecraft simulators. A recursive least-squares algorithm was used to estimate the unknown parameters including the moments of inertia and the center of mass [11]. Various formulations for system identification have been presented: torque method, momentum integral method, and energy balance method [12]. These formulations include the derivative of the angular velocities which are measured by rate gyro. Sensor noise is one of the main factors

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that affect the accuracy of estimation. To avoid the noise amplified during numerical differentiation, references [12,13] adopted integrated forms and demonstrated that it's robust to white, zero-mean noise by simulations. A second-order causal filter form was adopted in reference [14]. Reference [15] introduced a low pass filter and its simple form which is an integrator. Reference [15,16] estimated the inertia and center of mass of simulator for automatic mass balancing using integrated forms. But using integrated forms have a bad result when disturbance torques exist, which will be discussed later in this paper. Also Kalman Filter is widely applied to the system identification. Extended Kalman Filter (EKF) and unscented Kalman Filter (UKF) are both suitable for 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. The states and parameters are estimated simultaneously using a dual filter of EKF [17] and UKF [18]. Reference [19] uses three linear actuators as excitation for identification and estimates the states and the center of mass by joint EKF in simulation. The vertical offset between the simulator center of mass and the center of rotation is estimated for automatic mass balancing using UKF [20].

In this paper, the dynamics equation of spacecraft simulator and the excitation methods are described firstly. Tracking differentiator (TD) filter the noise coupled with the measured signals and generate derivate of the measured signals without knowledge of the noise standard deviation [21]. A method that combines two TD filters in series to reduce the effect of noise in angular accelerations is presented. This method is applied to recursive least-squares estimation (TD-TD-RLS). Because the integrated form does not need derivative of the angular velocities [12], another method using an extended tracking differentiator (ETD) filter is presented for RLS (ETD-RLS). ETD can filter noise and generate the integration of the function of signals. Then the effect of disturbance torques is analyzed. In next section, the states, the moments of inertia and location of the center of mass are estimated simultaneously using joint filter of EKF. The observability of the inertia parameters is analyzed. All these methods are demonstrated by a series of simulations. Finally, these methods are applied to the physical system.

2. Spacecraft simulator dynamics and excitation torque

2.1. The spacecraft simulator

The ground-based spacecraft simulator contains various components such as a planar air-bearing, spherical air-bearing, cold gas thrusters, reaction wheels, a vision camera system, a inertial measurement unit (IMU), an onboard computer PC104 and an automatic mass balancing system (see Fig. 1). The planar air-bearing offers a frictionless environment in two translational degrees of freedom, and the spherical air-bearing offers three rotational degrees of freedom with respect to the center of rotation: $\pm 30^{\circ}$about the horizontal axes and a full rotation about the vertical axis. Sixteen cold gas thrusters and three reaction wheels are used as actuators to the system. Spin axes of these three reaction wheels are placed parallel to the three axes of the simulator body frame. Reaction wheels can be operated in angular speed or torque command mode. The body frame is shown in Fig. 1. Vision camera system and rate gyro in IMU are used to provide Euler angles and angular velocities for the parameter estimation. An automatic mass balancing system, composed of three moving balance masses on linear stages which are driven by motor controller, adjusts the center of gravity close to the center of rotation.

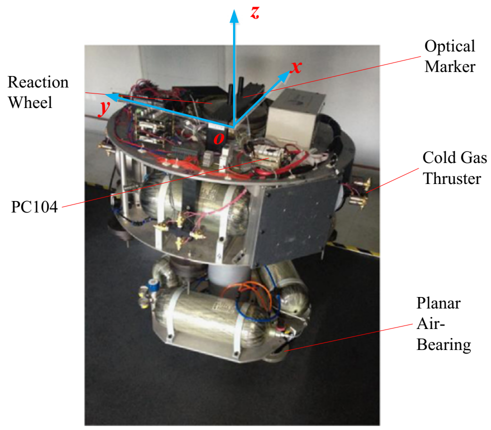

Fig. 1. Spacecraft simulator.

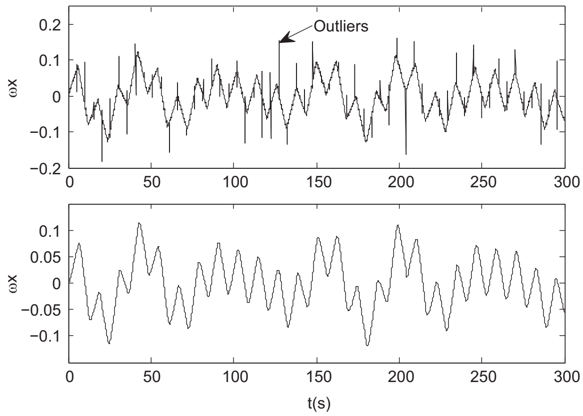

Fig. 2. Angular velocity ω_x.

2.2. Spacecraft simulator dynamics

We assume the lab-fixed reference frame as the inertial frame. The dynamics equation of a rigid body three-axis spacecraft simulator is written as

$$\frac{d\boldsymbol{H}}{dt} = \boldsymbol{J}\dot{\boldsymbol{\omega}} + \boldsymbol{\omega} \times \boldsymbol{J}\boldsymbol{\omega} + \left(\dot{\boldsymbol{h}} + \boldsymbol{\omega} \times \boldsymbol{h}\right) = \boldsymbol{R} \times m\boldsymbol{g} + \boldsymbol{T} \tag{1}$$

where $\boldsymbol{J}$ is the inertia dyadic of the spacecraft simulator including reaction wheels and automatic mass balancing system, $\boldsymbol{\omega}$ is the angular velocity, $\boldsymbol{h}$ is the momentum of the reaction wheels, $\boldsymbol{R}$ is the center of gravity with respect