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SPACECRAFT NAVIGATION USING GRAVITY GRADIENT INVARIANTS BASED ON CUBATURE KALMAN FILTER

Abstract

Background: For space missions in which the Global Navigation Satellite System (GNSS) signals are unavailable or denied, the geophysical information, for example, the gravitational and magnetic fields of the Earth could provide alternative navigation capabilities. The gravity gradients, or the gravitational gradients in the strict sense, are second order spatial derivatives of the gravitational potential and can be measured by a high-precision spaceborne gravity gradiometer, which usually consists of three orthogonal pairs of superconducting or electrostatic three-axis accelerometers. The gravity gradients at one location form a 3 × 3 tensor matrix which varies as a function of position and orientation with respect to the Earth reference frame. With a known global gravity gradient map and onboard attitude sensors, the position information can be obtained by matching the measured gravity gradients with the stored map. This was already investigated and validated in our previous studies. Real-world data from the European Space Agency's Gravity field and steady-state Ocean Circulation Explorer (GOCE) were used to test the navigation performance, and a 3D position accuracy of hundreds of meters was demonstrated.

Current Study: In the present study, we propose to use gravity gradient invariants instead of gravity gradient tensor matrices for spacecraft navigation. The gravity gradient invariants are certain component combinations that are invariant under coordinate rotation. Unlike the tensor matrix, the gravity gradient invariants are functions of position only. Thus, the attitude information can be omitted in the orbit determination process. The navigation computational complexity is accordingly reduced. Since the gravity gradient invariants are highly nonlinear functions of position, the cubature Kalman Filter rather than the extended Kalman filter is adopted for sequential orbit determination. The stochastic model of orbital motion, the observation equation, and the error covariance of gravity gradient invariants are discussed for the filter design. In order to test the orbit determination performance, a low-Earth-orbiting (LEO) spacecraft with gradiometer noise level of 1 mE at 300 km altitude is simulated. Preliminary results show that a 3D position accuracy of better than 100 m is achieved. Real data from the GOCE satellite are further tested and a 3D position accuracy of hundreds of meters is achieved.