ARTICLE IN PRESS

Progress in Aerospace Sciences xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Progress in Aerospace Sciences

journal homepage: www.elsevier.com/locate/paerosci

Review on gyroless attitude determination methods for small satellites

Chingiz Hajiyev*, Demet Cilden Guler

Faculty of Aeronautics and Astronautics, Istanbul Technical University, 34469 Maslak, Istanbul, Turkey

ARTICLE INFO

Keywords:
Gyroless
Small satellite
Attitude determination
Kalman filter
Single-frame method
Measurement fault

ABSTRACT

This study surveys the developments in the gyroless attitude determination system, especially for small satellites. Two kinds of gyroless satellite attitude determination algorithms were reviewed namely, vector measurements and Kalman filter based methods. Traditional and nontraditional Kalman filters were considered in the Kalman filter based methods including Unscented Kalman Filter (UKF) and Extended Kalman Filter (EKF). Also, robust versions of those Kalman filters, which were incorporated with single, and multiple measurement noise scale factors (SMNSF, MMNSF respectively) are investigated and compared in the presence of measurement faults.

1. Introduction

1.1. Why gyroless spacecraft?

Attitude determination system is the subsystem of a spacecraft, which is low power consuming, less expensive, and uses non-fragile gyroscopes. Developed micro electrical-mechanical systems (MEMS) are low power consuming, have cheap sensors, but they are inaccurate and have an inadequate resolution for providing the desired performance. In addition, gyroscopes have a tendency to degrade or fail in orbit with time because of their nature.

Three types of rate gyros are used in today's Inertial Measurement Unit (IMU) systems. These are ring laser gyro (RLG), fiber optic gyro (FOG) and MEMS. RLGs may have a "locked-in" condition at very slow rotation rates. FOGs in comparison to RLGs require no mechanical burden for their operation and thus eliminate a troubling noise source. The drawback is that the sensed angular velocity is limited on the phase difference due to the Sagnac effect. Solid-state inertial sensors, such as MEMS devices, have cost, size, and weight advantages. However, their accuracy and resolution are lower than expected to meet most mission requirements which is a great disadvantage [1].

1.2. Gyro failures

Due to the reasons stated in the previous subsection, gyroless attitude control software is necessary for continuous back up. If a satellite does not have any backup mode for gyro failure, the whole mission may fail. A couple of examples for the gyroscope failures are given as follows. The International Ultraviolet Explorer (IUE) launched in 1978 had six gyroscopes for the designed inertial system. In 1985, one of the gyros failed, and the IUE used only two gyros for the rest of the mission life. To continue operations and achieve all scientific goals of the spacecraft, innovative redesign of specific systems was developed on the ground [2]. The Hubble Space Telescope had six gyros including three redundant gyros. Also, its components have a possibility to be replaced with the new equipment by the astronauts. In 1999, the third gyro of the telescope failed, so the telescope started to use redundant, spare gyroscopes [3]. The gyroscope failures are caused by chemical, mechanical and electrical effects. The satellite operations center of the European Space Agency (ESA) reports that the ESA Remote Sensing Satellites (ERS)-2 required an orbital rescue because of the gyro failure. In 2000, a gyro design for the attitude and orbit control system was improved to minimize the necessary number of gyros to reduce the gyroscope failures [4]. In 2001, after the last gyroscope failed, a method of operating the ERS-2 sensors and actuators in a new way was developed for the gyroless ERS-2.

1.3. Gyro-free systems

Because of the failure of the gyros or the necessity of a design at the beginning of a mission, many of the spacecraft are designed gyroless. For both systems, it is needed to have a software that estimates the angular rates. The Solar Heliospheric Observatory (SOHO) lost its control temporarily by the end of its nominal mission in 1998. However, the equipment of SOHO was recovered to extend the mission except for the gyroscopes because of the damage by the extreme thermal stress of the environment. Hence, engineers had to solve the problem without using a gyro. In 1999, the gyro free

* Corresponding author.
E-mail addresses: cingiz@itu.edu.tr (C. Hajiyev), cilden@itu.edu.tr (D. Cilden Guler).

http://dx.doi.org/10.1016/j.paerosci.2017.03.003
Received 21 November 2016; Received in revised form 21 March 2017; Accepted 21 March 2017

Nomenclature

Roman Symbols

a_i	Non-negative Weight
b_i	Set of Unit Vectors in the Body Frame
r_i	Set of Unit Vectors in Reference Frame
A	Transformation Matrix
L(.), J(.)	Loss Function
P	Error Covariance Matrix
O_{local}	Observed Stars

Greek Symbols

λ	Wavelength
ϕ_j	Euler Angles Vector (deg)
φ	Roll Angle (deg)
θ	Pitch Angle (deg)
ψ	Yaw Angle (deg)
ω_x	Angular Velocity (x direction, deg/s)
ω_y	Angular Velocity (y direction, deg/s)
ω_z	Angular Velocity (z direction, deg/s)

Subscripts

B	Body
O	Orbit
R	Reference

Acronyms

GPS	Global Positioning System
ECI	Earth Centered Inertial
ESOQ	Estimator Of The Optimal Quaternion
EKF	Extended Kalman Filter
LKF	Linearized Kalman Filter
FOAM	Fast Optimal Attitude Matrix
IMU	Inertial Measurement Unit
LEO	Low Earth Orbit
MEMS	Micro Electrical-Mechanical Systems
MMNSF	Multiple Measurement Noise Scale Factor
UKF	Unscented Kalman Filter
QUEST	Quaternion Estimator
REKF	Robust Extended Kalman Filter
RMSE	Root Mean Square Error
RUKF	Robust Unscented Kalman Filter
SMNSF	Single Measurement Noise Scale Factor
SVD	Singular Value Decomposition
TAM	Three-Axis Magnetometer

software was uploaded to the satellite and SOHO became the first ESA 3-axis stabilized gyroless satellite [5]. The Defense Meteorological Satellite Program (DMSP) has a gyroless navigation mode and the satellite uses only Earth and Sun sensor data without gyroscope. The algorithm for yaw error estimates is an innovative software for satisfactory attitude results [6]. This model was successfully operated for 24 h and thus it can be used for critical time intervals without gyro data.

In Ref. [7], a magnetometer-only attitude determination algorithm was described. The initial values are obtained from a deterministic method for propagating them in extended Kalman Filter (EKF). With no gyro data, spacecraft states should include not only the attitude but also the rates. To estimate attitude, the time derivative of the magnetic field can be used as the second vector. In that paper, the Solar, Anomalous, and Magnetospheric Particle Explorer (SAMPEX) spacecraft does not have a gyroscope on-board and only relies on a three-axis magnetometer for attitude determination. The described method was tested by using the actual spacecraft data during the eclipse period to simulate possible failure of the digital sun sensor and in the presence of a three axis magnetometer measurement only. The proposed combined algorithm works for 1.5° in attitude and 0.01 deg per sec (deg/s) on the angular rates.

Another method is presented in [8] and demonstrated with actual spacecraft data without possessing any attitude rate measurement equipment. Using a gyroless system increases the sensitivity of the estimates on the model uncertainty and measurement noise. As a result, the proposed algorithm in the study uses a Minimum Model Error (MME) approach. The problems resulting from the absence of attitude rate measurements are solved using the MME based approach in the presence of significant model error or noisy data. Spacecraft like SAMPEX which does not have any angular rate devices or spacecraft without any angular rate measurements as a result of any failures in existing gyros are the basis of this paper. Corrected models by using the results of actual flight data from SAMPEX spacecraft indicate that an algorithm related to this problem led to the accurate estimations for either spacecraft's position or attitude rate. In Ref. [9], the MME approach which is an optimal attitude estimation and smoothing algorithm was developed for spacecraft which do not have a device measuring angular rates as in [8]. Only the attitude sensors such as magnetometers, sun sensors, star sensors, etc. were used for the described model in the paper. The general form of optimal estimation approach using the solution of the nonlinear two-point-boundary-value problem and the linearized solution were considered. The MME based estimation was applied for the spacecraft's attitude.

For a satellite, launch and start of the orbit are two critical time intervals. During these intervals, attitude is estimated by making use of the sensor measurements. In Ref. [10], a simple method was suggested for attitude estimation of a low-Earth-orbiting satellite in the sun acquisition mode. Because of the necessity of quick and reliable attitude knowledge for satellite missions, gyroscopes may fail, therefore the satellite may also fail. For reliable and quick results, the paper uses only Sun sensors and magnetometers. Also, the recommended algorithm was compared with the results of Kompsat-I satellite telemetry data for the verification.

Star tracker missions without using gyro rate data are given as an examples in this section. In [11], two different approaches were used for obtaining angular rates. The study considers a case of gyro failure. Attitude and angular rates are estimated by a dynamic model of the spacecraft in the first technique. In the second approach, the spacecraft attitude is independent of the estimation of angular rates. Star camera rates are the basis of the second technique to find spacecraft body angular rates. Thus, the independence of body angular rates makes the second algorithm bias-free from attitude estimates. Ref. [12] presents a normal mode attitude control with a complete design of the microsatellite DEMETER. The paper describes three phases. The first step is to recall the characteristics of the satellite, specifications, and constraints of the mission. Then, this is followed by the dual mode control synthesis and designing a conventional filter due to concern for attitude control. A gyroless mission operation mode which is the satellite's normal mode was applied to the algorithm. Also, the attitude of the satellite was determined by using only an autonomous star tracker in the paper.