Gyroless Attitude Nonlinear Observer for RazakSAT Satellite

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Muaz Zafran

Nur Najihah

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To all my family members

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LIST OF ABBREVIATIONS

ACF	Autocorrelation Function
ACS	Attitude Control System
ADCS	Attitude Determination and Control System
ADS	Attitude Determination System
ASMO	Augmented Sliding Mode Observer
AKF	Augmented Kalman Filter
COMM	Communication Subsystem
C&DH	Command and Data Handling
DCM	Direction Cosine Matrix
EHGO	Extended High Gain Observer
EKF	Extended Kalman Filter
EPS	Electrical Power Subsystem
HGO	High Gain Observer
KF	Kalman Filter
LEO	Low Earth Orbit
LPF	Low-pass Filter
LSE	Least Square Estimation
MME	Minimum Mean Error
MRP	Modified Rodrigues Parameter
NEqO	Near Equatorial Orbit
PDF	Probability Density Function
PF	Particle Filter
PSD	Power Spectral Density

RMSE	Root Mean Squared Error
RPF	Regularized Particle Filter
SMO	Sliding Mode Observer
SVD	Singular Value Decomposition
TT&C	Telemetry, Tracking and Command
UKF	Unscented Kalman Filter

LIST OF SYMBOLS

X_O, Y_O, Z_O	orbit frame axis
X_B, Y_B, Z_B	body frame axis
X_I, Y_I, Z_I	inertial frame axis
$\varphi - \theta - \emptyset$	roll – pitch – yaw angles (Euler angles)
$q = [q_1, q_2, q_3. q_4]^T$	quaternion
ω_{BO}	angular velocity of body frame relative to orbit frame
ω_{OI}	angular velocity of orbit frame relative to inertial frame
ω_{BI}	angular velocity of body frame relative to inertial frame
$c(.)$	cosine function
$s(.)$	sine function
$(\dot{\ })$	time derivative of the variable
ω_0	orbital rate
$[A]$	direction cosine matrix (DCM)
$I = diag[I_x, I_y, I_z]$	satellite's moment of inertia
$\omega = [\omega_x, \omega_y, \omega_z]$	satellite's angular velocity
$T = [T_x, T_y, T_z]$	space environmental disturbances torque
$x(t)$	system state (continuous)
$y(t)$	measurement (continuous)
$v(t)$	process noise (continuous)
$w(t)$	measurement noise (continuous)
x_k	system state at time k (discrete)
y_k	measurement at time k (discrete)
v_k	process noise at time k (discrete)

w_k	measurement noise at time k (discrete)
R_v	process noise variance
R_w	measurement noise variance
Δt	time interval
$(\cdot)_k$	k-th time step of the variable
$p(\cdot)$	probability distribution function (pdf)
$q(\cdot)$	pdf for importance sampling function
$L_f(h)$	Lie derivative of scalar function *h* with respect to vector field *f*
ρ_k	autocorrelation function
$\mathrm{E}\{.\}$	expectation operator
$\hat{x}_{k\|k}$	posteriori state at time k
$P_{k\|k}$	posteriori variance at time k
$\hat{x}_{k\|k-1}$	priori state at time k
$P_{k\|k-1}$	priori variance at time k
G_k	Kalman gain
x_0	initial state
P_0	initial variance
A, B	linear system matrices
F, H	linearized system matrices
$y_{1:k}$	previous measurements until time k
x_k^i	set of random samples (or particles) at time k
W_k^i	normalized weight for i^{th} sample at time k
$\widetilde{W}_k^i$	unnormalized weight for i^{th} sample at time k
$X_k = \{x_0, \dots, x_k\}$	states trajectory

$Y_k = \{y_0, \ldots, y_k\}$	measurements trajectory
$X_k^i = \{x_0^i, \ldots, x_k^i\}$	samples trajectory
N_s	Number of particles (or samples) /sample size
N_{eff}	Number of effective particles (or samples) / effective sample size
$N(\mu, \sigma^2)$	Gaussian distribution with mean μ and variance σ^2

ABSTRAK

Pemerhati Tak Linear Tanpa Giroskop untuk Satelit RazakSAT

Penentuan sikap keadaan satelit merupakan salah satu aspek penting dalam Sistem Penentuan dan Kawalan Sikap Satelit (ADCS) sesebuah satelit. Sikap keadaan satelit perlu ditentukan untuk dihantar kepada sistem kawalan dalam mencapai sesuatu misi satelit tertentu seperti pemerhatian Bumi, komunikasi, penyelidikan saintifik dan lain-lain misi. Dalam kebiasaan amalan ADCS, keadaan semasa halaju dan sikap kapal angkasa diperolehi masing-masing daripada pengukuran giroskop dan sensor sikap. Walau bagaimanapun, giroskop adalah mahal dan sering terdedah kepada kegagalan berfungsi. Oleh itu penyelidikan ini bertujuan untuk mengkaji sistem anggaran untuk kapal angkasa tanpa giroskop. Dalam penyelidikan ini, model matematik tidak linear sistem ini diterbitkan menggunakan gabungan persamaan gerakan dinamik dan persamaan gerakan kinematik menggunakan parameter sudut Euler. Kebolehtinjauan sistem anggaran yang diterbitkan dipastikan menggunakan teknik derivatif Lie untuk memastikan kebolehtinjauan sistem. Model tidak linear tersebut juga ditentusahkan menggunakan data telemetri penerbangan RazakSAT, satelit Malaysia yang telah mengorbit dalam Orbit Hampir Khatulistiwa pada tahun 2009 menggunakan 'extended Kalman filer' (EKF), algoritma yang telah banyak diaplikasikan dalam praktis kapal angkasa. Dalam penyelidikan ini juga, hingar putih bukan Gaussian dalam sistem anggaran didiagnosis dan dianalisis berdasarkan data telemetri RazakSAT menggunakan teknik-teknik statistik. Prestasi anggaran keadaan semasa ketiadaan giroskop menggunakan algoritma 'particle filter' (PF) juga dikaji dan dibandingkan dengan EKF dari segi aspek ketepatan, beban masa komputasi dan ketahanan terhadap hingar bagi tujuan pelaksanaan yang cekap. Hasil kajian menunjukkan bahawa sistem tanpa giroskop dapat menyediakan maklumat halaju sudut dalam ketepatan 0.1 deg/s, yang sesuai untuk penentuan sikap berketepatan sederhana seperti ketika mod pengemasan dan detumbling. Dari segi aspek ketepatan dan ketahananan terhadap hingar, PF menunjukkan kebolehannya memberi keputusan anggaran yang lebih tepat dalam keadaan hingar bukan Gaussian dan bukan putih dan lebih tahan terhadap ketidakpastian pengukuran. Manakala dari segi aspek masa komputasi, hasil kajian menunjukkan bahawa EKF adalah lebih cepat daripada algoritma PF. Walaubagaimanapun untuk aplikasi ini, PF adalah sangat dicadangkan semasa ketidakpastian pengukuran yang amat tinggi disebabkan oleh kegagalan yang tidak dijangka daripada sensor sedia ada. Kajian sistem tanpa giroskop ini mampu menyumbang sebagai sistem alternatif atau sokongan semasa ketiadaan data halaju sudut satelit yang disebabkan oleh kerosakan sensor atau direka bagi tujuan mengurangkan sensor yang mana secara tidak langsung mengurangkan kos dan perkakasan komplikasi.

ABSTRACT

Gyroless Attitude Nonlinear Observer for RazakSAT Satellite

Satellite attitude determination is one of the important aspects in Attitude Determination and Control System (ADCS) of a satellite. Satellite attitude is important to be determined in a satellite to be fed back to controller in accomplishing a specific satellite mission such as Earth observation, communication, scientific research and many other missions. In commonly practice of ADCS, the angular velocity and attitude information of a spacecraft are obtained respectively from measurement of gyroscopes and attitude sensors. However, gyroscopes are generally expensive and are often prone to degradation or failure. Hence this research work is intended to study the state estimation system for gyroless spacecraft. In this work, the nonlinear mathematical model of the system is derived using combination of dynamics equation of motion and kinematics equation of motion using Euler angles attitude parameter. The observability of the derived nonlinear system is investigated using Lie derivative technique to ensure the system observability. The derived nonlinear model is also validated and verified using real in-flight telemetry attitude data of RazakSAT, the Malaysian satellite was orbiting in Near Equatorial Orbit in 2009 via extended Kalman filter (EKF), the most widely used algorithm in spacecraft practice. The non-Gaussian non-white noise in estimation system based on RazakSAT telemetry attitude data also is diagnosed and analyzed in this work using statistical techniques. Finally, the performance of state estimation during gyroless condition using particle filter (PF) algorithm is studied and compared with the EKF in terms of accuracy, computational time load and robustness aspects for efficient on-board implementation. The result shows that the gyroless system is able to provide the information of angular velocity within 0.1 deg/s accuracy, which is suitable for moderate accuracy attitude determination such as during housekeeping and detumbling mode. In terms of accuracy and robustness aspects, the PF shows its ability to provide more accurate estimation in non-Gaussian and non-white noise circumstances and more robust to measurement uncertainty. Meanwhile in terms of computational time aspect, the result shows that EKF is faster than PF algorithm. For this application, the PF is strongly suggested during contingency condition of extremely inaccurate or large uncertainty measurements such as due to unexpected failure of the existing sensor. The study of gyroless system contributes as an alternative or backup system during unavailable angular velocity data resulted from faulty sensor or deliberately designed for sensor reduction which indirectly represent cost and hardware complexity reduction.

CHAPTER 1

INTRODUCTION

1.1 Background

Today, a satellite is undoubtedly important to the world. On the average, the world use some form of space asset many times per day with the aid of satellite including weather, television, telephones, navigation, internet and more. The importance applications of a satellite in man daily life make the development of the satellite became an extensive research field. Malaysia also is already going into the race of aerospace technology.

In general, a satellite is defined as any object orbiting in an orbit. In the context of spaceflight, a satellite is an artificial object which has been intentionally placed into orbit. Such objects are sometimes called artificial or man-made satellites to distinguish them from natural satellites such as the Moon. In this thesis the satellite refers to the artificial satellite.

Historically, Malaysia satellite programme was initialized by the 4th Prime Minister of Malaysia,Tun Dr. Mahathir Mohamad in 1993 to develop Malaysia's first satellite communications system. The first satellite in Malaysia is Malaysia East Asia Satellite (MEASAT), a communication satellite owned and operated by a Malaysian communications satellite operator MEASAT Satellite Systems Sdn. Bhd. Meanwhile TiungSAT, the first Malaysian microsatellite was developed through the technology transfer and training programme between Astronautic Technology Sdn. Bhd. (ATSB)

Malaysia and Surrey Satellite Technology of the United Kingdom in 2000 for experiments in Earth imaging, observation of meteorology, detection of cosmic rays, data storage and communications. Development of Malaysia satellite programme continued with development of RazakSAT, the first remote sensing satellite launched into a unique Near Equatorial Orbit in 2009 for imaging opportunities in the equatorial region. It was jointly developed by ATSB and Satrec Initiative, a commercial satellite manufacturer in Korea. Meanwhile, the piggyback satellite Innovative Satellite, InnoSAT is a nano satellite mission to demonstrate local innovative space technology amongst the instituition of higher learning in the space sector. It is developed by the Universiti Sains Malaysia (USM), Universiti Teknologi Malaysia (UTM) and Universiti Malaysia Perlis (UniMAP). The purpose of this payload is to provide a satellite navigation module based on a space GPS receiver (SGR) that is low-cost to build which uses generic, off-the-shelf (COTS) components and in-house developed algorithms.

Basically, there are four important subsystems of a satellite in accomplishing its mission in space. They are attitude determination and control subsystem (ADCS), telemetry, tracking and command (TT&C) or also known as communication (COMM) subsystem, command and data handling (C&DH), and electrical power subsystem (EPS) (Wertz & Larson, 2004; Sharun, 2013). Every subsystem has its own specific task to maintain the satellite while orbiting, as described briefly as follows:

i. Attitude determination and control subsystem (ADCS) serves to determine the current states of the satellite and control by stabilizing or orienting it into desired directions during the mission despite of the external disturbance torques acting on it.

ii. Telemetry, tracking and command (TT&C) / communication (COMM) provides the interface between the spacecraft and ground station systems which receive, process, and transmit data signals downlink and uplink.

iii. Command and data handling (C&DH) is the 'brain' of the whole autonomous satellite which control and monitors the overall operation system of the satellite using on-board computer (OBC).

iv. Electrical power subsystem (EPS) provides, stores, distributes, and controls satellite electrical power required to operate all electronic devices of a satellite during the mission.

Among many function of subsystems, ADCS is a mission-critical real-time embedded system and as such receives considerable care to ensure reliable operation in space (Wertz, 1978). Generally, ADCS is decomposed into several components including the spacecraft dynamics itself, the attitude determination system (ADS) which consisting of sensors and attitude estimation algorithm, and attitude control system (ACS) which include the control algorithm and actuators. The general structure of ADCS is shown in Figure 1.1. In general, the satellite's attitude is measured using sensors. However, since most of the sensors are inherent with noises such as random noise and bias noise, hence the filtering algorithm is required to provide the best estimation of the current attitude in spite of the noise presence in the measurements. Subsequently, the estimated attitude will be fed back into the control algorithm, in which the control algorithm will send the desired command to the actuators, as the actuators provide the required forces or torques to control the satellite's attitude into the desired attitude.

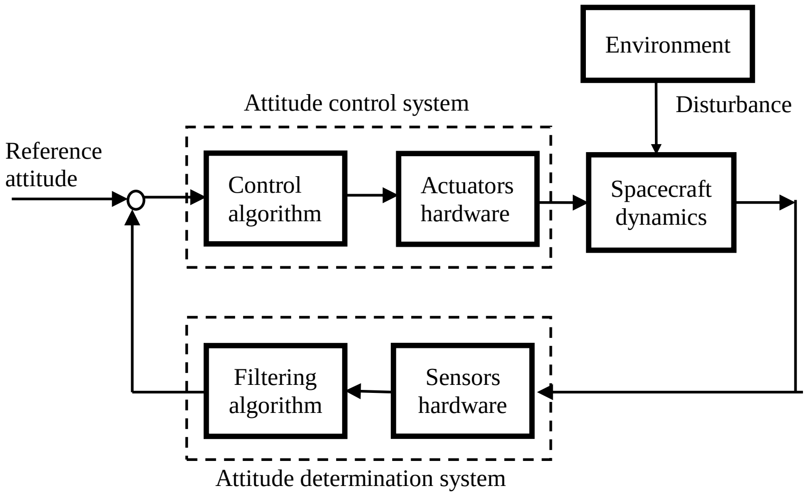

Figure 1.1: General structure of a satellite's Attitude Determination and Control Subsystem (ADCS).

Attitude determination is one of the important processes in ADCS that ensuring the success of a satellite mission. It is a process to determine the current attitude of the satellite to be fed back into the controller for attitude control purpose. In general there are two approaches in determining the satellite attitude which are deterministic approach and recursive estimation approach. Deterministic approach is an approach where the attitude is found based on two or more vector observations from a single point at a time. Meanwhile, recursive approach is an estimator that utilizes dynamics and/or kinematics models and subsequently can estimate the attitude of a spacecraft using a time series of measurements from one or more vector observations.

The advantages of deterministic approach are the attitude of the satellite can be estimated using measurements of more than two vectors and efficient for on-board implementation. However the deterministic approach fails when only one set of vector measurements is available. The unavailability of some other sensor measurements could be due to faulty sensor or deliberately designed for sensor reduction which indirectly reduces the hardware complexity and production cost of a satellite. Hence the recursive estimation approach is very important as a backup or alternative system to determine the attitude in such condition problem. As summary, the background of this research work is depicted in the following figure.

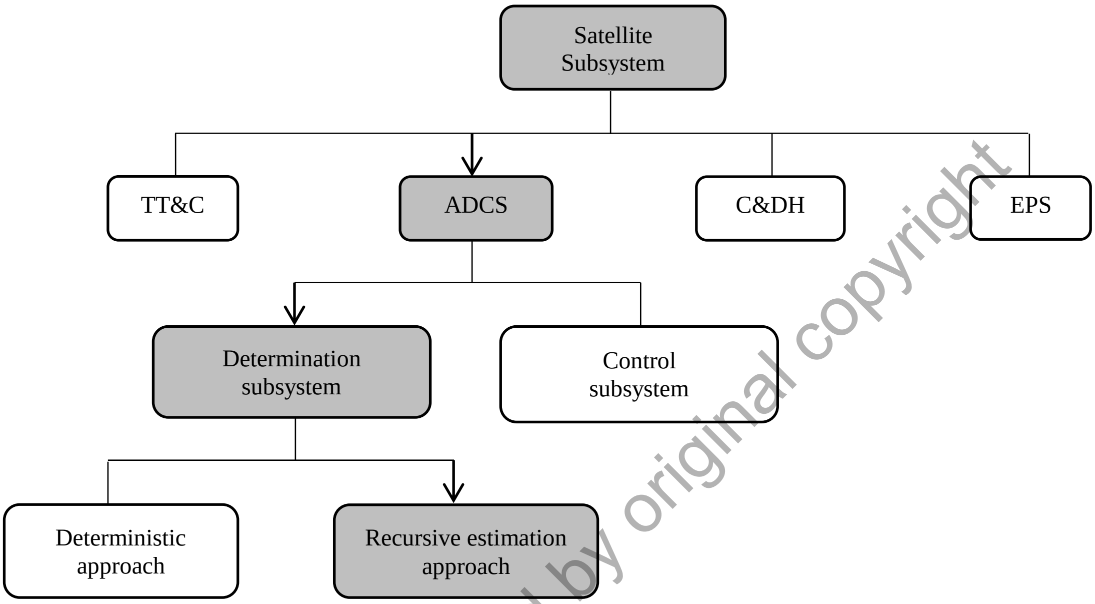

Figure 1.2: Summary of research background.

1.2 Motivation and Problem Statement

In common practice of ADS, the satellite's attitude and angular velocity information is obtained through deterministic approach by using attitude sensor and gyroscope respectively as depicts in Figure 1.3. However, gyroscopes are generally expensive and are often prone to degradation or failure. Hence this research is intended to study the satellite's attitude determination system without gyroscope or so called gyroless problem using recursive state estimation algorithms as shown in Figure 1.4, which can be an alternative or backup system during unavailable satellite's angular velocity data. In Figure 1.3 and Figure 1.4, ω and θ are respectively represent the angular velocity and attitude parameter, while $(\tilde{\cdot})$ and $(\hat{\cdot})$ are their respective measurement and estimated states.

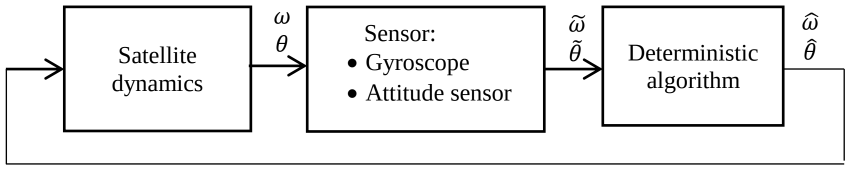

Figure 1.3: Block diagram of common ADS.

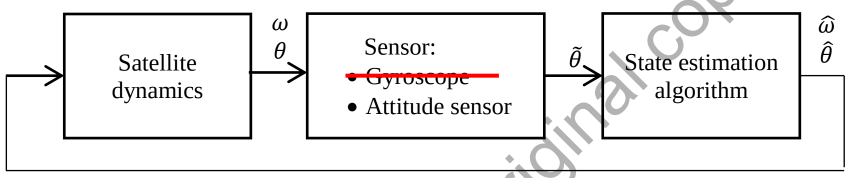

Figure 1.4: Block diagram of gyroless ADS.

Hence by having real telemetry data of RazakSAT, one of the Malaysian satellites, it is the intention of this research to study and investigate the satellite attitude estimation during gyroless circumstances.

In state estimation problem, two important elements are involved which are dynamics model and estimation algorithm. From the literature, the most popular kinematics equation model to represent the attitude parameter is quaternion kinematics model. However, quaternion representation contains one redundant parameter in its four dimensional lead to no clear physical interpretation. Hence, in this thesis we will derive the dynamics model for RazakSAT by using the kinematics equation of Euler angles parameter due to its straightforward physical interpretation for observability analysis rather than quaternion which cannot provide direct interpretation for observability analysis.

Meanwhile, the most commonly used estimation algorithm in satellite attitude estimation during gyroless condition whether in real practice or theoritically is the extended Kalman filter (EKF). Nevertheless, it is known that EKF algorithm strictly assumed that the nature of the noise or errors in the system is Gaussian white noise. Yet, in real world this is not always true. In practice, this could be due to geomagnetic field measurement as been reported in TechSAT real data, where double-peaked distribution of the geomagnetic field measurement by three-axis magnetometer data was observed (Oshman & Carmi, 2006). Errors due to multipath effects (Zhou, Yang, Zhang, & Edwan, 2011) and gravitational field fluctuations generated during warm inflation also may lead to the non-Gaussian distributed noise (Gupta, Berera, Heavens, & Matarrese, 2002). Hence in this work, we will analyze and investigate the Gaussianity and whiteness of noise in RazakSAT data for estimation process.

However, there is an estimation approach that does not require the assumption of a specific noise as EKF which is particle filter (PF). Since the seminal paper (Gordon, Salmond, & Smith, 1993), PF has become one of the most popular methods for stochastic estimation problems, and some authors believe and claim that beyond the EKF is the PF (Ristic, Arulampalam, & Gordon, 2004). The popularity is due to the advantage of PF algorithm that does not strictly assume the Gaussian white noise in the system as EKF, which will lead to less accurate estimation if the assumption is incorrect. In this thesis, we will study the state estimation for gyroless RazakSAT by using PF algorithm which will be compared with EKF, the most commonly used algorithm in spacecraft community.