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Performance of a novel heat based model for spacecraft attitude estimation

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ABSTRACT

This paper presents a novel heat based measurement model for attitude determination (AD) using temperature data via two filtering techniques. Within the space environment, the Sun and Earth are considered as the major sources of external radiation that affect satellite surface temperature. In order to perform the required AD task, the satellite surface temperatures are related to its attitude via a proposed heat model (HM), assuming that the satellite navigational data is available. The proposed HM relates the net heat flux of three satellite orthogonal surfaces to its attitude. Filtering implementation of the proposed HM using the Unscented Kalman Filter (UKF) for AD is the key contribution of this paper, while the results are compared with those of the Extended Kalman Filter (EKF) for performance assessment. The results demonstrate the positive applicability of the proposed HM for AD via filtering, while performance evaluation of both filtering techniques is performed using a Monte Carlo simulation. In addition, threshold boundaries for the satellite initial attitude and rates error for which the proposed HM is able to produce acceptable AD results are outlined. The study is completed with a pertinent conclusion and future research directives.

1. Introduction

Attitude Determination (AD) is a critical issue in many space missions in which accurate knowledge of space vehicle's attitude is required for pointing. While the subject of AD research is ongoing, it usually consists of three parts that include proper choice of attitude representation, selection of attitude sensors, and deciding on the appropriate filtering algorithm.

Euler angles [1], quaternions [2], and Gibbs vector [3] have been widely utilized as means of attitude representation in many studies. Moreover, Sun sensors, magnetometers, gyroscopes, horizon sensors and star trackers are among the most common sensors used for AD task either separately [4–6] or in combination [7–9]. Selection of attitude sensors is usually based on the mission requirements and decided upon by the system engineers. There has been a recent study focused on utility of temperature sensors for heat flux computation as a primary step in AD [10], where the authors have analyzed limitations, resolution, and accuracies of thermal data in the process of heat flux computation. Temperature data are also used for filter tuning where magnetometers were used to extract the required data for AD [11]. A heat model that uses heat flux for AD is also introduced [12] where the satellite attitude is determined via the basic Levenberg–Marquardt (LM) deterministic least square algorithm. As LM algorithm does not account for the measurement noise effect, the results are not sufficiently accurate. Experimental validation of the proposed HM has also been investigated [13] in a near space environment, where a small cubic satellite is tested in a vacuum chamber equipped with a Sun Simulator. A sensor pack, Advanced Coarse Earth Sun Sensor (ACESS) [14] is also commercially available that provides omnidirectional coarse estimation of the Earth and Sun position vectors in the satellite reference frame. In essence a combination of six ACESS packs can provide the satellite navigational data, while the proposed HM uses only three non-contact thermopiles (NCT) for attitude determination.

There are also various forms of Kalman filters utilized for AD. EKF is a popular nonlinear filter that is widely used in some practical applications. In the EKF structure, nonlinear attitude equations are used in the forward estimation process, while the estimates are updated in a recursive manner using the measurement data [15–17]. Extension of EKF has led to Multiplicative EKF whose performance is enhanced in term of computational efficiency [18,19].

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Nomenclature

Upper case

A	surface area
C	transformation matrix
F_h	shape factor parallel to relative position vector
F_v	shape factor perpendicular to relative position vector
G	Earth flux
H	sensitivity matrix
I	identity matrix
J	moment of inertia tensor
K	Kalman filter gain
M	external torque
P	covariance matrix
Q	heat flux
Q^*	covariance of process noise
R	covariance of measurement noise
S	Solar radiation flux
T	temperature
Z	measurement vector

Lower case

c	specific heat capacity
f_a	Albedo factor
m	mass
n	normal to surface
q	quaternion
r	position
t	time
v	measurement noise
w	process noise
x	state

Greek

α	absorptivity
ε	average emissivity
θ	angle between normal to the surface and relative position vectors
σ	Stefan–Boltzmann constant
ω	angular velocity

Overscript

$\rightarrow$	vector
$\wedge$	estimate

Superscript

b	body
I	inertia
s	Sun
T	transpose

Subscript

i	number of surface
rel	relative

Unscented Kalman Filter (UKF) is also among the other well-known alternatives of EKF family of nonlinear filters that is sample based. UKFs are suitable for applications involving complicated measurement equations. Although UKF outperforms EKF, its utility is computationally intensive due to increased number of sigma points [20–23].

A key underlying assumption for EKF and UKF family of filters related to the Gaussian nature of the noises associated with the process and the measurement models. To overcome this restriction, the notion of sample based filters or Particle Filters (PFs) has been introduced posing new filter structures based on sequential Monte Carlo simulations in which different distributions are approximated via weighted particles [24–27]. Since the key contribution of this study is focused on the development and evaluation of a new measurement model, the basic EKF and UKF family of nonlinear filters are utilized to implement the proposed HM.

As one of the key ingredients of the filtering algorithms, a novel measurement model is developed and utilized in the present study. The proposed HM is founded base on the concept of Net Heat Flux (NHF) received by Three Satellite Orthogonal Surfaces (TSOS) assuming that the satellite surfaces are isolated from internal heat radiation sources. Thus, the Sun and Earth are the only external heat sources considered. In this respect, direct solar radiation, Earth flux, and its albedo are the major means of heat exchange between the satellite and the space environment. To establish the required HM for AD, NHF of each satellite surface is related to the satellite attitude, where NHF of each surface is represented via a normal (to surface) vector using the concept of view factors [28]. Subsequently, the spacecraft inertial attitude can be established using the knowledge between the satellite relative position vectors (with respect to the Sun and Earth) in the Earth Centered Inertial (ECI) coordinate system and the spacecraft body coordinate system. As mentioned before, the proof of our HM based AD is presented using the two well-known filtering algorithms of EKF and UKF. In addition, estimation accuracy, computational burden as well as the performance of the two filtering methods are compared and analyzed via a Monte Carlo simulation.

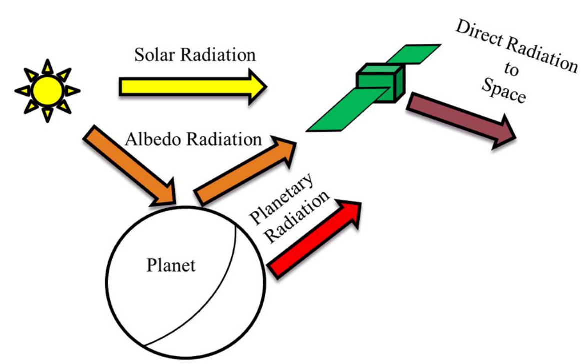

Fig. 1. Thermal environment of a typical spacecraft [29].

This paper is arranged as follow: The proposed HM is introduced in section 2. In section 3, the developed HM is implemented using both filtering techniques of EKF and UKF. Section 4 is devoted to results and their comparison in terms of AD and accuracy level and performance evaluation via the Monte Carlo simulation. Pertinent conclusion and future research directives are attended to in section 5.

2. Development of the HM

Radiation is considered the major heat exchange mechanism within the space environment [29]. Therefore, a typical satellite surface can receive direct solar radiation, planetary (Earth) radiation as well as Earth reflecting radiation as albedo. These radiation forms are shown in Fig. 1 for a typical orbiting satellite.

The ultimate purpose of developing a new HM is to derive a relation between the NHF that satellite surfaces receive and its at-