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Experimental validation of a novel radiation based model for spacecraft attitude estimation

A. Labibian (Joint PhD Candidate)[a], Seid. H. Pourtakdoust (Professor)[b,*], M. Kiani (PhD)[b], Ali Akbar Sheikhi (Researcher)[b], A. Alikhani (Assistant Professor)[c]

[a] *Aerospace Research Institute and Sharif University of Technology, Tehran, 14665 834, Iran*
[b] *Center for Research and Development in Space Science and Technology, Sharif University of Technology, Tehran, 145888 9694, Iran*
[c] *Aerospace Research Institute, Ministry of Science, Research and Technology, Tehran, 14665 834, Iran*

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ABSTRACT

Attitude Determination (AD) is one of the key requirements of many current and emerging remote sensing missions. As such AD has been traditionally accomplished through a variety of algorithms and measurement models pertinent to sensing mechanisms. The current paper addresses conceptual validation and utility of a novel radiation based heat (measurement) model for space application. The proposed new Heat Attitude (HA) model utilizes temperature data to relate the Satellite Surfaces' (SS) Net Heat Flux (NHF) to attitude assuming that the satellite navigational data are available. As Sun and the Earth are considered the main external sources of radiation, their effects are modeled for the SS temperature changes via a novel measurement model and sensing mechanism. In this respect and in order to experimentally validate the capability of the proposed HA model, a Cubic Laboratory Satellite (CLS) with three orthogonal copper coated surface plates is constructed. Next, Non-Contact Thermopiles (NCT) are installed to measure the SS radiative temperatures in a vacuum chamber equipped with a Sun simulator. Subsequently, the CLS is tested under static and dynamic scenarios where the temperature data are used for error analysis and model validation via an Extended Kaman Filter (EKF). Comparison of the CLS true and HA model EKF estimated attitudes demonstrate a good accuracy. In this sense, the proposed novel HA model is promising and paves the way for a new low cost alternative approach for space AD applications.

1. Introduction

ATTITUDE Determination (AD) has always been considered an important task for satellite Attitude Control Systems (ACS). There are generally three major parts for AD that include Attitude Representation (AR), Attitude Sensors (AS) and Estimation Algorithms (EA), all of which are still considered significant topics among researchers and engineers.

For the first part, AR can be accomplished via a variety of schemes such as the Euler angles, quaternions and Rodrigues parameters as some of the more widespread approaches that are not the focus of this research. Moreover, AS is usually dictated by mission requirements rendering utility of Sun sensors, magnetometers, star tracker and gyroscope either distinctively [1] or in combination for redundancy and/or increased accuracy [2]. Recently, there have been some studies in which temperature sensors are utilized for heat flux computation as a primary step for AD [3] or as an aid in EA for filter tuning and convergence check [4]. Additionally absorbed heat flux is also investigated [5], where the authors have utilized a basic deterministic modified Levenberg-Marquardt algorithm for AD with no measurement noise that should be considered for practical applications. In this sense, utility of NCT as the only means of measurement for AD via nonlinear filrteing techniques, that is the focus of the present work has not yet been reported.

Finally, EA research is still ongoing and new robust, accurate, hybrid and/or nonlinear filtering algorithms based on Extended Kalman Filter (EKF) [6,7], Unscented Filter (UF) [8,9] and Particle Filter (PF) [10,11] are being investigated by scientists. It is important to note that most EAs require a measurement model to relate the noisy measured data to the satellite attitude via one of AR methods.

In this paper, a novel temperature based HA measurement model is validated for space systems AD. The proposed HA model relates the SSs received NHF to the satellite attitude [12] and is

* Corresponding author.
E-mail addresses: a.labibian@gmail.com (A. Labibian), pourtak@sharif.edu (Seid.H. Pourtakdoust), m_kiani@ae.sharif.ir (M. Kiani), Aliakbar.sheikhy@yahoo.com (A.A. Sheikhi), Aalikhani@Ari.ac.ir (A. Alikhani).

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Nomenclature

Upper case Letters

A	Surface area
C	Transformation matrix
F	View factor (shape factor)
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
K	Kalman filter gain
Q	Heat flux
Q^*	Covariance of process noise
R	Covariance of measurement noise
S	Solar radiation flux
T	Temperature

Lower case Letters

c	Specific heat capacity
e	Error
f	Vacuum chamber wall reflective factor
f_a	Albedo factor
m	Mass
n	Normal to surface
r	Position
t	Time
v	Measurement noise
w	Process noise
x	State
z	Measurement vector

Greek Symbols

α	Absorptivity
ε	Average emissivity
φ,θ,ψ	Euler angles
σ	Stefan-Boltzmann constant

Overscripts

$\rightarrow$	Vector

Superscript

b	Body
I	Inertia
s	Sun
T	Transpose

Subscript

i	Number of surface

experimentally validated for a CLS in a vacuum chamber equipped with a Sun simulator. For most orbiting satellites, Sun and Earth are the main external heat sources that affect the SS temperature fluctuations. In turn, SSs NHF can be related to satellite Position Vectors (PV) with respect to Sun and Earth respectively in the satellite body frame using the concept of shape factors [13]. Subsequently, the satellite attitude knowledge can be determined via any well-known EA using these satellite PVs, given the assumption that the satellite navigational data are available for AD.

As mentioned before, the key intended contribution of the current paper is to experimentally validate the proposed temperature based HA model. For this purpose, a CLS model is constructed and tested in a vacuum chamber equipped with a Sun simulator. The CLS is made of three orthogonal copper plated surfaces properly insulated, so as to not receive any internal radiation and/or conduction effects. The CLS surface temperatures are measured via NCTs and transferred to a Personal Computer (PC) for AD. As the most widely utilized EA, EKF is utilized in this paper for AD and the results are compared with the CLS true attitude.

The remainder of this paper is arranged as follow: Section 2 introduces the proposed HA model, its relation to the NHF of SSs and finally to the satellite attitude. Section 3 is devoted to the validation process of the proposed HA model including construction aspects of the CLS, sensoring and hardware installations and finally implementation of EKF for AD and its results. Section 4 is dedicated to a complete relevant errors and uncertainty analysis over the proposed HA model, followed by the conclusion and future directives in section 5.

2. Heat-attitude model representation

Radiation is the most significant mechanism of heat exchange in space environment. As such, the Sun and Earth are considered the two main external radiative heat sources affecting the satellite heat capacity via four key mechanism that include direct solar radiation, Earth radiation, Albedo radiation and finally radiation from spacecraft to deep space [14]. As these mechanisms are described in many classical references [13], their usual description and details are not covered here. However, matters involving their relation to the satellite attitude is requires for the problem of AD and thus are briefly discussed [12] here. It is however important to note that to establish the desired proposed HA model, the SSs are assumed isolated from the internal radiating sources via specialized Multi Layer Insulations (MLI). Next, in order to establish the desired relation between the SS received heat flux with the satellite attitude, orientation of a SS with respect to a radiative heat source is considered as in Fig. 1:

As shown in Fig. 1, each SS unit normal vector, $\vec{n}$ can be decomposed in two directions of parallel and perpendicular to the satellite PVs with respect to any of the radiating heat sources, where $P$is obviously the projection of $\vec{n}$ in direction of the satellite PV,$\vec{r}$.

On the other hand, each SS received heat flux can be in turn related to the above mentioned directions via the concept of view factors [13]. For example, the received heat flux of the SS in direction of $\vec{r}$ (Q_h) can be determined in the following form:

$$Q_h = Q_{source}AFP \quad (1)$$

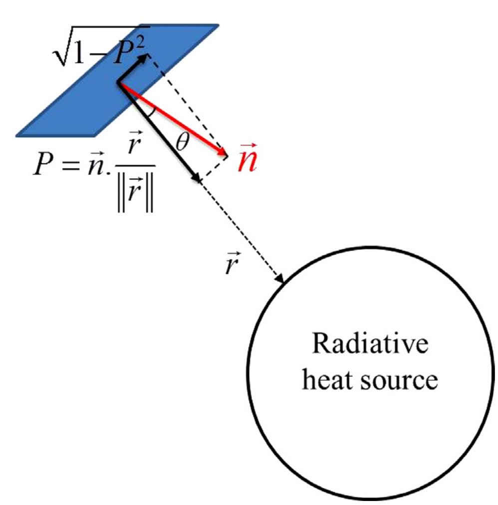

Fig. 1. Decomposition of SS normal vector.