Acta Astronautica 105 (2014) 344–354

Contents lists available at ScienceDirect

Acta Astronautica

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

Attitude determination of planetary exploration rovers using solar panels characteristics and accelerometer

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ARTICLE INFO

Article history:
Received 8 July 2014
Received in revised form
7 October 2014
Accepted 9 October 2014
Available online 19 October 2014

Keywords:
Planetary rover
Navigation
Attitude determination
Solar panel
q method

ABSTRACT

In this study, we propose a new attitude determination system, which we call Irradiance-based Attitude Determination (IRAD). IRAD employs the characteristics and geometry of solar panels. First, the sun vector is estimated using data from solar panels including current, voltage, temperature, and the normal vectors of each solar panel. Because these values are obtained using internal sensors, it is easy for rovers to provide redundancy for IRAD. The normal vectors are used to apply to various shapes of rovers. Second, using the gravity vector obtained from an accelerometer, the attitude of a rover is estimated using a three-axis attitude determination method. The effectiveness of IRAD is verified through numerical simulations and experiments that show IRAD can estimate all the attitude angles (roll, pitch, and yaw) within a few degrees of accuracy, which is adequate for planetary explorations.

1. Introduction

Planetary rovers are being increasingly used in space exploration missions. With their ability to traverse the surface of planets they are capable of in-situ exploration even in areas where landers cannot land, such as steep craters. The National Aeronautics and Space Administration (NASA) sent two rovers, named Mars Exploration Rovers (MER) Spirit and Opportunity, to Mars in 2003 [1]. The two rovers subsequently explored the surface of Mars and gathered a wealth of information. In 2011 NASA also sent Curiosity to explore the habitability of Mars [2]. The Japan Aerospace Exploration Agency (JAXA) is currently planning a mission to the moon called the SELENE-2 mission [3]. In this mission, rovers are expected to travel across wide open areas and observe terrain features using onboard scientific instruments.

In planetary exploration missions using rovers, navigation relies on integrated local measurements, such as combinations of inertial sensors, and wheel and visual odometry. These systems are essential for obtaining data on the attitude of rovers that are required for accurate guidance. This system for planetary rovers is called an attitude determination system.

A number of studies have proposed attitude determination systems for rovers. The Mars exploration rovers, Spirit and Opportunity [4], explored the surface of Mars and gathered a wealth of information using an attitude determination system with cameras and inertial sensors. Furgale et al. [5] proposed a system that combined a sun sensor and an accelerometer, and showed its efficiency in experiments.

For future missions using rovers, a redundant attitude determination system is now a requirement. First, because rovers are required to enable long traverse explorations and long mission terms. In addition a sensor malfunction was reported in the Curiosity mission [6]. A redundant attitude determination system is needed in such cases. Generally there are two means of building a redundant system, one is

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http://dx.doi.org/10.1016/j.actaastro.2014.10.013
0094-5765/

to equip with identical redundant sensors, and the other is to use a different combination of sensors. Therefore in this study, we aim at building an attitude determination system by the different combination of sensors that rovers are already equipped with.

In this study, we propose a new attitude determination system, which we call Irradiance-based Attitude Determination (IRAD). IRAD combines the characteristics of solar panels, and an accelerometer. The sun vector can be estimated by measuring the current, voltage, and temperature of the solar panels as the electric power generation of each solar panel depends on their arrangement and the position of the sun. By combining this sun vector with the gravity vector obtained using an accelerometer, the attitude of the rover can be estimated. The *q* method [7] is generally known as a technique for obtaining an attitude from two observation vectors. Santoni et al. [8,9] proposed an attitude determination system for small spinning spacecraft, which combines the characteristics of solar panels with a magnetometer. This system was aimed at regular octagonal pillar shaped spacecraft, which is a characteristic shape of spinning spacecraft. Burton et al. [10] proposed an online attitude determination filter using the electrical current from body mounted solar panels and the spacecraft dynamics for the CubeSat nano-satellites. In this study we employ the minimization of a cost function using the normal vectors of the solar panels of the rovers to apply to various shapes of rovers. The efficiency of IRAD was validated through numerical simulations and experiments.

IRAD is useful for planetary rovers. First, it does not require any external sensors. Second, the solar panels necessary for power generation can also be used as sensors for attitude determination.

2. Mathematical models

This section provides the mathematical models for the analysis used in this study. We first define the frames of reference and mathematical models for solar panels and noise which has an effect upon an attitude determination system. These noises should be considered and compensated to estimate the attitude precisely.

2.1. Frames of reference

As shown in Fig. 1a, the topocentric frame is defined with respect to the local horizon, the Z_t axis is the normal vector to the tangent plane, the Y_t axis is along North and the X_t axis is defined by the right-handed system. In contrast, as shown in Fig. 1b, the origin of the rover frame is located at the rover itself, the X_r axis is along the direction of travel, the Z_r axis is vertical to the rover and the Y_r axis is defined by the right-handed system. We define rotation around the X_r axis as roll, the Y_r axis as pitch, and the Z_r axis as yaw.

2.2. Solar panels model

IRAD employs the electric power generated by the solar panels to estimate an attitude of the rover. Therefore solar panel modeling is required as discussed in this section.

There is relationship between the voltage and current of a solar panel, which is called the *I–V* curve. It is possible to store the *I–V* curve in the memory of a rover, but it varies depending on the irradiance and temperature of the solar panel, so it is not realistic to store all the *I–V* curves corresponding to possible irradiance and atemperature

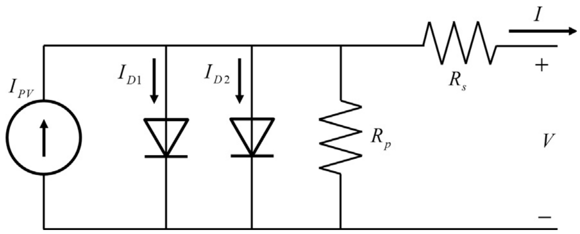

Fig. 2. Equivalent circuit of a cell of a solar panel described in the two-diode model [11].

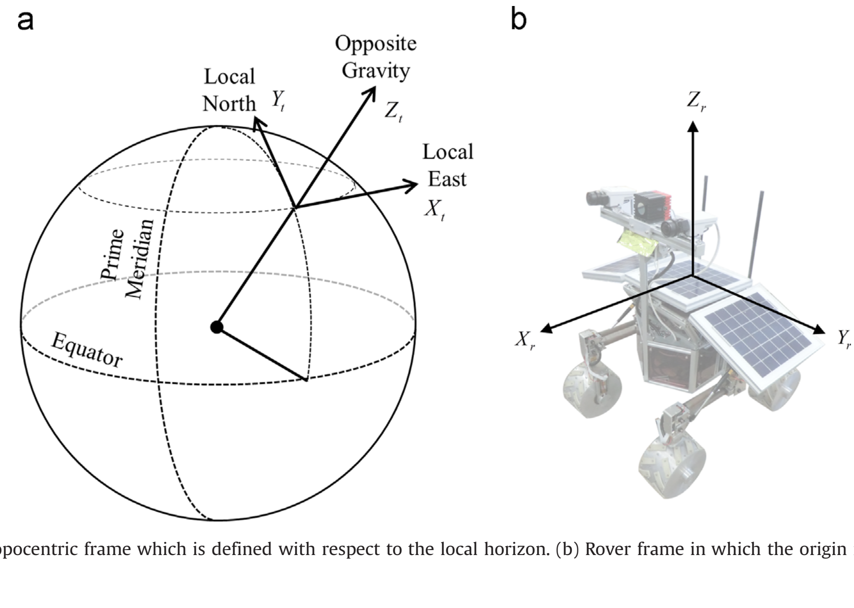

Fig. 1. (a) Topocentric frame which is defined with respect to the local horizon. (b) Rover frame in which the origin is at the rover.