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A new star tracker concept for satellite attitude determination based on a multi-purpose panoramic camera

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ABSTRACT

This paper presents an innovative algorithm developed for attitude determination of a space platform. The algorithm exploits images taken from a multi-purpose panoramic camera equipped with hyper-hemispheric lens and used as star tracker. The sensor architecture is also original since state-of-the-art star trackers accurately image as many stars as possible within a narrow- or medium-size field-of-view, while the considered sensor observes an extremely large portion of the celestial sphere but its observation capabilities are limited by the features of the optical system. The proposed original approach combines algorithmic concepts, like template matching and point cloud registration, inherited from the computer vision and robotic research fields, to carry out star identification. The final aim is to provide a robust and reliable initial attitude solution (lost-in-space mode), with a satisfactory accuracy level in view of the multi-purpose functionality of the sensor and considering its limitations in terms of resolution and sensitivity. Performance evaluation is carried out within a simulation environment in which the panoramic camera operation is realistically reproduced, including perturbations in the imaged star pattern. Results show that the presented algorithm is able to estimate attitude with accuracy better than 1° with a success rate around 98% evaluated by densely covering the entire space of the parameters representing the camera pointing in the inertial space.

1. Introduction

The need for limiting weight and power consumption of on-board instruments is particularly relevant to small and micro satellites which are nowadays consistently used for several applications in low Earth orbit (LEO) [1]. In this respect, the attitude determination and control system provides a major contribution to the overall mass and power budgets, thus significantly impacting the cost of the mission design [2]. For instance, as regards the attitude determination function, several combinations of sensors, including star trackers, Sun, Earth, and magnetic sensors, may be exploited [3], mainly depending on the pointing requirements of the payload selected to accomplish the mission goals. Another aspect which is recently gaining increasing relevance in the design of small/micro satellites is the need to provide them with adequate level of space situational awareness (SSA) [4]. For instance, SSA is becoming an essential element to accomplish the mission goals considering that all the spacecraft flying in LEO have to face the threat of space debris whose impact with the satellite surface could generate different levels of damage up to a complete destruction [5].

Based on the considerations above, micro and small satellites could benefit from the possibility of carrying a single, compact and light sensor able to ensure multi-functional capabilities, like attitude determination and situational awareness. In this context, panoramic cameras have undeniable advantages since their wide field-of-view (FOV) may allow simultaneously imaging the Sun (or the Earth), another space object flying at close, intermediate, or far range, and a wide portion of the star field. Consequently, if adequate technological and algorithmic solutions are conceived, such sensors may be able to fulfill various tasks, either simultaneously or in different operative modes, by operating as star trackers, sun or Earth sensors, and situational awareness cameras.

A multi-purpose panoramic camera is under-development for spacecraft operation [6] which exploit an innovative optical unit capable of

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imaging a hyper-hemispheric (HH) FOV [7]. In this paper, the attention is focused on the star tracker function of this sensor.

Modern star trackers [8–10] are composed of an optical system, a detector and a processing sub-unit that executes image processing and attitude determination algorithms. These sensors are beyond dispute the most accurate instruments for spacecraft attitude determination as they can provide accuracies even better than 1 arcsecond [11]. In order to achieve this performance over most of the celestial sphere, star trackers rely on high-resolution and high-sensitivity detectors to accurately image as many stars as possible. Indeed, the higher the sensitivity of the detector is, the more the minimum star brightness required to get a reliable signal reduces. On the other hand, the high-resolution constraint limits the size of the FOV which typically ranges from a few degrees (e.g. $4^\circ \times 4^\circ$) up to a few tens of degrees (e.g. $20^\circ \times 20^\circ$). Once a certain number of stars is detected in the image, they must be correctly matched with the elements of a star catalogue (purposely organized and stored on board) which covers the star population of the entire celestial sphere within a certain range of brightness (which depends on the sensitivity of the detector). This step is known as star identification and it is the most challenging phase of the attitude determination process. Finally, as soon as at least two stars are identified and, consequently, two star directions are available both in the camera reference frame (SRF), based on star location on the image plane, and in a standard reference frame, e.g. the inertial frame (IRF), thanks to the association in the catalogue, the rotation matrix representing the spacecraft pointing in the inertial space can be estimated exploiting assessed algorithms, e.g. TRIAD and QUEST [12]. A survey of the most important techniques developed for star identification can be found in Refs. [13,14] and also in Ref. [15] with specific reference to those approaches which are more suitable for application on board small satellites. A distinction between two main categories can be made. On one side, some approaches [11,16,17] tackle the issue of star identification as a subgraph isomorphism, which consists in matching clusters of stars (subgraphs) identified by their angular separations with similar structures according to which the catalogue is organized. On the other side, star identification can be performed as a pattern recognition method [18–20], which consists in assigning to each star in the image and in the catalogue a specific signature which is derived from the position and/or brightness of the neighboring stars.

However, the state-of-the-art star identification algorithms, briefly discussed above, are not applicable if panoramic cameras are exploited, due to their peculiar hardware features. The optical head is designed to allow observing an extremely wide portion of the celestial sphere, as the FOV covers up to 360° in azimuth and several tens of degrees in elevation. However, the small diameter of the pupil causes a significant loss of energy projected on the detector surface thus highly limiting the number of detectable stars. Finally, the need for limiting the size of the optical head poses a constraint on the achievable resolution, which does not depend only on the number and size of pixels, but also varies along the detector surface as a function of the direction of the incoming light.

This paper presents a new algorithm conceived for star tracker attitude determination which is able to deal with the issues of using a panoramic camera. The main original contribution of the proposed technique, which can be used to determine the camera pointing in lost-in-space condition, is given by the star identification method. Specifically, this is carried out by globally matching the full pattern of stars detected in the sensor FOV with similar sets of stars a-priori stored on board within a database. This operation relies on a customized and original implementation of concepts like template matching [21] and point cloud registration [22], whose use is consolidated in the computer vision, robotics and space systems communities for different tasks like object recognition [23], localization and mapping [24], and pose determination [25]. Algorithm performance is evaluated within a purposely developed simulation environments which includes a realistic simulator of the operation of a panoramic camera. The results of the simulations are valid as a proof of concept for the proposed approach and demonstrate a good level of accuracy in lost-in-space mode, i.e. degree and sub-degree order, and an adequate robustness considering highly variable pointing conditions of the camera in the inertial space, the presence of *unexpected/lost* stars as well as of *fake* stars due to hot pixels randomly located on the focal plane.

This paper is organized as follows. Section 2 describes in detail the panoramic camera including both the classic and hyper-hemispheric configurations. Section 3 presents the original techniques conceived for star identification as well as the implementation of the final attitude determination step. Finally, section 4 presents the numerical simulation scenario as well as the simulation results.

2. Sensor hardware

The multi-purpose sensor which is proposed to operate as a star tracker is composed of an optical head which allows panoramic vision capabilities, a detector matrix, a proximity electronics, and a miniaturized processing device for signal and data processing. The imaging principle of a classic panoramic camera architecture is explained in Fig. 1.

The considered panoramic sensor images a 360°-FOV in azimuth (*Az*)

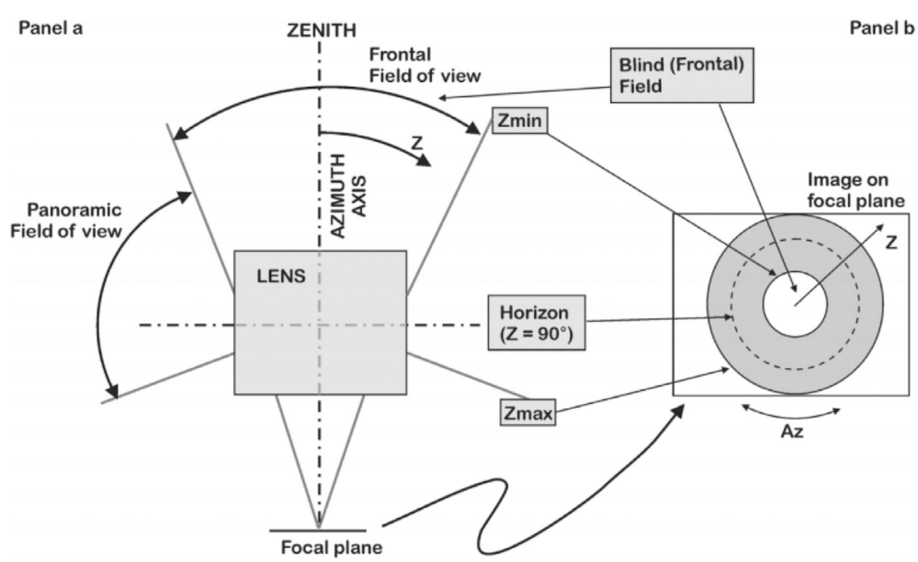

Fig. 1. Imaging principle of a classic panoramic camera [7].