

Innovative Algorithm for Spacecraft Attitude Determination

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ABSTRACT

The paper presents feasibility and effectiveness of an innovative algorithm for spacecraft attitude determination, based on the real time fusion of raw data measurements provided by APS cameras, less limited by metrological constraints than traditional cameras used for star detection, and MEMS gyros, characterized by low-mass, low-power and low recurrent costs. The basic concept and the followed S&T methodological approach is described, which includes the use of cameras and gyros, even if the above basic concept states that gyros measurement data are neither strictly necessary, nor are increasing the attitude measurement accuracy in steady state conditions. Indeed, the availability of the gyro measurement data significantly contributes to the robustness of the spacecraft attitude measurement system particularly in “lost in space” and in “occulted camera” conditions. High quality gyros are not required. Angular rate measurements are fused with camera star measurements at raw data level. By the data processing the gyro attitude with respect to the “master camera” - denoted as “gyro on board attitude” - is estimated. The main novelty content and expected advantages with respect to the state-of-art are illustrated in detail, involving the following four main aspects: 1. fusion at the raw data level of all the gyro and camera measurements, what increases the spacecraft attitude measurement robustness and accuracy 2. Camera model self calibration. 3. Camera and gyro on board attitude estimation. 4. System scalability.

INTRODUCTION

To day the standard methodological approach for spacecraft autonomous attitude determination is based on the star observation through digital cameras [1]. The proposed innovation lies in the algorithm for processing the “raw measurement data” provided by the cameras. The innovative

algorithm allows extracting information nowadays not available in commercial products. The availability of this additional information allows, at equality of cameras, a performance improvement beyond the state-of-art. Moreover, it also allows achieving the performance offered by current commercial products with the use of less expensive cameras.

The term camera “raw measurement data” (shortly “raw data”) is here used to denote the coordinates, expressed in the camera sensor reference frame, of the detected star image photocentres before any compensation of the camera geometrical or thermal errors. These raw data, typically expressed in pixels, are the camera system output used as input to the data processing in order to estimate the spacecraft attitude. The presented algorithm intends to compute the spacecraft attitude through an unique data fusion performed at the raw data level of all the spacecraft camera output data. The system also includes the use of MEMS gyros with the aim to increase the measuring system dependability in critical operative conditions, while in nominal operative conditions the spacecraft attitude measurement is got by the star measurements only.

As a starting point, it is conceptually important to determine which is the information content present in the raw data flow provided by a single camera, regardless of what might be the most appropriate data fusion algorithm in order to extract this information. It is well known, since the feasibility study of the ESA HIPPARCOS mission [2], that from raw data flow of a star telescope it is possible to carry out at the same time the measurement of the following variables: 1) the telescope calibration parameters following their time variations, 2) the telescope attitude with respect to the celestial reference frame, 3) the observed star coordinates in the same celestial reference frame. The HIPPARCOS mission has also confirmed that the above results are achievable by stars

measurements only. Indeed, the telescope attitude reconstruction was performed on-ground for the overall mission duration with an accuracy in the order of 40 milliarcsec and a star catalogue was built with an accuracy in the order of 2 milliarcsec in the star celestial coordinates.

The EICAS research group [3] is active in the field of autonomous spacecraft attitude determination from stars since the '80s [4][5], having developed the algorithm for the on-ground reconstruction of the spacecraft attitude from star measurements only. Today the group has developed a data fusion algorithm able to operate on board in real time the three functions mentioned above, that is: camera model self-calibration (assumed time-varying parameters), spacecraft attitude determination with respect to the sky reference frame and updating of the star celestial coordinates. Given the high completeness and accuracy of the HIPPARCOS Catalogue, it is obvious that the third function does not have specific use in space applications. However, it is worth mentioning here that EICAS used this same algorithm for on-ground applications [13] (hereinafter referred to), in which even the capability for real-time updating of catalogue data has appeared extremely helpful.

In the following we consider the algorithm of data fusion - developed for space applications - that from the raw data flow output of a set of cameras allows to compute 1) the parameters of each camera calibration model (assumed to be time-varying), 2) the on board attitude of cameras assumed to be time-varying with respect to the spacecraft reference frame, 3) the spacecraft attitude with respect to the celestial reference frame. To focus on main innovations led by the proposed algorithm, it appears convenient to summarize the error causes affecting the final spacecraft attitude measurement, moving through the overall data process that from the raw data output of the digital cameras allows to compute the attitude measurement.

ANALYSIS OF ERRORS AFFECTING THE SPACECRAFT ATTITUDE MEASUREMENT

The camera raw processing is performed according to the following basic steps. Through the camera mathematical model the camera raw data (star image photocentre coordinates expressed in the camera sensor reference frame) are transformed one-to-one in the star field coordinates, i.e. in the star coordinates related to the camera reference frame. Then, through the camera attitude with respect to the celestial reference frame, the star field coordinates are transformed one-to-one in the star celestial coordinates. The camera attitude is determined by minimizing the difference between the resulting star celestial coordinates and the available star catalogue coordinates. The residuals point out the presence of errors that are the effects of the following three potential

causes. The first one is the measurement error affecting the raw data. Such an error is denoted in the following as the random error contribution. The second one is the error affecting the camera mathematical model. Such an error is denoted in the following as the systematic error contribution. The third error cause is the error affecting the star catalogue coordinates. Such an error is here fully neglected.

The Random Error

The camera raw measurement data can be modeled as a stochastic process, where each data is the sum of an expected value and a random variable, here denoted as random error. The random error has the characteristic of white non stationary process. The errors are typically uncorrelated among themselves, both in the case of raw data related to the same sky image as well as in the case of raw data related to different sky images. The error statistical properties are significantly varying as a function of the camera operational conditions. There are many causes that induce random errors in the raw data, among these the most important are:

1. Photon noise (for star and sky background)
2. Electronic noise (Temporal Noise)
3. Quantization noise
4. Star blooming
5. Focal length variation with star color
6. PSF (Point Spread Function)
7. Radiation-induced false stars
8. Radiation-induced dark current spikes
9. Pixel defects

Some error causes are induced by the environment conditions, others depend on the used sensor technology. However there are not sources of random error which nowadays can be removed. It must therefore to state the concept that the effect of the random error in the spacecraft attitude measurement can be mitigated only by recourse to redundancy of raw data availability and use of suitable data filtering techniques.

The random error is variable with the magnitude of the star observed, the exposure time used and also as a function of the spacecraft angular rate. To provide an idea about the magnitude of this error, a table (Table 1) is included that refers to a good quality camera with a field of view diameter of 20 degrees, equipped with an APS technology sensor with the size of 1000×1000 pixels and pixel size of 72 arcsec. In the table, the raw data standard deviation is expressed in arcsec. By considering the pixel size of 72 arcsec, the random error results to be in the range 0.25-0.5 pixel. Such a random error evaluation - expressed in pixel - may be roughly

extended to any other camera (well designed) using the same APS sensor with different optics, different field of view (FOV) and operating with different star magnitude.

Table 1. Camera single frame performance

Angular Rate [°/s]	0	3	6	10
Exposure Time [ms]	98	23	15	7
Faintest star detected [mi]	6	4.5	4	3.25
Mean number of detectable stars	39	7	4	2
Faintest Star APS coordinate random error stand. dev. [arcsec]	16	22	28	34

The Systematic Error

The star field coordinates computed from the camera raw data through a camera mathematical model are affected by systematic errors depending on the approximation level of the used mathematical model. The systematic error (or bias) is usually separated in three components - namely large, medium and small scale errors - and suitable camera calibrations are performed in order to correct them.

The large scale errors are induced by variations of the lens temperature, which have two different effects: 1) the thermal optical axis shift, which is corrected by an additive term (to be added to the coordinates resulting from the raw data), as a non-linear function of the lens temperature; 2) the scale factor thermal effect, which is corrected by introducing a multiplier coefficient, which is also a nonlinear function of the lens temperature. The non-linearity can be modelled differently depending on the required accuracy, however, the complete model for the correction of large scale errors due to temperature variations involves a parameter number - typically in the range of 5-10 parameters - to be estimated through the camera calibration.

The medium scale error is produced by the aberrations of the camera optical system. The correction of this error, usually referred to as “geometric correction”, is applied to the raw data after having executed the above mentioned “thermal correction”. The geometric correction is a nonlinear function of the star coordinates (x, y) available at raw data level. Such a nonlinear function is usually approximated by a polynomial series expansion, typically arrested at the third power. Such a model involves 20 parameters to be estimated through the camera calibration.

The small scale error is typically linked to the presence of pixel defects and, in the common approach, it is not compensated but it is considered as a contribution to the “random error”.

The correction of the systematic error requires the camera model calibration. Nowadays, the cameras used for the determination of space vehicles are calibrated in laboratory and their calibration stability is guaranteed for the overall camera life duration. The proposed innovative algorithm allows performing on board in real-time the camera self-calibration by camera raw data processing. When the camera self-calibration function is activated, the number of unknown parameters to be estimated from the camera raw data flux increases, going from the 3 variables required for the spacecraft attitude up to 20-30 parameters for each used camera, depending on the complexity of the selected camera mathematical model.

Other Systematic Errors

From star measurements the reference frame attitude of each single camera can be measured with respect to the celestial reference frame. In order to get the spacecraft attitude (or better the spacecraft payload attitude), the cameras are installed on board rigidly interconnected with each other and fixed at the spacecraft reference frame. Then, each camera relative attitude with respect to the spacecraft reference frame is perfectly calibrated on ground and assumed as invariant for the overall mission duration, in such a way that the spacecraft attitude with respect to celestial reference frame can be derived from the measured camera attitudes. Such a requirement is expensive and prevents the cameras to be mounted as far apart, as may be convenient in order that each camera points to a sky area far from the other cameras, so that all the cameras can never be occulted up all at once.

The alternative solution, here considered, is that only one camera - called “*master camera*” - be rigidly connected in an invariant way to the payload, while the other “camera attitudes with respect to the master camera” (in the following shortly denoted as “*on board camera attitudes*”) are real-time estimated from the considered camera raw data. Of course, each camera attitude is assumed to be randomly variable in time with a power spectrum to be specified case by case, but, always belonging to a frequency band very limited with respect to the spacecraft attitude sampling frequency.

Following this approach, it is not necessary that the on board camera attitude be accurately measured in the laboratory before the spacecraft launch, neither that their on board attitude be guaranteed invariant for the overall spacecraft mission duration.

By the introduction of the on board camera attitude calibration, the number of the time variant parameters to be real-time measured from the camera raw data processing increases of 3 units (excluded the master camera, the attitude of which is by definition the spacecraft attitude).