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Performance analysis of opto-mechatronic image stabilization for a compact space camera

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Abstract

The paper presents new performance results for the enhanced concept of an opto-mechatronic camera stabilization assembly consisting of a high-speed onboard optical processor for real-time image motion measurement and a 2-axis piezo-drive assembly for high precision positioning of the focal plane assembly. The proposed visual servoing concept allows minimizing the size of the optics and the sensitivity to attitude disturbances. The image motion measurement is based on 2D spatial correlation of sequential images recorded from an in situ motion matrix sensor in the focal plane of the camera. The demanding computational requirements for the real-time 2D-correlation are covered by an embedded optical correlation processor (joint transform type). The paper presents briefly the system concept and fundamental working principles and it focuses on a detailed performance and error analysis of the image motion tracking subsystem. Simulation results of the end-to-end image motion compensation performance and first functional hardware-in-the-loop test results conclude the paper.

Keywords: Opto-mechatronics; Optical correlator; Image motion tracking; Image motion compensation; Visual servoing

1. Introduction

Size and mass of high resolution satellite cameras are usually determined by the optics. The main problems, associated with minimizing the optics size, are the degradation of the modulation transfer function (MTF), resulting in image smoothing, and darkening of the image. MTF degradation can be compensated to some extent by inverse filtering, but this can be done only at the expense of noise amplification, so a high initial signal-to-noise ratio (SNR) is required. With compact high resolution optics, however, a high SNR can be obtained only with a very long exposure time, as the focal plane image is very dark. This requires precise image motion compensation during the long exposure interval.

Image shift due to orbital motion is conventionally being compensated by time-delayed integration (TDI) which performs a corresponding shifting of the accumulated charge packages by a special TDI-capable image sensor (Brodsky, 1992). TDI sensors have a number of disadvantages (larger pixels, additional image blurring, etc.) and do not compensate the attitude instability. This problem is currently being solved by high precision satellite attitude control systems (Salaün, Chamontin, Moreau, & Hameury, 2002; Dial & Grodecki, 2002) and by enlarging the optics aperture (to reduce the exposure time). Both solutions increase however significantly the mission cost.

To keep compact camera sizes together with small aperture optics and moderate satellite attitude stability requirements, it would be rather straightforward to use imaging systems with long exposure time and some image stabilization mechanisms to prevent from image motion distortions.

Such solutions can use one of the following stabilization principles:

(a) Digital image correction: the camera motion is estimated from the digital input images captured by the camera and the movement correction is performed by digital processing of the camera images.

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(b) Sensor based image correction: the camera motion is assessed with an external motion sensor and the movement correction is performed by digital processing of the camera images.
(c) Opto-mechatronic stabilization: the camera motion is compensated by a mechanically driven optical system.

The most elegant solution is the full digital image correction (a), which is used in consumer video cameras (Uomori, Morimura, Ishii, Sakaguchi, & Kitamura, 1990) and video coding algorithms (Engelsberg & Schmidt, 1999). The first group deals only with compensation of certain types of translational image motion at rather low accuracy. The latter group uses more sophisticated algorithms, which can remove full first-order (affine) deformations between images in a sequence and assemble these aligned images within a single reference coordinate system to produce an image mosaic. The advanced algorithms applied, such as pyramid-based motion estimation and image warping (Hansen, Anandan, Dana, van der Wal, & Burt, 1994) or fuzzy adaptive Kalman filtering (Gullu & Erturk, 2003), allow even subpixel accuracy, but require advanced processing hardware.

The sensor-based image correction (b) suffers from the fact, that the motion sensor is normally non-collocated with the actual image sensor. Therefore any mechanical distortions (misalignment, structural deformations, vibration) result in image motion measurement errors, which affect the final quality of the corrected image.

The opto-mechatronic stabilization (c) is the most versatile one, because it can cope with large motion amplitudes and can make use of all benefits of the digital corrections.

The principles applied here, are very similar to the well known visual servoing (Hutchinson, Hager, & Corke, 1996). Visual servoing classically means the task to use visual information to control the pose of a robot's end-effector relative to a target object or a set of target features. Mapped onto a remote sensing camera, this task can be equivalently described as using visual information from an image sensor to control the motion of this image sensor relative to the scene to be observed.

A wide variety of visual servoing applications has been developed so far in macro-robotics (Oh & Allen, 2001) as well as in micro- and nano-robotics. In particular the latter class has strong commonalities with remote sensing camera design in term of micro- and sub-micrometer accuracies and the actuation principles applied, e.g. MEMS micro-assembly (Ralis, Vikramaditya, & Nelson, 2000; Weber & Hollis, 1989).

For visual servoing in general and opto-mechatronic stabilization in particular two tasks are of essential importance: (a) visual motion estimation & tracking and (b) pointing control.

Motion estimation is the problem of extracting the two-dimensional (2D) projection of the 3D relative motion into the image plane in the form of a field of correspondences (motion vectors) between points in consecutive frames. For practical applications a block or window based approach has been proved to be most appropriate. The spatial dynamics of image windows is being analyzed by feature or area based methods, to derive image motion information. Feature-based methods basically use computationally efficient edge detection techniques, but they rely on structured environment with specific patterns (Hutchinson et al., 1996).

Area based methods have been proved to be much more robust in particular for image data representing unstructured environment. They exploit the temporal consistency over a series of images, i.e. the appearance of a small region in an image sequence changes little. Block matching algorithms measure the motion of a block of pixels in consecutive images, such as the sum of squared differences (SSD) algorithm, which needs to solve a minimization problem with the desired image shift vector as optimization variable (Hutchinson et al., 1996; Oh & Allen, 2001), or to apply the method of direction of minimum distortion (DMD) (Haworth, Peacock, & Renshaw, 2001; Jain & Jain, 1981).

The classical and most widely used approach is the area correlation, used originally for image registration (Pratt, 1974). Area correlation uses the fundamental property of the cross-correlation function of two images, that the location of the correlation peak gives directly the displacement vector of the image shift. Different correlation schemes are known besides the standard cross correlation, e.g. phase correlation (Weber & Hollis, 1989) or the Joint Transform Correlation (Jutamulia, 1992).

A more recent and evolving application area is the video coding (e.g. MPEG-standard) where sub-pixel accuracy is required and multiple moving area blocks have to be tracked using adaptive correlation techniques (Xu, Po, & Cheung, 1999) as well as hierarchical multi-resolution algorithms based on complex wavelets (Magarey & Kingsbury, 1998).

The limitation of the applicability of area-based methods comes from the trade-off between computational effort, robustness to non-structured image texture and signal-to-noise ratio.

The higher robustness of area based methods to weakly structured image texture and small signal-to-noise ratio (this is valid in particular for correlation-based methods) has to be paid by a considerable high computational effort. As the complete image area content has to be processed at pixel level, the real-time application is restricted to rather small image blocks in the range 8×8 to 32×32 pixels. This limits the accuracy, which is poor when the block size gets too small.

The second task to be solved for visual servoing is the feedback control for high precision camera pointing. The pointing control is commonly based on two possible fine/coarse pointing principles. The first one uses a single actuator in a cascaded control loop with a high bandwidth inner loop (velocity or relative position control) and a low