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OPTO-MECHATRONIC IMAGE STABILIZATION FOR A COMPACT SPACE CAMERA

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Abstract: The paper shows 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 concept allows to minimize 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 a 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).

Keywords: opto-mechatronics, optical correlator, image motion compensation.

1. INTRODUCTION

Size and mass of high resolution satellite cameras are usually determined by the optics. 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 a high precision satellite attitude control and by enlarging the optics aperture (to reduce the exposure time). Both solutions increase significantly the mission cost.
An accurate image motion compensation during long exposures can be realized by a mechanical shift of the focal plane assembly in such a way to compensate the motion of the focal plane image.
For *high resolution satellite imagers*, however, real-time image motion detection becomes much more difficult due to high accuracy requirements, low brightness and fast motion of the focal plane image. For example, for an Earth observation mission with a ground resolution of 2 m per pixel at 600 km orbit

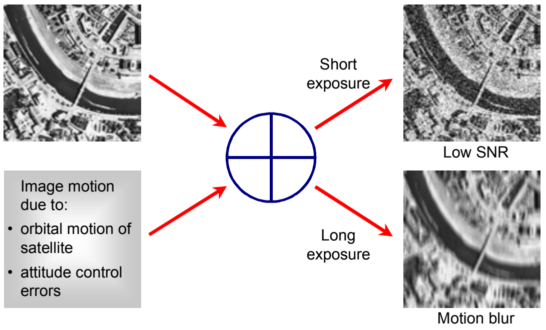


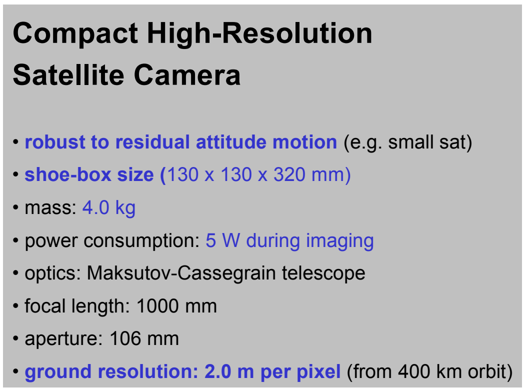
Fig. 1 Camera imaging disturbances

altitude the focal plane image moves with a velocity of 3450 pixels per second. Without motion compensation the exposure time should be limited to 0.2 ms to prevent image blurring. Such a short exposure will results in a signal to noise ratio below 10 dB (for an aperture diameter of 150 mm). Simple image motion sensors are not able to provide the required accuracy or even become completely unusable in such conditions (see Figure 1).

An innovative concept of an opto-mechatronic 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 has been proposed by Janschek and Tchernykh (2001). The proposed concept allows to minimize the size of the optics and the sensitivity to attitude disturbances. This paper presents new results in terms of an enhanced system structure (motion deblurring by image deconvolution), simulation and hardware-in-the-loop test results.

2. SYSTEM CONCEPT

A system layout of the opto-mechatronic stabilization assembly is shown in Figure 2. The focal plane motion with respect to ground is measured by an *auxiliary matrix* (area) *image sensor* and an *optical correlator*. The auxiliary sensor is installed in the focal plane of the imaging system which produces a sequence of images. From these sequences the image motion measurement is based on a 2 dimensional spatial correlation of sequential image pairs. The correlation approach results in subpixel accuracy for the shift vector determination, it is independent from specific image textures and it is extremely robust against noise. The demanding computational requirements for the real-time 2D-correlation are covered by an embedded optical correlation processor (Joint Transform type).



Compact High-Resolution Satellite Camera

- **robust to residual attitude motion** (e.g. small sat)
- **shoe-box size** (130 x 130 x 320 mm)
- mass: 4.0 kg
- power consumption: 5 W during imaging
- optics: Maksutov-Cassegrain telescope
- focal length: 1000 mm
- aperture: 106 mm
- **ground resolution: 2.0 m per pixel** (from 400 km orbit)

Fig. 3 High resolution camera specification

A mechanical compensation of the disturbing focal plane motion is performed by 2-axis piezo-platform. Feedback signals derived from these in-situ image motion measurements allow a precise motion compensation. Residual image disturbances can be compensated by image deconvolution using the measured focal plane motion trajectory.

The high speed measurement of the image motion is fundamental for the proposed application: to minimize the delay in feedback loop, the exposure time for the motion sensor should be very short, which results in extremely low SNR of the motion sensor images (down to 0 dB).

As a result of the proposed image motion compensation, a camera with a ground resolution of 2 m per pixel (from 400 km orbit) can be realized within an envelope of 130x130x130 mm and a mass within 4 kg (Figure 3). Such a camera can be easily installed onboard small satellites with moderate attitude stability or as a secondary payload on non-remote sensing platforms (low Earth orbit communication satellites, space station).

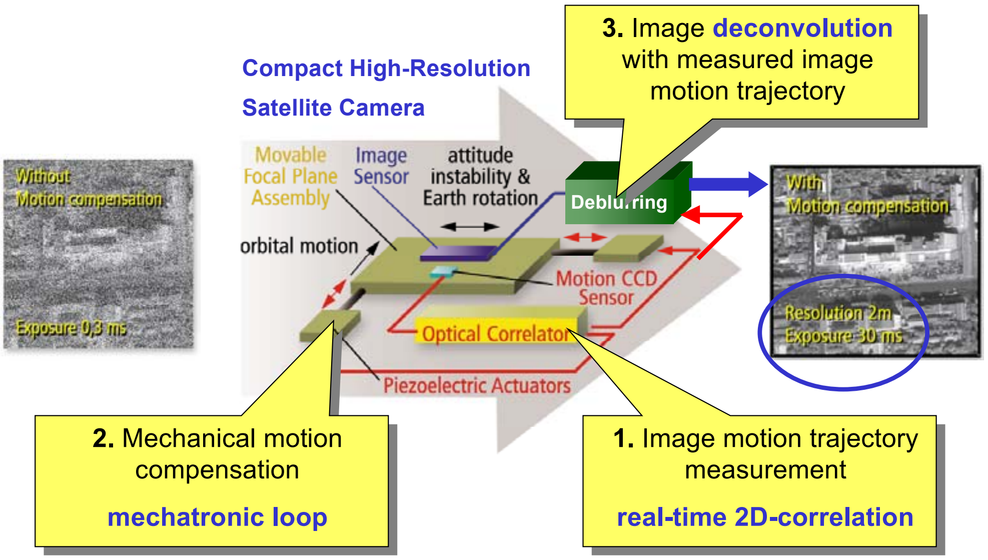


Fig. 2 Opto-mechatronic system concept

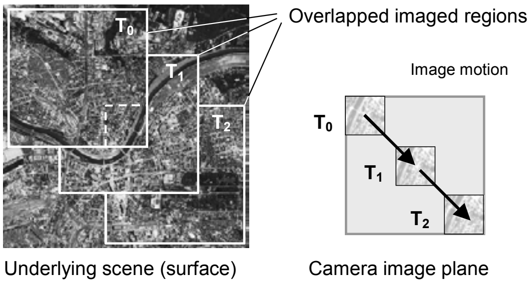


Fig. 4 Image motion tracking

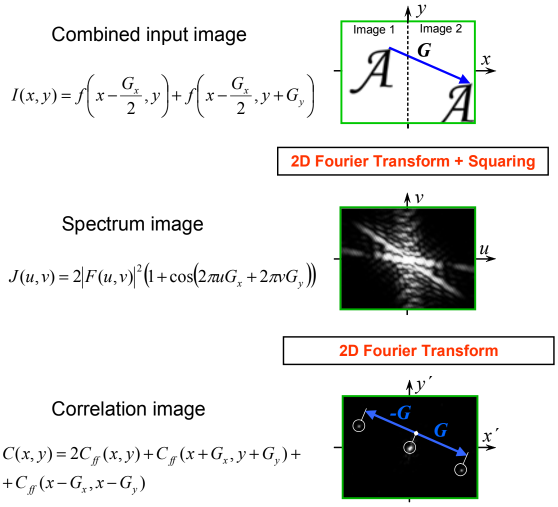
3. IMAGE MOTION MEASUREMENT BY 2D-CORRELATION

The image motion is measured by 2D correlation of the sequential images (Figure 4) and post-processing of the correlation image.

The so-called joint transform correlation scheme is used to minimise the overall computational effort. It makes use of two subsequent 2D-Fourier transforms without using phase information (Figure 5).

As a result, the vector of mutual shift of the images can be determined. High redundancy of the correlation procedure permits to obtain subpixel accuracy of shift determination even for low SNR dark images. It has, however, one significant drawback – a huge amount of calculations, required to perform the 2D correlation digitally. To overcome this limitation, fast optical image processing techniques can be applied.

A *Joint Transform Optical Correlator* (JTC) is an opto-electronic device, capable of the fast determination of the shift between two images of the same area. JTC includes two identical optoelectronic modules – Optical Fourier Processors (OFP), as sketched in Figure 6.



$$I(x,y)=f\left(x-\frac{G_x}{2},y\right)+f\left(x-\frac{G_x}{2},y+G_y\right)$$

$$J(u,v)=2\left|F(u,v)\right|^2\left(1+\cos\left(2\pi uG_x+2\pi vG_y\right)\right)$$

$$C(x,y)=2C_{ff}(x,y)+C_{ff}(x+G_x,y+G_y)+$$
$$+C_{ff}(x-G_x,x-G_y)$$

Fig. 5 Principle of joint transform correlation

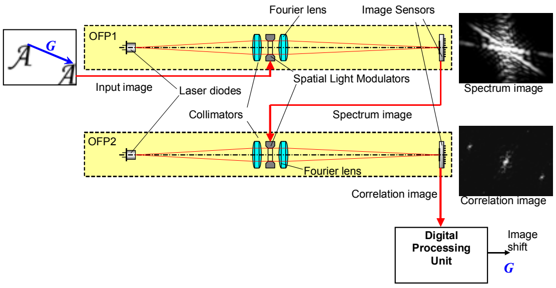


Fig. 6 Joint Transform Optical Correlator (JTC)

Two digital images (current and reference images) are entered into the optical system of the first OFP by a transparent *spatial light modulator* (SLM). After optical Fourier transformation, the joint power spectrum (JPS) is read by the CCD image sensor and loaded to the SLM of the second OFP.

A second optical Fourier transformation forms the correlation image. If both input images are of the same region, the correlation image will contain two symmetric correlation peaks. The shift of these correlation peaks relative to optical axis corresponds to the shift between the current and reference images (Jutamulia, 1992).

The position of peaks on the correlation image and the shift value can be measured with sub-pixel accuracy using standard algorithms for centre of mass calculation. Optical processing thus allows a unique real time processing of high frame rate video streams.

This advanced technology (which is not yet commercially available today) and its applications are studied during last years at the Institute of Automation of the Technische Universität Dresden. Different hardware models have been manufactured, e.g. under ESA (European Space Agency) contract.

Due to special design solutions the devices are very robust to mechanical loads and do not require precise assembling and adjustment (Tchernykh et.al. 2000). Recent airborne test flight results showed very promising performances (Tchernykh et.al.2002).

The typical optical correlator accuracy of shift determination errors is below 0.2 pixel (1σ) even for extremely noisy images with SNR less then 0 dB. Processing rates up to 3200 correlations per second are possible. This makes an optical correlator particularly suitable for the determination of the motion of dark and fast moving images in mobile vehicle applications (space, robotics) under weak illumination conditions.

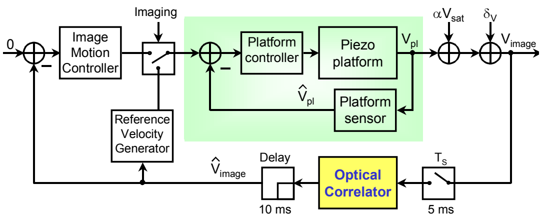


Fig. 7 Control loop structure

4. OPTO-MECHATRONIC FEEDBACK LOOP

The general control loop structure is shown in Figure 7.

The inner loop controls the velocity V_{pl} of the movable focal plane platform with respect to the satellite frame. V_{pl} is measured by a conventional displacement sensor and is maintained equal to the required command value from the outer loop. The inner loop is closed continuously and has a bandwidth of a few hundred Hz.

The outer loop controls the velocity of the image motion with respect to the platform V_{im}. This velocity should be minimised during imaging to prevent the image blur. For this, the disturbing image motion due to satellite motion (αV_{sat}) and due to attitude control errors (δ_V) should be compensated. The value of V_{im} is measured by the optical correlator and applied to the image motion controller. The controller produces the value of the platform velocity, required for compensation. This value is entered into the inner loop.

The outer loop is closed only during imaging phases and has a bandwidth of few Hz (due to the measurement delay), so inner and outer loops are well decoupled in frequency domain. This limited bandwidth of the outer loop is sufficient for accurate image motion compensation, as the spectrum of the image motion disturbances due to satellite motion αV_{sat} and attitude control errors δ_V are well limited by typically 1 Hz.

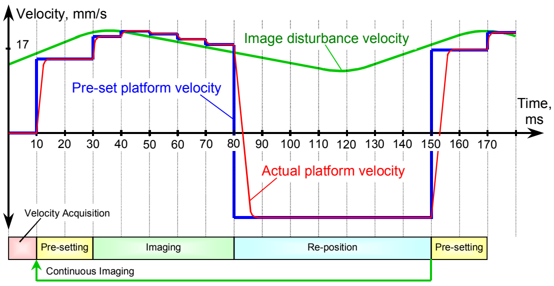


Fig. 8 Velocity profiles

The velocity profiles (with respect to the satellite frame) during the main stages of operation are sketched in Figure 8.

After activation of the system the optical correlator measures the image velocity with respect to the platform (velocity acquisition interval in Figure 8). During the synchronisation interval the outer loop controller uses this data to produce the command value for the platform velocity, required to compensate the image motion, and sends this value to the inner loop controller. Within 10 ms the platform accelerates to the required velocity, than the residual image motion is checked by the optical correlator and (if necessary) corresponding corrections of the pre-set platform velocity are performed.

When synchronisation is completed, the system enters the image following mode: the platform follows the motion of the image and the image velocity with respect to the platform is close to zero. During this phase the image can be exposed without motion blur effect and distortions. The duration of the image following mode for the given reference mission parameters and maximum travel distance of the movable platform 2 mm can be up to 100 ms.

After finishing the image exposure the platform needs to be repositioned for the next imaging cycle. This is done by applying an appropriate fixed negative value to the command input of the inner control loop. To prevent an error accumulation, repositioning is terminated by a limit switch.

The value of platform velocity at the end of the imaging cycle can be used as initial velocity estimation for the next cycle. Such a procedure will eliminate the need for the velocity acquisition interval and thus improves the imaging repetition frequency.

In particular beneficial for this application is the robustness to image noise. To provide the required bandwidth of the visual feedback the images from the auxiliary image sensor will be taken with a very short exposure and thus will have a sufficient low signal-to-noise ratio.

5. IMAGE DECONVOLUTION

A correction of the image blurring due to the residual (i.e. uncompensated) image motion during exposure can be performed by a 2D-deconvolution operation.

This uses the motion of the blurred images on the base of record of the image motion made with the auxiliary image sensor and optical correlator (see Figure 9).

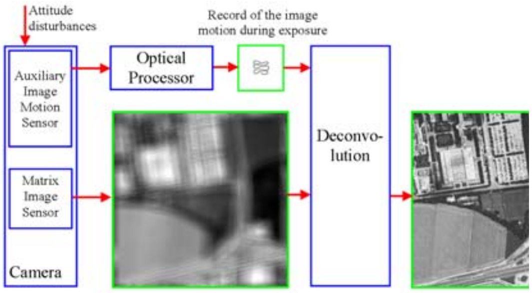


Fig. 9 Image deblurring by deconvolution

6. SIMULATION RESULTS

Figure 10 shows simulated images for the given reference mission parameters (2 m per pixel from 600 km orbit), taken in presence of attitude disturbances, which are possible for a moderately stabilised satellite (residual angular velocity w.r.t. nadir of 0.02°/s).
The noise figures were calculated for limited aperture optics (aperture diameter of 150 mm), average detector characteristics and observation conditions.

A B C

Fig. 10 Image correction – simulation results

Figure 10-A corresponds to the case with no image motion compensation. This image has a very low signal to noise ratio (6 dB) due to an extremely short exposure time (0.15 ms), which is necessary to prevent motion blur.

Figure 10-B simulates the effect of electronic TDI (64 steps). Compensation of the image shift due to the orbital motion allows to increase the exposure time up to 19 ms and to improve the SNR value (up to 30 dB). The uncompensated image motion with a residual shift of 2 pixel due to attitude control errors results in motion blur and resolution degradation.

Figure 10-C simulates the effect of the proposed opto-mechatronic image motion compensation. The exposure can be increased up to 50 ms, what improves the SNR to 40 dB. The residual image shift of 0.5 pixel image shows an image which is free from blurring due to the appropriate compensation of the attitude instability effect.

The simulation results clearly indicate the advantages of the proposed system for image motion compensation: its application makes it possible to produce high quality images even with moderate attitude stability of the satellite and a limited aperture of the optical system.

7. HARDWARE-IN-THE-LOOP TESTS

For a laboratory demonstration of the proposed opto-mechatronic concept an camera breadboard assembly has been developed (see Figure 11).
It consists of a piezo platform of the type L-114 from Micro Pulse Systems (www.micropulsesystems.com).
The actuator allows a maximum velocity of 50 mm/s at a resolution < 1 μm .
As auxiliary matrix sensor a standard CCD-camera has been used.

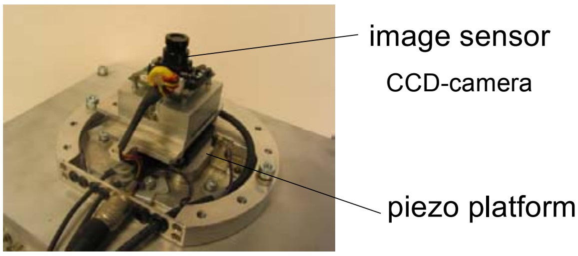


Fig. 11 Camera laboratory breadboard

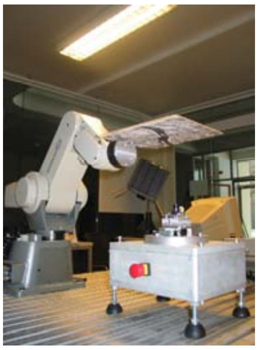


Fig. 12 HWIL testbench

A complete hardware-in-the-loop (HWIL) test bench has been built-up using the xPC-Target environment as implementation platform for the control algorithms (see Figure 12 and 13). The camera motion is simulated by a 5-DOF industrial robot, where representative trajectories can be realized properly.

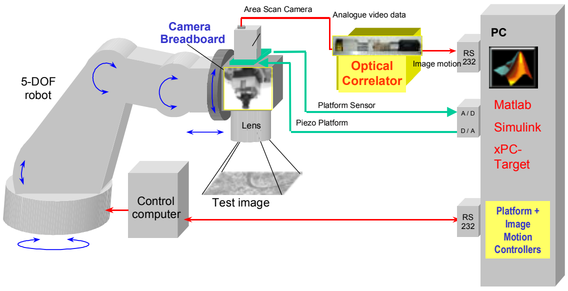


Fig. 13 HWIL test configuration

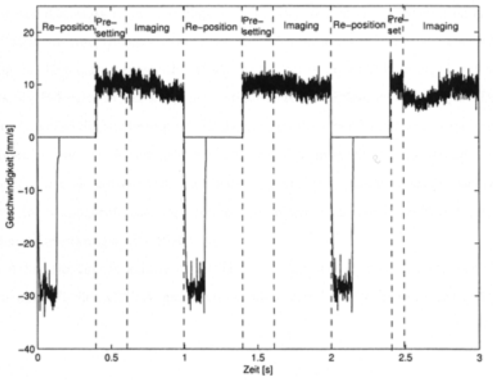


Fig. 14 HWIL test result: platform motion

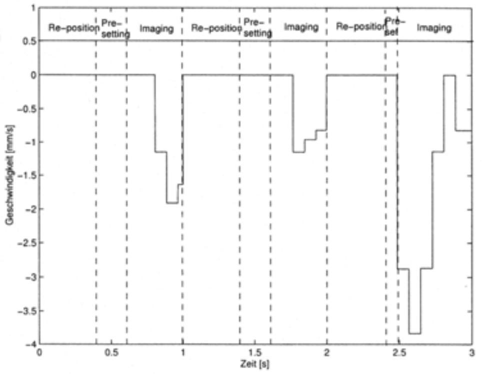


Fig. 15 HWIL test result : image motion measurement by 2D-correlation

Preliminary HWIL test results at functional level are shown in Figures 14 and 15. These tests show the principal closed loop operation at the first integration level, with the 2D correlation performed by software. Currently the optical correlator hardware is being integrated in the loop, which will allow more advanced performance tests.

8. CONCLUSIONS

An opto-mechatronic concept for compensation of the image motion in the focal plane of a satellite camera has been proposed. The system includes an image motion sensor and optical correlator for precision measurement of the motion of dark and fast moving image. The implementation of the proposed system allows to increase the quality of the obtained images and to reduce the requirements to the optics aperture diameter and attitude stability of the satellite.

Currently a system study funded by the European Space Agency (ESA) is performed (Janschek et.al. 2004), where the proposed concept is extended to a high performance pushbroom scan sensor with a steerable mirror (instead of the piezo platform as proposed in this paper).

REFERENCES

Brodsky, R.F. (1992). Defining and Sizing Space Payloads. In: Space Mission Analysis and Design, second edition, (James R. Wertz and Wiley J. Larson, (Ed)), pp. 264, 265. Microcosm, Inc., Torrance, California.

Janschek, K., Tchernykh, V. (2001) Optical Correlator for Image Motion Compensation in the Focal Plane of a Satellite Camera. *Space Technology* , Volume 21 (2001), Issue 4, pp.127-132.

Janschek, K., Tchernykh, V. Dyblenko, S. (2004) Conceptual Design Report, ESA-ESTEC/Contract No. 17572/03/NL/Sfe, Application Study for an Optical Correlator, May 2004.

Jutamulia S. (1992) Joint transform correlators and their applications. Proceedings SPIE, 1812, 233-243.

Tchernykh, V., Janschek, K., Dyblenko, S. (2000) Space application of a self-calibrating optical processor or harsh mechanical environment. *Proceedings of 1st IFAC Conference on Mechatronic Systems - Mechatronics 2000, September 18-20, 2000, Darmstadt, Germany.* Pergamon-Elsevier Science. Volume 3, pp.309-314.

Tchernykh, V., Dyblenko, S., Janschek, K., Göhler, W., Harnisch, B. (2002) SmartScan - Hardware Test Results for Smart Opto-Electronic Image Correction for Pushbroom Cameras. *Proceedings of the SPIE, Earth Observing Systems VII.* Edited by Barnes, William L., Vol. 4814, pp. 264-272.