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OPTICAL CORRELATOR FOR IMAGE MOTION COMPENSATION IN THE FOCAL PLANE OF A SATELLITE CAMERA

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Abstract: The paper presents the concept of a system for the compensation of the image motion in the focal plane of a satellite camera. The image motion is compensated by corresponding shift of the image sensor, controlled through direct visual feedback. The system includes an auxiliary image sensor and an optical correlator for the high precision measurement of the motion of a dark and fast moving focal plane image. Questions of system realisation are considered, expected performances are estimated on base of the optical correlator hardware model testing.

Keywords: visual feedback, optical correlator, image motion compensation.

1. INTRODUCTION

1.1 Problem description

If the attitude/position of the imaging system are not stable during the exposure time, the obtained image will be blurred and small image details will be lost. This problem is particularly essential for high resolution satellite imaging systems: due to the large focal length and high resolution even a small attitude instability will cause considerable image distortions and blurring. Another problem for satellite imagers is the fast motion of the planet image in the focal plane due to orbital motion of the satellite.

1.2 Existing solutions (state of the art)

Image shift due to orbital motion is conventionally be 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.

The effects of the attitude instability and the satellite motion can be overcome by real-time compensation of the focal plane image motion. For that, the optical elements (mirrors, lenses) can be rotated or the whole focal plane assembly can be moved. This motion can be controlled on base of attitude information (from attitude sensors) and known orbit parameters. This approach, however, is not suitable for high resolution missions due to residual errors, emerging from non-rigidity of the spacecraft structure, orbit parameters knowledge and attitude errors. To eliminate these errors, the actuators should be controlled through direct *visual feedback* by an image motion sensor. This solution is known for commercial photo camera optics: a number of photo lenses with motion compensation elements is already in production.

They use relatively simple sensors to detect and measure the image motion to be compensated.

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

1.3 Proposed solution

This paper introduces an innovative approach to monitor the motion of a dark and fast moving focal plane image with required accuracy by a combination of an *auxiliary matrix* (area) *image sensor* and an *optical correlator*. The auxiliary sensor is installed in the focal plane of the imaging system. It produces the sequence of images, which are processed in real time by the optical correlator. The optical correlator detects the image motion by measuring the shifts between the sequential images.

The focal plane assembly is shifted in order to compensate the detected image motion. The shift is performed by piezo actuators, controlled on base of the image motion information from optical correlator. Such compensation of the image motion allows long exposures for main image sensor, improving the signal-to-noise ratio of obtained images without motion blur and distortions. It also makes possible to reduce the camera dimensions and the sensitivity to attitude instability.

2. IMAGE MOTION MEASUREMENT BY OPTICAL CORRELATION

2.1 General principle

The image motion is measured by 2D correlation of the sequential images (Figure 1) and post-processing of the correlation image.

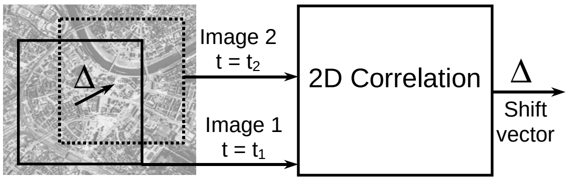
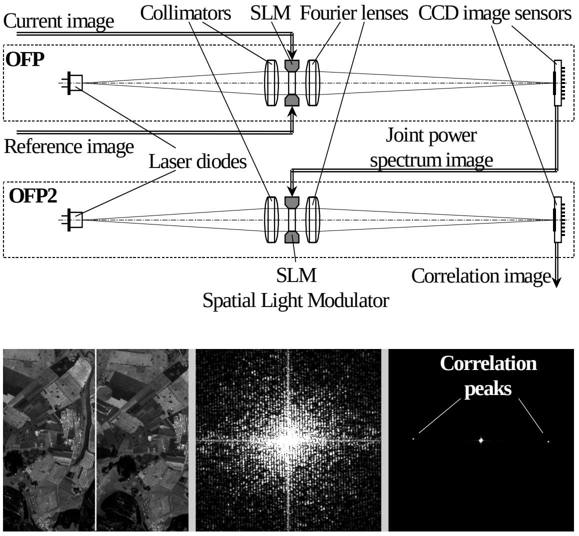


Fig. 1. Image motion determination with 2D correlation

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 technique can be applied.

2.2 Optical Correlator background

A *Joint Transform Optical Correlator* (JTC) is an opto-electronic device, capable of 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 2.



Current + reference images

Joint power spectrum image

Correlation image

Fig. 2. Joint transform optical correlator

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.

2.3 Practically achievable accuracy of the images shift determinations for noisy images

The accuracy was estimated in a series of tests performed with laboratory model of the optical correlator (Figure 3), developed and manufactured within the frame of research project, funded by ESA/ESTEC (Janschek, et al., 2000).

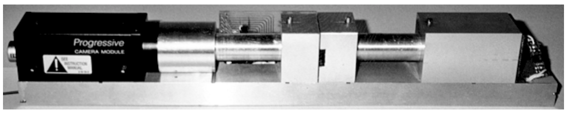


Fig. 3. Optical correlator laboratory model

The model has a limited image processing rate, but represents realistically the full-scale system in terms of accuracy and range of shifts determination. Figure 4 represents the dependence of errors of images shift determination with optical correlator on signal-to-noise ratio of the input images.

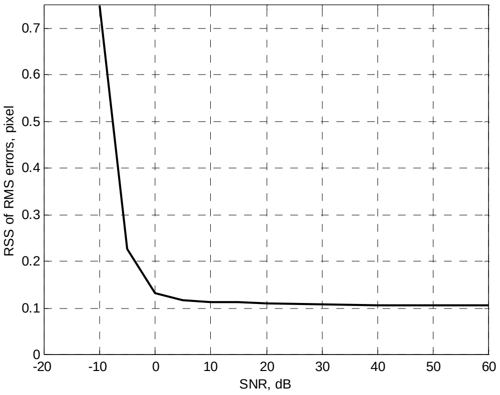


Fig. 4. Errors of images shift determination with optical correlator

The test results show, that high accuracy of shift determination (RSS of RMS errors below 0.2 pixel) can be obtained even for extremely noisy images with SNR less, then 0 dB. This makes an optical correlator particularly suitable for the determination of the motion of dark and fast moving images in the focal plane of a satellite imaging system.

3. IMAGE MOTION COMPENSATION BY VISUAL FEEDBACK

3.1 General principle

An *auxiliary image motion sensor* (small CCD or CMOS matrix) is installed in the focal plane of the satellite camera together with the main image sensor (Figure 5).

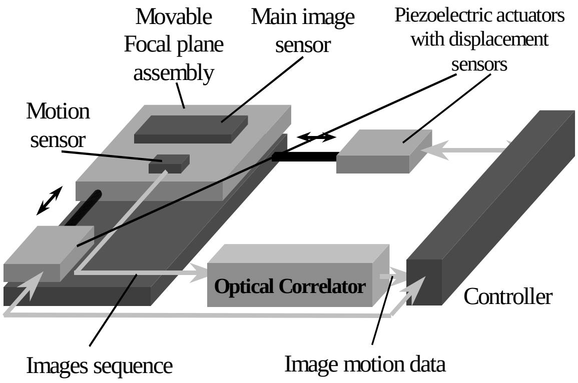


Fig. 5. General concept of image motion compensation

The motion sensor produces the sequence of images with sufficiently high frame rate. These images are taken with very short exposure time (below one millisecond) to prevent blurring and are therefore very dark and noisy. The optical correlator performs the real-time image processing and delivers the image motion value to the controller. The controller drives the piezoelectric actuators in order to compensate the image motion by corresponding motion of the focal plane assembly. As a result, the position of the focal plane assembly is fixed with respect to the image and the main image sensor can accumulate the light energy for considerably long time without image distortions and smoothing. The actuators also contain the displacement sensors, which measure the position of focal plane assembly with respect to the satellite structure.

3.2 Dynamic errors correction and response time requirements

Due to the non-zero response time of the system, residual errors of the image motion determination can emerge. This errors can be corrected by applying an image motion predictor (feedforward control) into the control loop.

The image motion dynamics in the focal plane of the satellite camera is generally determined by the following processes:

Linear image motion due to the orbital motion of the satellite and the planet rotation. This motion is fast but very steady and can be easily predicted by a simple linear predictor.

Random image motion due to the attitude control errors. This motion is usually slower and have the limited frequency range – generally below one Hz. If the response time of motion sensor is small compared to the period of image motion, it can be also predicted by linear extrapolating of previous values (linear predictor) with small residual error. For example, if the spectrum of image motion is limited to 1 Hz and the response time of the motion sensor is 10 ms, then the residual error of image position prediction on base of two previous measurements will be within 1%.

High frequency vibration due to the high-speed rotation of reaction and momentum wheels used for satellite attitude control. The amplitude of the corresponding image motion is relatively small (within few pixels even for high resolution imagers), but its frequency can be up to 100 Hz. Parameters of vibration (frequency, amplitude) are, however, expected to change very slowly, what makes possible accurate prediction of image position even if the response time of the measurement system is in the same order as the period of vibration (10 ms). Sampling frequency of the image position measurements should be, however, at least two times higher, than the maximum vibrations frequency.

Taking into account the above mentioned features of the image motion dynamics it can be concluded, that with application of prediction algorithms, an accurate image motion compensation can be obtained with a response time of the image motion detection about 10 ms and sampling rate of 200 measurement per second.

3.3 Control loop structure

The general control loop structure is shown in Figure 6. The outer loop is mandatory for motion compensation. The role of the inner augmentation loop, with internal direct platform position feedback, becomes apparent from the two primary operational modes for motion control, as sketched in Figure 7. After each imaging operation (typ. 100-200 msec) the focal plane platform has to be repositioned with respect to orbital flight direction. During this phase the feedback signal from the Optical Correlator based image motion measurements will not be available. The internal feedback allows during this re-positioning phase a controlled and precise re-initialisation of the platform.

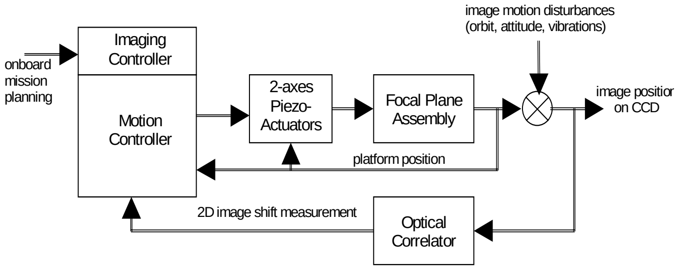


Fig. 6. Control loop structure

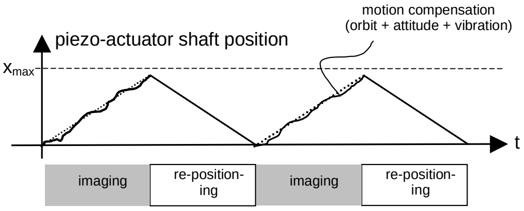


Fig. 7. Operational modes for motion control

4. EXPECTED PERFORMANCES

4.1 Image motion determination

The enabling technology of *Optical Fourier Processors* as basic element for an optical correlator has been successfully developed and adapted to satellite applications by the authors (Janschek, *et al.*, 2000). In the frame of this project (ESA/ESTEC contract), representative *real-time correlation performance* results could be derived from *hardware laboratory tests*.

The introduced single-channel Joint Transform Correlator employs the innovative technique of self-calibration (Tchernykh, *et al.*, 2000). This technique makes the Joint Transform Optical Correlator insensitive to mechanical deformations and suitable for satellite onboard applications.

Following performances were estimated for the full-scale system:

- Correlator unit dimensions - 20 x 32 x 180
- Mass – 0.2 kg
- Power consumption – 2 W
- Acceptable SNR of the input images – 0 dB
- Images shift determination error - $\sigma < 0.2$ pixel
- Sampling frequency – 200 Hz
- Response time – within 10 ms

4.2 Image motion compensation

With an image motion determination system as presented above the following performances have been estimated:

- completely compensate image shift due to orbital motion of the satellite (with residual error within 0.2 pixel for nadir-looking camera);
- reduction by a factor of 100 of the effect of random attitude error (for spectrum of attitude deviations limited by 1 Hz);
- reduction to subpixel values of the effect of vibrations.

Compensation of the image motion allows to increase the exposure time to the values, limited only by maximum travel distance of focal plane assembly. For example, for high resolution mission (2 m per pixel) it will be possible to have the exposure time up to few tenths of second (64 steps of electronic TDI will permit only 0.02 s). This will result in low noise images, free from motion blur and distortions even with low aperture optics and a moderately stabilised satellite.

4.3 End-to-end imaging performance

Figure 7 shows the simulated images from the high resolution camera (3 m per pixel from 600 km orbit), taken in presence of attitude disturbances, typical for a moderately stabilised satellite (random high frequency component of attitude instability (vibrations) σ=0.0003° or 1 pixel for given mission parameters).

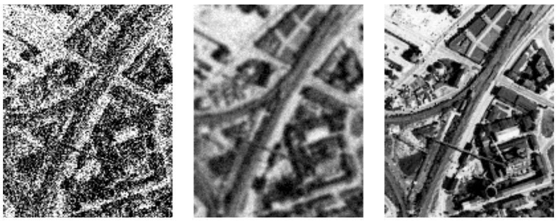

1 2 3

Fig. 7. Simulated satellite images: 1 – without image motion compensation; 2 – with electronic TDI;
3 – with mechanical image motion compensation (visual feedback)

Image 1 corresponds to the case with no image motion compensation. This image has a very low signal to noise ratio due to an extremely short exposure time, which is necessary to prevent motion blur. Image 2 simulates the effect of electronic TDI (64 steps). It has good SNR, but is blurred due to short-time attitude disturbances. Image 3 simulates the effect of mechanical image motion compensation with visual feedback. It has a high SNR and is free from distortions by attitude instability.

4. CONCLUSIONS

A new concept of a system 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 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.

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