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SPACE APPLICATION OF A SELF-CALIBRATING OPTICAL PROCESSOR FOR HARSH MECHANICAL ENVIRONMENT

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Abstract: An optical image processing device based on a Joint Transform Optical Correlator provides high processing speed and could be very usable in real-time image processing applications. In harsh mechanical environment the performance of the correlator could degrade due to mechanical deformations of the optical system. With special self-calibration methods the Joint Transform Optical Correlator can be built insensitive to mechanical disturbances. *Copyright ® 2000 IFAC*

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1. INTRODUCTION

An *optical correlator* is an optoelectronic device, which is capable to perform optically the 2D correlation between two images (current and reference), employing the lens feature to produce optically the 2D Fourier transform of the image. For two images of the same region, the mutual shift vector can be measured with sub-pixel accuracy.

The optical transformations are performed practically instantly, which provides the potential for rather high image processing rates. With state-of-the-art opto-electronic components the dimensions and power consumption of the optical correlator-based image-processing module is considerably smaller, than for a digital processor with equivalent performance.

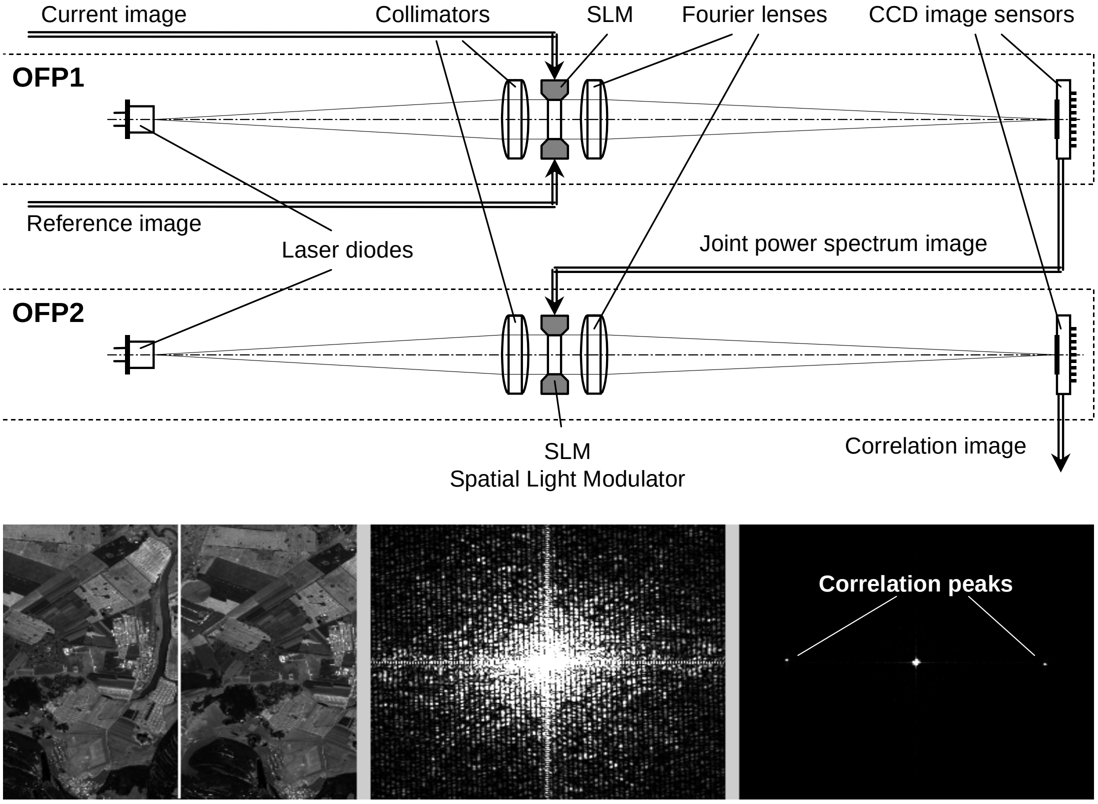
Such features of the optical correlator makes it suitable for onboard real time image processing on remote sensing satellites including applications such as navigation (Kusimov, *et al.*, 1998), attitude determination (Janschek, *et al.*, 1999a) and correction of the image distortions, caused by camera pointing instability (Janschek, *et al.*, 1999b,c). For onboard installation, however, the problem of sensitivity of the optical system to mechanical distortions must be considered. The current paper investigates this problem area for space applications, where the opto-electronic device will be subject to launch overloads and shocks, as well as to thermal and vibrational distortions during orbital flight.

2. JOINT TRANSFORM OPTICAL CORRELATOR BACKGROUND

The *Joint Transform Optical Correlator* (JTC) includes two identical optoelectronic modules – Optical Fourier Processors (OFP), as sketched in Figure 1.

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 can be measured with sub-pixel accuracy using standard and simple algorithms for centre of mass calculation.



Current + reference images　Joint power spectrum image　Correlation image

Fig. 1. Joint Transform Optical Correlator

3. EFFECT OF THE OPTICAL SYSTEM DEFORMATIONS ON THE JTC ACCURACY

From the mechanical point of view, each one of the two OFP can be represented as an assembly of three optoelectronic units: *light source* (laser diode), *optical unit* (lenses and SLM) and *image sensor* (Figure 2), with all three units mounted on one common base plate.

The units themselves can be considered as rigid (i.e. no inner displacements occur). In the ideal case all units are centralised relatively to the common optical axis *Y*. The SLM and image sensor planes are located perpendicular to this axis, the light emitting point of the light source and the centre of the photosensitive matrix of the image sensor coincide with the focal points of the collimator lens and Fourier lenses respectively.

The possible *mechanical deformations* of the OFP are shown in Figure 2 with dashed arrows. The main source of these deformations are bending modes of the long base plate with mounting fixes for the units. These deformations will cause changes of positions and orientations of the optoelectronic units.

Four types of *units misalignments* are being considered:

- *longitudinal shift* along the common axis *Y*
- *transversal shift* in the plane *XZ* perpendicular to the common axis *Y*,
- *rotation* about the common axis *Y* (Figure2, c)
- *rotations* about axes *X* and *Z* (Figure2, a,b), perpendicular to the common axis (inclinations).

The rotational bending effects are considered for small angles (within 1 – 2 degrees).

The following *deformation effects* of the optical system which affect the accuracy of the measurement of the planar shift between the current and reference images of the JTC have to be taken into account:

- *Rotation of the light source* about any axis will cause no effect on the correlator performance, if the centre of rotation coincides with the emitting centre and the angle is within a few degrees.

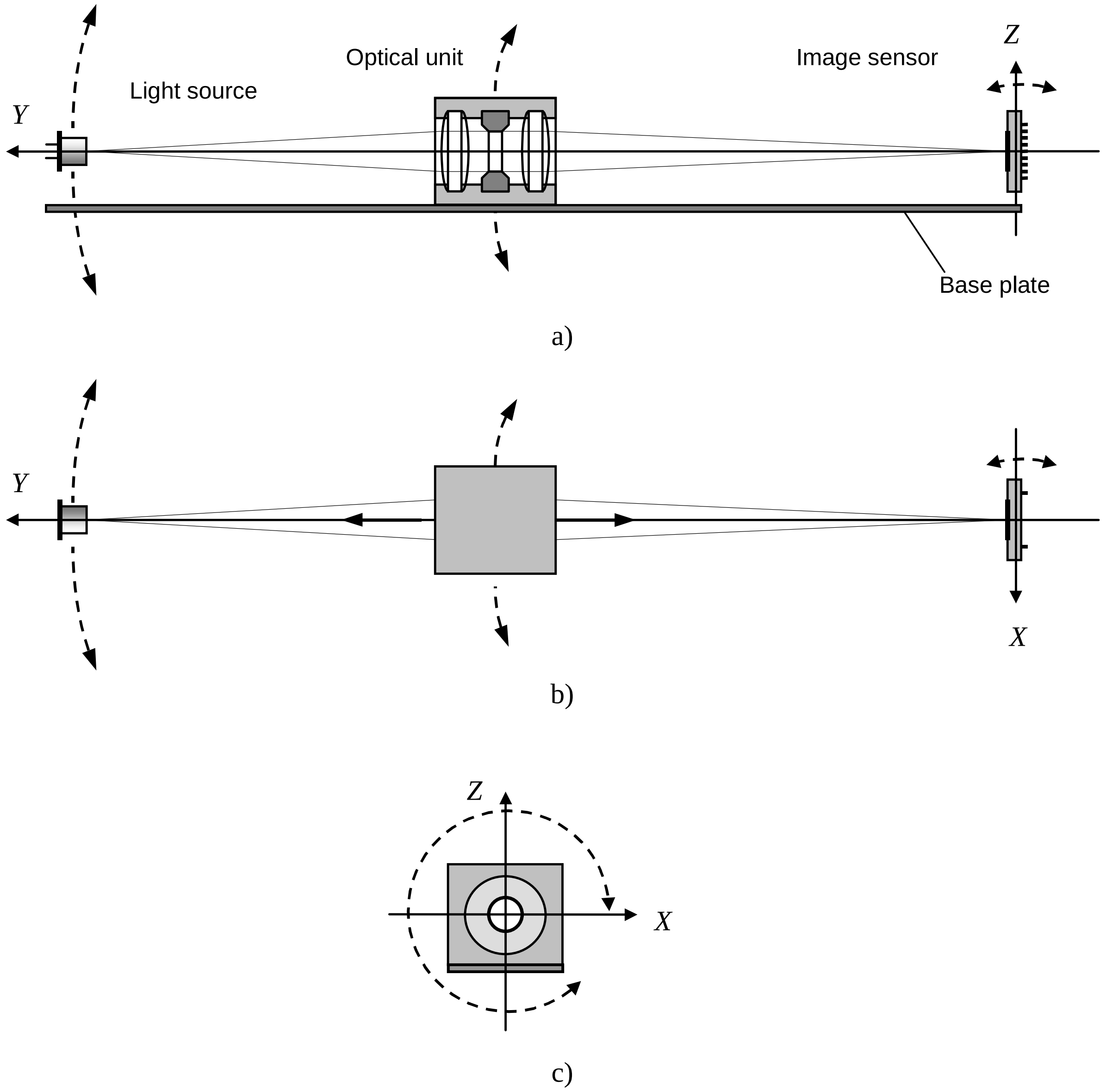


Fig. 2. Main units of the optical Fourier processor and possible mechanical deformations, a) side view, b) top view, c) rear view

- *Inclination of the optical unit* will result in degradation of the JPS fringes and correlation peaks due to the off-axis aberrations, but for small angles this effect is negligible small. For the symmetrical optical system (the focal length of the collimator and Fourier lens are equal), no shift errors are anticipated (at least for the small angles).

- *Inclination of the image sensor* will result in some correlation peaks degradation due to defocusing, but, taking into account the small transversal size of the sensor, this effect can be considered negligible for small angles. Scaling of the images due to the sensor inclination will be very small for the small angles (typ. 0.015% for 1 degree inclination) and can also be ignored.

- *Rotation of the optical unit and image sensor* about the common axis will result in corresponding rotation of the correlation image. For devices with a resolution of 320 x 240 pixels the shift error can reach 2.8 pixels per one degree.

- *Longitudinal motion of the light source and image sensor* will result in a degradation of the JPS fringes and correlation peaks due to defocusing. The range of allowable motion depends of the system focal length and SLM size. For usual proportions of the OFP, longitudinal displacements within ± 0.25 % of focal length are acceptable in most cases. Such displacements will cause also a scaling of the correlation image: the corresponding error can reach ± 0.4 pixel for image sensor resolution of 320 pixels.

- *Transversal motion of the light source and image sensor* of the second OFT will cause equal shift of the correlation image. Due to the small pixel size of the image sensor, the corresponding error of correlation peak position determination can be rather high, for example, for a focal length of 100 mm and pixel pitch 7.4 μm every millimetre of shift corresponds to 135 pixels. For the first OFP the small transversal motion of all components is not critical, as it only causes the shift of the input image for the second Fourier transform, which is shift invariant.

Summarising this brief analysis, it can be deduced, that in case of the optical system deformation, the traditional scheme of JTC is subject mainly to the errors due to the *shift of the correlation image, rotation and scaling*.

4. SELF-CORRECTION OF LOW FREQUENCY DEFORMATIONS

4.1 General scheme

The following *method of self-correction* can be applied, if the speed or frequency of a deformation is small enough to make negligible the small delta rotation between the two moments of two successive Fourier transformations. In this method the errors, caused by the optical system deformations, can be eliminated by using the single optical processor scheme of JTC with *doubled resolution* of the image sensor (Figure 3).

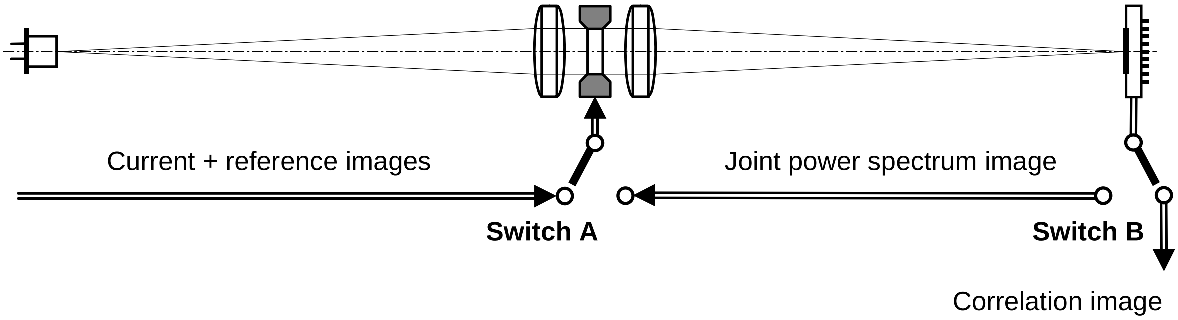


Fig. 3. JTC with single optical processor

Both optical Fourier transforms are performed by one OFP sequentially. Two analogue switches A and B serve for the commutation of a video signal between SLM and CCD. Current and reference images are loaded to the SLM through the switch A. Then the laser gives a short light pulse to project the spectrum image on the image sensor array. The switches A and B change the position and the spectrum image is read from image sensor and directly loaded to the SLM. After finishing of the readout/loading the laser, the correlation image is read from the image sensor. Simultaneously a new input image is written on the SLM through the switch A.

4.2 Self-correction procedures

As both Fourier transforms are done by the *same* OFP, the *scaling errors* are corrected automatically due to the Fourier transform feature to reduce the spectrum image, if the input image is enlarged and vice versa.

The *rotation error* can be compensated by flipping the spectrum image horizontally or vertically before loading it to the SLM for the second Fourier transform. In this case the rotation of the image in the first Fourier transform will be compensated by the opposite rotation in the second transform.

Using of an image sensor with doubled resolution (with respect to SLM) permits to obtain the correlation image with both correlation peaks. Measuring of the difference between the peaks positions (instead of position of one peak) automatically corrects for *shift errors*.

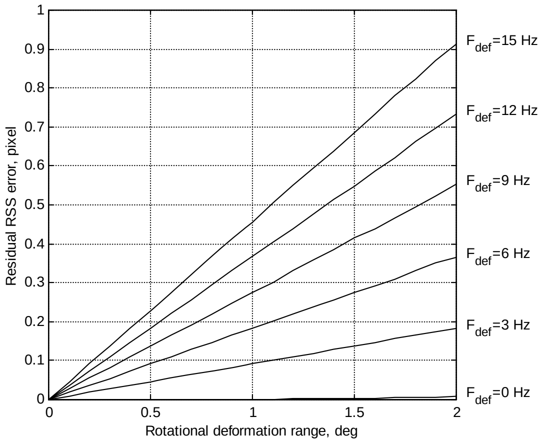
The application of the correction procedures as described above within a single processor JTC scheme allows a simple and efficient *full correction* of the image shift measuring errors caused by the deformation of the optical system (within a certain range of deformation).

4.3 Performance analysis

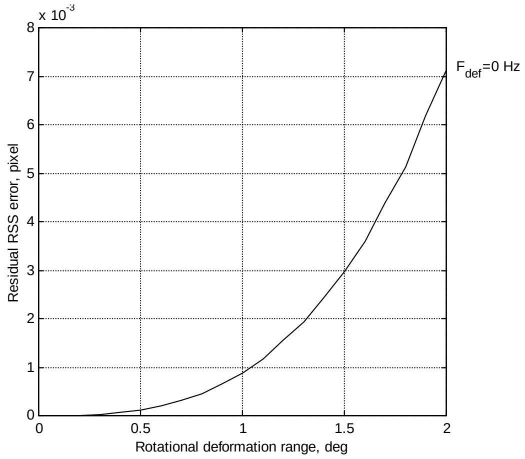
Representative performances of this method have been studied on the basis of simulations with a model of mechanical deformations. Figure 4 shows the estimated performance of this self-correction technique under different mechanical conditions – different frequencies and amplitudes of the deformations. The deformation is considered as rotation (for all axes X,Y,Z), as a simple shift of optical units is self compensated. The horizontal axis of the plots shows the rotation range and the amplitude of deformations.

Figure 4-a shows an ideal case with only constant deformations, this is a limit of correction quality. (F_{def}=0 Hz means no deformation takes place). The performance of the self-correction significantly degrades with increasing frequency (F_{def}) and amplitude of deformations (Figure 4-b). The longitudinal misalignment can be within ±0.5% of the focal length, transversal misalignment within ± 100 pixel. The processing speed of the correlator is 200 Fourier transformations per second.

The self-correction technique was successfully used for a real hardware model of the optical Fourier processor, developed under ESA-contract (Figure 5).



a)



b)

Fig. 4. Estimated performance of self-correction for different mechanical conditions, a) residual root-summ-square (RSS) error under deformation frequencies, b) residual RSS error under constant deformations

This model showed the robustness to mechanical deformation within the range ±1 deg and accuracy of image shift determination of 0.2 pixel (σ).

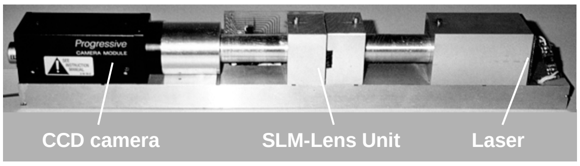


Fig. 5. Hardware model of the optical Fourier processor

5. CORRECTION OF HIGH-FREQUENCY DEFORMATIONS

The method of the rotation and scaling error correction, described in the previous chapter, has one limitation – it assumes, that the optical system deformation does not change between the moments of the first and second Fourier transforms. If this is not true, i.e. if the optical system is subject to high frequency vibrations, some residual error will remain uncorrected.

To correct the residual errors, caused by high frequency vibration, it is possible to include a special *calibration reference pattern* into the input images, which gives two additional correlation peaks in the correlation image. The position of these peaks can be used as reference for the determination of the residual errors.

The calibration reference pattern can be created as two identical sets of randomly distributed white pixels shifted by a certain distance. As the total area, occupied by these pixels, is small compared to whole image, they will not affect the main correlation process (correlation analysis is extremely tolerant to random noise). In order to make the additional correlation peaks easily distinguished from the main peaks, they can be situated on the axis of symmetry of the correlation image, where the main correlation peaks amplitude fall to zero due to the low overlapping of the input images.

The position of these reference correlation peaks is measured with some error. Therefore the residual error from high frequency deformations cannot be removed completely. Figure 6 shows the estimation for the final residual error after correction of high frequency deformation. Here the position of reference correlation peaks is assumed to be measured with an error (RMS) of 0.1 pixel.

The slight decreasing of the correction performance for a large deformation range is a result of non-correctable deformations (here: inclination). The frequency and amplitude of the deformation do not strongly affect the correction performance.

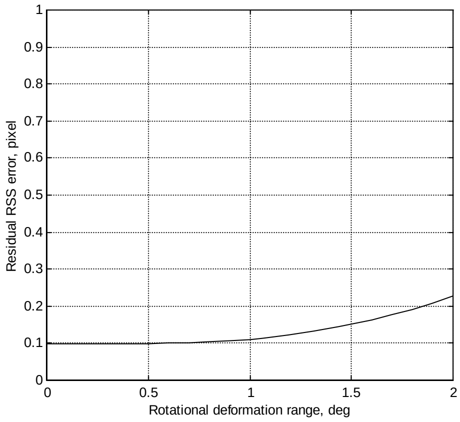


Fig. 6. The final residual error after correction of high frequency deformations

6. CONCLUSIONS

The *Joint Transform Optical Correlator* can be made insensitive to *slow deformations (low frequency)* of the optical system (within a certain range) by using a single optical Fourier processor for both Fourier transforms, joint spectrum image flipping and doubling the resolution of the image sensor (to process the images of both correlation peaks in the correlation plane).

The effect of *fast deformations (high frequency)* can be reduced by including a special calibration pattern into the input image to obtain in the correlation plane the additional pair of the correlation peaks, which can be used as a reference for correction of the errors. Such a robust optical correlator can reliably work in other space applications with harsh mechanical environment – image based guidance, control, collisions avoidance for automotive vehicles, e.g. planetary rovers.

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