Integrated Camera Motion Compensation by Real-Time Image Motion Tracking and Image Deconvolution

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***Abstract*— This paper presents the concept of a smart satellite pushbroom imaging system with internal compensation of attitude instability effects. The compensation is performed within the optical path by an active opto-mechatronic stabilization of the focal plane image motion in a closed loop system with visual feedback. Residual distortions are corrected by image deblurring through deconvolution. Both corrective actions are derived from a real-time image motion measurement which is based on an auxiliary matrix image sensor and an onboard optical correlator. The paper describes the principles of operation, the main system elements and gives detailed performance figures derived from a simulation performance model, which contains all relevant components of the smart imaging system.**

I. Introduction

REMOTE sensing cameras on satellites need a highly stable attitude of the hosting observation platform. So called scan cameras with linear image sensors use the Earth image motion in the focal plane (caused by the satellite orbital motion) to scan the image along the flight direction. Focal plane attitude stability during the scanning motion is very essential for the image quality. Attitude perturbations disturb the image motion, what results in a degradation of the modulation transfer function (MTF) and geometrical distortions of the obtained images. Especially sensitive to this kind of disturbances are high resolution pushbroom scanners with Time Delayed Integration (TDI), which allow in principle a ground pixel resolution of less than 1 meter at a 700 km orbit altitude [1]. An example for the degradation of image quality due to attitude instability is shown in Fig. 1.

To overcome this problem of image distortion, four general principles can be applied.

The first and most common principle is to improve the attitude stability of the host satellite and to minimize the vibrations, produced by momentum and reaction wheels and other moving elements of the satellite (Fig. 2, principle 1). This results in dedicated remote sensing satellites with high precision attitude control systems [2], [3]. The smooth attitude behavior must be paid on the other hand by a significant increase of the cost of the satellite.

An alternative approach – camera stabilization - tries to decouple the camera motion from the satellite body motion by means of a vibration isolating camera platform (Fig. 2, principle 2). It requires some multi-axis fine-pointing mechanism, which is capable to carry the camera together with its optics (several kg). This solution is very common for airborne remote sensing systems, but not so adequate for satellite applications. Due to the fundamental mass restrictions and challenging lifetime requirements (several years without maintenance possibilities), this principle is used only in very specific space applications, such as laser inter-satellite link communication [4], [5].

A third approach – focal plane stabilization - tries to decouple merely the focal plane motion from the disturbing satellite body motion (Fig. 2, principle 3). By an appropriate measurement of the focal plane motion, the image motion can be reconstructed and compensated mechanically in a feedback loop. This solution is attractive for several reasons. First, it tries to compensate the disturbance only at the most important location of an imaging system: the focal plane, where the image sensor is located. Second, it does not require moving big and heavy parts, but only to move some small elements of the focal plane assembly. Piezo-electric actuation principles are very adequate to solve this task and some space proven solutions are already existing [4], [5].

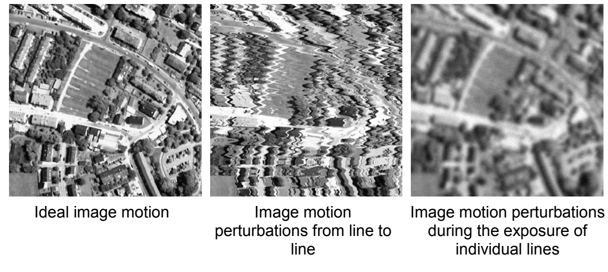

Fig. 1. The effect of perturbations of the focal plane image motion (simulated images).

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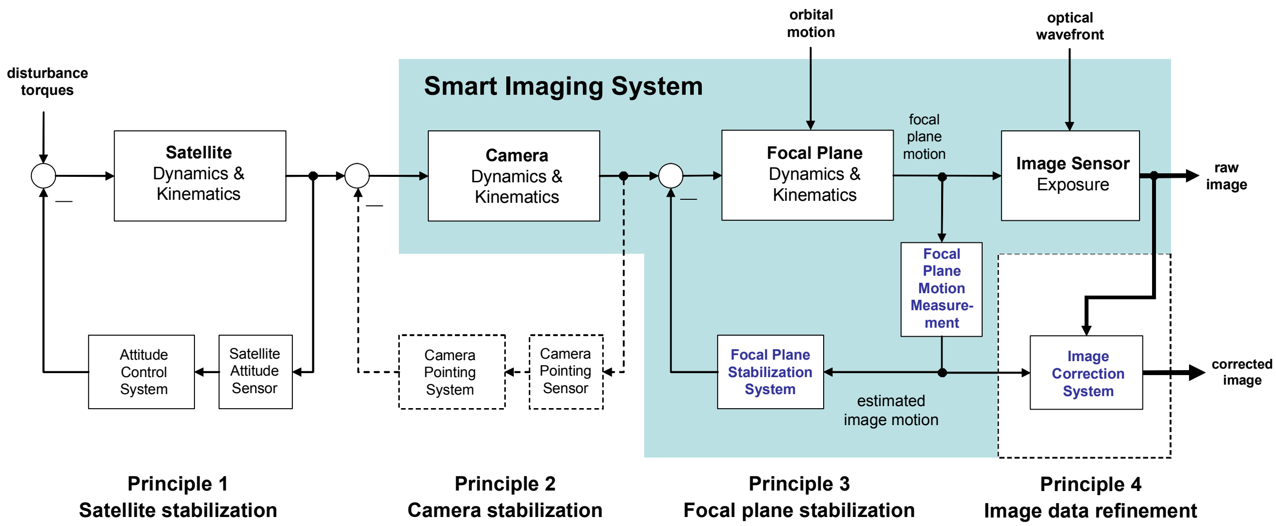

Fig. 2. Image stabilization principles for a remote sensing satellite.

In a fourth step, a further image quality improvement can be achieved by appropriate image data refinement algorithms (Fig. 2, principle 4). All these algorithms rely on additional information on image motion, at least some a-priori information on the expected disturbance motion has to be provided [6].

The three basic principles 1 to 3 of active motion compensation can be categorized more generally as hierarchical coarse/fine pointing control. Such control structures are well known from biological systems, such as the very efficient coarse head/body motion control paired with the fine retina control [7], [8]. In mechatronic systems two realization variants are commonly used. 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 bandwidth outer loop with high accuracy feedback signals [9]. The second variant uses two actuators in parallel: a low-bandwidth large stroke (coarse position) actuator serves to move a high-bandwidth short-stroke (fine position) actuator, which results in a dual input-single output (DISO) system [10]. In both cases the challenges for control design come from structural vibrations and noise and time delay from the feedback signals.

The best suitable motion sensor for camera focal plane stabilization is an image sensor. Building then a motion control feedback loop, leads to the so-called visual servoing structure [11]. A wide variety of visual servoing applications has been developed so far in macro-robotics [12] as well as in micro- and nano-robotics. In particular the latter class has strong commonalities with remote sensing camera design in terms of micro- and sub-micrometer accuracies and the actuation principles applied, e.g. MEMS microassembly [13], [14].

The big challenge for application of visual servoing in focal plane stabilization is measuring the disturbing image motion in real time and with high precision. Laser inter-satellite link communication systems use a co-operative laser beacon signal from a remote laser terminal to determine relative orientation measurements [4], [5]. Such a solution is not adequate at all for a remote sensing camera, which must be operated autonomously without any external aids.

Autonomous image motion estimation can be done advantageously from a focal plane image sensor by analyzing the temporal-spatial dynamics of image blocks. Feature based tracking methods basically use computationally efficient edge detection techniques, but they rely on structured environment with specific patterns [11], which is not the case in most remote sensing applications.

Area based tracking methods have been proved to be much more robust in particular for unstructured environment image data. They exploit the temporal consistency over a series of images, i.e. it is assumed that the appearance of a small region in an image sequence changes little.

The classical and most widely approach applied is the area correlation, used originally for image registration [15]. 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 beside the standard cross correlation, e.g. phase correlation [13] or the Joint Transform Correlation [16].

A solution for in-situ focal plane image motion measurement based on area correlation has been proposed by the authors and proved by detailed investigations and experimental airborne testing [17], [18]. The TU Dresden SMARTSCAN system uses an auxiliary matrix image sensor in the focal plane of a pushbroom camera and processes the auxiliary image data by 2D-correlation to derive focal plane image motion data with subpixel accuracy. With this image motion record it is further possible, to correct the distorted images of the linear sensor posteriori by off-line post-processing in a ground station. This variant of a smart imaging system implements principle 4 of Fig. 2. The demanding onboard processing requirements for real-time correlation are provided by a special embedded optical correlator technology, which has been developed and tested at the Institute of Automation at the Technische Universität Dresden.

A first variant of an embedded opto-mechatronic focal plane assembly with visual feedback has been proposed by the authors in [19], [20]. This solution implements the principle 3 of Fig. 2 by using again the same focal plane motion measurement concept and a 2-axis piezo-drive assembly for high precision positioning of the complete focal plane assembly including the main image sensor. For this solution detailed theoretical investigations and prototyping of a laboratory model have been performed.

In this paper the integration of both stabilization principles 3 and 4 for optimized image quality is presented. For the focal plane stabilization an alternative opto-mechatronic variant is investigated, which controls directly the optical path by actuating one of the telescope imaging mirrors. This solution shows several advantages for high resolution multi-spectral pushbroom cameras, but requires extremely high-speed correlation processing with minimum delay time.

As the real-time record of the image motion is available, a further electronic image enhancement in terms of deblurring can be achieved by applying deconvolution of the raw image with the measured image motion record.

II. Focal Plane Stabilization

The image motion in the focal plane of a satellite camera can be stabilized with a tilt mirror included in the optical system of the camera. The required motion of the mirror is in general very small (typically within ± 0.001°), what allows to use piezo actuators and to reach a mechanical bandwidth of mirror rotation of up to 1000 Hz. This is sufficient for compensation of vibrations, caused by momentum and reaction wheels, which are standard actuators for accurate satellite attitude control. The spectrum of significant vibrations resulting from wheel unbalance are generally within a few hundreds Hertz. To achieve the required imaging accuracy, the operation of the mirror must be controlled in a closed loop system with visual feedback, based on in-situ image motion determination directly in the focal plane of the camera (Fig. 3).

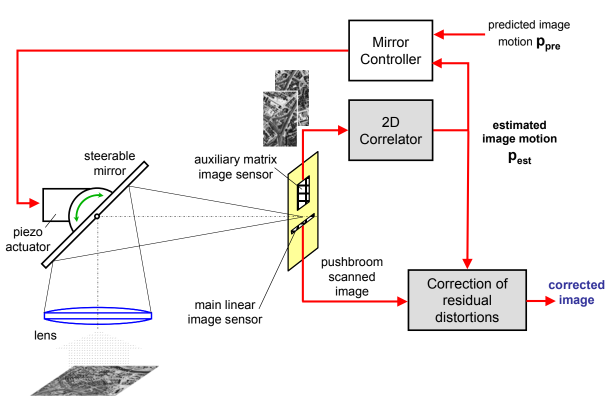

Fig. 3. Smart image motion compensation assembly.

III. Image Motion Measurement by 2D-Correlation

The realization of visual feedback requires fast and accurate determination of the focal plane image motion. For effective closed loop control a high sampling rate (exceeding the bandwidth of the tilt mirror – at least few kHz) and a small time delay (within 0.2 … 0.5 ms) are required. The error of image motion determination should be within 0.1 pixels per frame (one sigma) also in presence of large image noise and with different image textures.

Image motion is considered as a time discrete motion of small image blocks in the camera image plane (Fig. 4). This is caused by a mutual motion of the camera and a scene in the camera field of view. The pattern of all motion tracks generally carries information about the motion of the camera with respect to the observed scene as well as information about the 3D structure of the scene. Real-time image motion tracking is characterised by a large amount of processed image information, which is required for high reliability and robustness to noise and distortions. The most powerful methods used today are 2D-Fourier analysis and 2D-correlation.

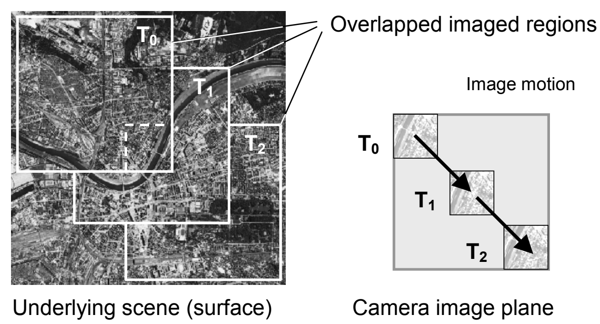

Fig. 4. Image motion tracking.

The basic step for image motion tracking is the measurement of the shift between two overlapped images of a consecutive image sequence. The second image will be shifted with respect to the first by a shift vector. This vector can be effectively determined by two dimensional (2D) correlation of the images. The peak location of 2D-correlation function represents the mutual shift vector between the original input images (Fig. 5).

For processing efficiency the so-called joint transform correlation scheme is used. It makes use of two subsequent 2D-Fourier transforms without using phase information, i.e. only the processing of the power spectrum magnitude is needed (Fig. 6).

As a result, the vector of mutual shift of the images can be determined by locating the bright correlation peaks in the

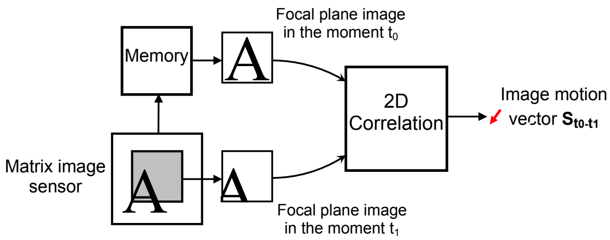

Fig. 5. Image shift vector determination by 2D-correlation.

correlation image (Fig. 6, bottom). This localization of correlation peaks is a standard task of elementary image processing and can be solved with standard algorithms (e.g. center of mass determination) at subpixel accuracy with standard digital processors. The benefit of the correlation based image shift determination lies in its high inherent signal redundancy which allows to generate sharp peaks even for low SNR (signal to noise ratio) dark images. It also shows little dependency on the actual image content. No specific texture patterns are being required, difficulties will only arise for spatially flat and homogeneous image contents.

The correlation approach, however, has one significant drawback – a huge amount of calculations, required to perform the 2D correlation digitally. This makes digital schemes practically impossible to meet the sampling rate and delay requirements for focal plane stabilization. To overcome this limitation, fast optical image processing techniques can be applied.

For the correlation technique under consideration a special opto-electronic scheme, known as *Joint Transform Optical Correlator* (JTOC), can be used [16]. A Joint Transform Optical Correlator includes two identical opto-electronic modules – Optical Fourier Processors (OFP). Any of these Optical Fourier Processors computes the power

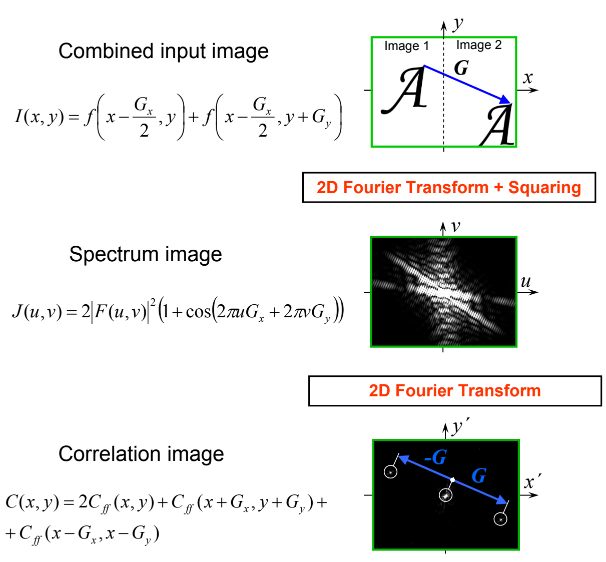

Fig. 6. Joint Transform Correlation.

spectrum of the digital input image with speed of light using diffraction effects. It uses a transparent *spatial light modulator* (SLM) to enter the input image into the optical path of a coherent light source (laser beam) and reads out the power spectrum of the input image as intensity distribution from a CCD or CMOS sensor in the focal plane of the OFP [21]. As the actual 2D-Fourier transform is performed with speed of light, the end-to-end processing speed is limited only by the data transfer of the opto-electronic input # output devices (SLM # CCD/CMOS). 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 extensively in the last years at the Institute of Automation of the Technische Universität Dresden. Different hardware models have been manufactured and tested successfully under ESA (European Space Agency) contracts. Due to special design solutions the devices are very robust to mechanical loads and do not require precise assembling and adjustment [22], [23]. Recent airborne test flight results have shown very promising end-to-end performances [18].

The typical optical correlator accuracy of shift determination errors is below 0.1 pixels (1σ) even for extremely noisy images with SNR less then 0 dB. With currently available opto-electronic components it is possible to perform up to 10000 correlations per second (correlated images of 128x128 pixels) with the processing delay of 0.2 ms. Thus, the performances of the optical correlator cope very well with the requirements to an image motion sensor in the visual feedback loop.

IV. Image Deblurring by Deconvolution

Any motion of the focal plane image during exposure results in blurring of the obtained image. In pushbroom scanners with Time Delayed Integration (TDI) the regular image motion component, caused by motion of satellite, is compensated by corresponding shifting of the accumulated charges. This method, however, does not compensate the irregular image motion component, caused by attitude disturbances and vibrations. Uncompensated image motion causes image blurring, which can be modelled for a certain part of the image as a result of convolution with the motion trajectory during exposure. The blurred image part can be described by

$$g(x,y) = f(x,y) * b(x,y) \tag{1}$$

with $f(x,y)$ the original image part and $b(x,y)$ the image motion trajectory.

Generally motion blur effects can be avoided by minimising of the exposure time. This approach however results in image underexposure / noise amplification and is therefore not suitable for high resolution Earth observation systems (high resolution imagers are generally very sensitive to underexposure due to large aperture ratio and low brightness of the focal plane image).

The effect of blurring can be corrected by a deconvolution procedure. This operation can be in principle performed without knowledge of $b(x,y)$, by some kind of adaptive high-pass filtering. The effectiveness of such so-called *blind deconvolution* approaches is however considerably poor, with large residual image distortions, high noise amplification and large processing time.

Much better results can be obtained if the image motion trajectory $b(x(t),y(t))$ during exposure is known. In this case the blurred image can be deconvoluted by inverse filtering, which can be practically carried out in Fourier space by performing a (complex) division of the Fourier transform of the blurred image by that of the image motion trajectory. The Fourier transform of the corrected image part is then given by

$$F'(u,v) = G(u,v)/B(u,v), \qquad (2)$$

with $G(u,v)$ the Fourier transform of the blurred image part and $B(u,v)$ the Fourier transform of the image motion trajectory. The corrected image $f'(x,y)$ can be obtained from $F'(u,v)$ by inverse Fourier transform.This approach provides high quality of motion blur compensation but requires the precise record of the actual image motion $b(x(t),y(t))$ during the exposure interval. Such record should have subpixel accuracy and high sampling rate. These high requirements can be met with the proposed image motion determination system with auxiliary matrix image sensor and optical Correlator, where $b(x(t),y(t))= \mathbf{p}_{est}(t)$ (see Fig. 3).

Fig. 7 illustrates the effect of simulated image motion blurring and the possible results of blur avoidance by exposure time minimisation (bottom right) and blur compensation by deconvolution (bottom left).

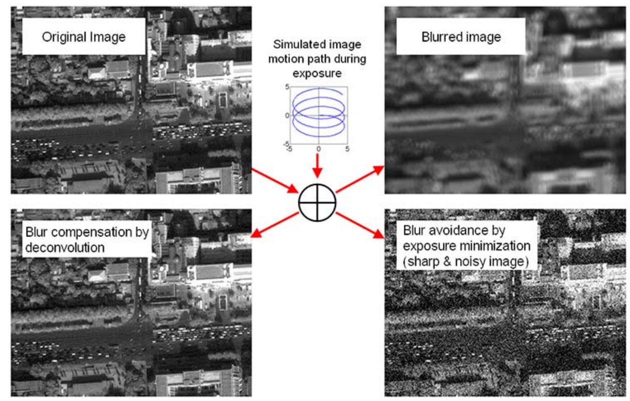

Fig. 7. Motion blur simulation and blur compensation.

V. System Realization Concept

The proposed focal plane stabilization of the image motion can be realized by including three additional modules into an existing pushbroom scan satellite camera (Fig. 8).

All components of the *Focal Plane Module*, including the auxiliary matrix image sensor, should be installed directly in the focal plane of the camera, close to the main pushbroom scan sensors.

The *Optical Correlator Module* can be positioned separately, being connected to the focal plane module by a cable. It will receive the image flow from the Focal Plane Module, determine the image motion and control the

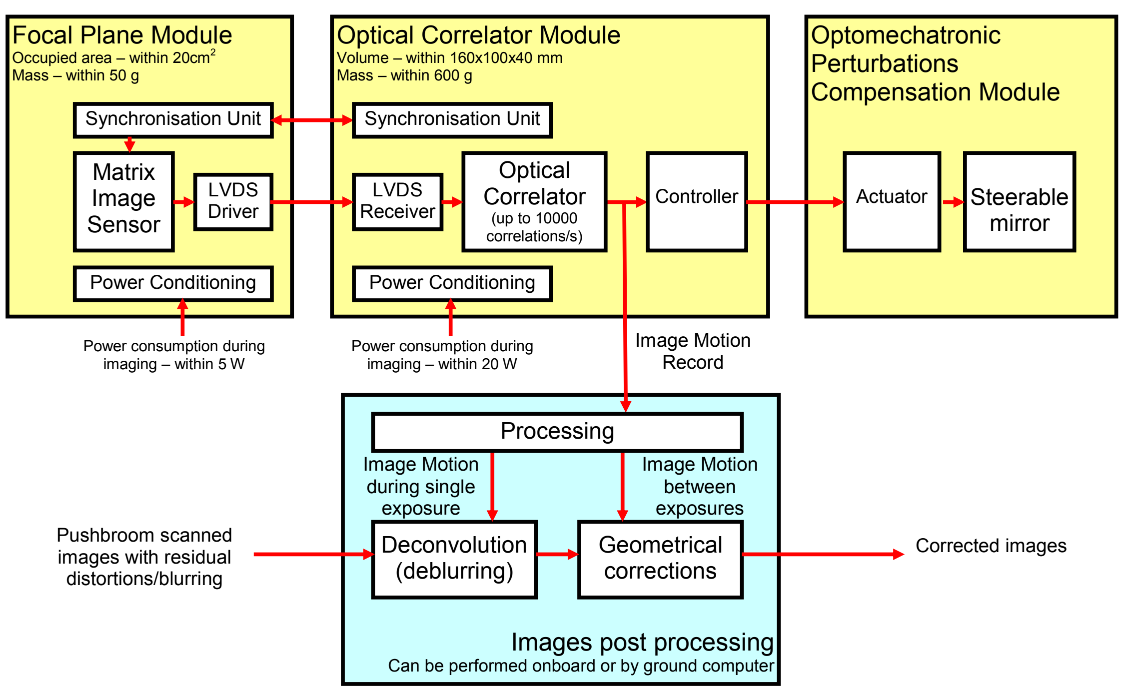

Fig. 8. Layout of the integrated smart image motion compensation system.

operation of the steerable mirror (*Opto-mechatronic Perturbations Compensation Module*) in order to compensate for the deviation from the ideal image motion.

Residual distortions of the obtained images, caused by uncompensated disturbances of focal plane image motion, are corrected offline by deconvolution (blurring) and interpolation (geometrical distortions). Both approaches use the image motion record, produced in real time (during exposure of the image) by an onboard optical correlator.

VI. Performance Analysis

A. Reference mission description

A high-end remote sensing mission with realistic camera parameters has been defined as baseline for the evaluation of possible system end-to-end system performances. The high resolution pushbroom scan camera contains two linear image sensors in the focal plane of the common optics (Fig. 9).

A panchromatic sensor (PAN) operates in 10 lines TDI mode and has the angular resolution of 1 µrad/pixel. Attitude perturbations at focal plane level considered for the performance analysis were the sum of two harmonics with frequencies of 72 and 43 Hz. A detailed list of reference mission parameters is given in Table I.

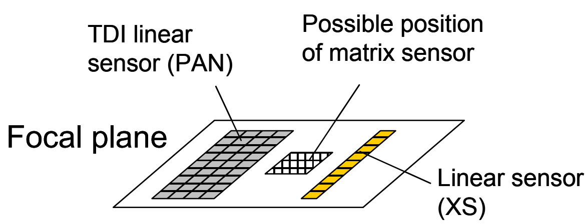

Fig. 9. Focal plane reference configuration.

B. System performance model

A simplified simulation performance model of the focal plane stabilization assembly has been developed. The model includes all relevant elements at an appropriate level of modeling fidelity: a mirror controller, a model of the tilt mirror with piezo actuator and a software model of the image motion sensor together with the optical correlator in the feedback loop (Fig. 10).

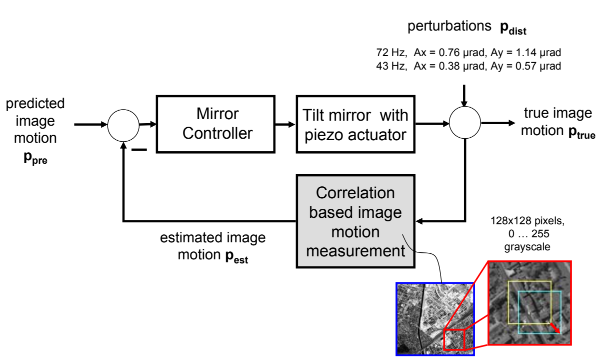

Fig.10. Performance evaluation model.

TABLE I
REFERENCE MISSION PARAMETERS

Mission parameters	
Altitude	695 km
Attitude perturbations	72 Hz, A_x = 0.76 µrad, A_y = 1.14 µrad 43 Hz, A_x = 0.38 µrad, A_y = 0.57 µrad
Image scan time	12 s
Camera parameters	
Pixel size	PAN: 13 µm; XS: 52 µm
Angular pixel size	PAN: 1.007 µrad; XS: 4.029 µrad
Integration time	PAN: 0.1034 ms; XS: 0.4136 ms
PAN / XS distance	1538 pixels

The *predicted image motion* $\mathbf{p}_{\mathrm{pre}}$ corresponds to the case without attitude disturbances, when the image motion in the focal plane is determined only by the nominal orbital motion of the satellite. *Perturbations* $\mathbf{p}_{\mathrm{dist}}$ are added to the predicted motion to simulate the effect of attitude disturbances. The *true image motion* $\mathbf{p}_{\mathrm{true}}$ represents a result of perturbations compensation by light deflecting with the tilt mirror. With ideal compensation, the true image motion $\mathbf{p}_{\mathrm{true}}$ should be equal to the predicted motion $\mathbf{p}_{\mathrm{pre}}$. A *tilt mirror* is assumed to produce an image shift proportional to the input signal. The mirror dynamics including the piezo-actuator is simulated as a second order filter with a cut-off frequency of 1000 Hz and a damping factor of 0.35.

The model of the *correlation based image motion measurement* (bottom block in Fig. 10) includes an image generator and a software model of the optical correlator.

The image generator produces the current and reference image fragments for the correlation according to the true image motion $\mathbf{p}_{\mathrm{true}}$. The required shifts of the image have been performed with subpixel accuracy using spline interpolation. To simulate the expected low signal-to-noise ratio, random noise has been added to each fragment before correlation. The correlator is represented by a software model with certain processing delay.

The image fragments are generated on base of a large high resolution aerial image. The image contains areas with different texture, what allows to test the system operation with different image content.

The mirror controller is represented by the following transfer function:

$$R(s)=\frac{U(s)}{E(s)}=\frac{K_r\left(\frac{1}{\omega_r^2}s^2+2\frac{D_r}{\omega_r}s+1\right)}{s\left(\frac{1}{\omega_n}s+1\right)}\cdot\frac{\frac{1}{\omega_p^2}s^2+2\frac{D_p}{\omega_p}s+1}{\frac{1}{1.5\cdot\omega_p^2}s^2+2\frac{0.8}{1.5\cdot\omega_p}s+1}\cdot\frac{\frac{1}{\omega_s^2}s^2+2\frac{1}{\omega_s}s+1}{\frac{1}{\omega_s^2}s^2+2\frac{0.1}{\omega_s}s+1} \tag{3}$$

with
K_r = 2000; D_r = 0.5; ω_r = $2\pi\cdot600$ s^{-1}; ω_n = $2\pi\cdot600$ s^{-1}; D_p = 0.35; ω_p = $2\pi\cdot1000$ s^{-1}; ω_s = $2\pi\cdot72$ s^{-1}.

The first term forms a PID control, the 2nd term represents a supplementary filter for suppression of the gain on resonant frequency of the actuator, the 3rd term - a supplementary filter for increasing the gain on frequencies of the perturbations.

C. Simulation experiment description

The simulation performance model of the focal plane stabilization assembly has been realized as a Simulink model. The simulation experiments have been performed for a time interval of 12 seconds. With a sampling frequency of 10000 samples per second altogether 120000 image fragments have been generated and 120000 correlations performed per simulation run.

D. Simulation results - suppression of image motion perturbations

As a direct result of the simulation experiments, a record of the true image motion $\mathbf{p}_{\text{true}}(t)$ in 12 seconds of simulated system operation has been obtained. This record represents the results of the image motion stabilization (compensation of simulated perturbations) with the optical correlator in the visual feedback loop. With ideal (full) compensation $\mathbf{p}_{\text{true}}(t)$ should be equal to the predicted image motion $\mathbf{p}_{\text{pre}}(t)$. Fig. 11 shows the residual deviation of $\mathbf{p}_{\text{true}}(t)$ from the predicted motion after compensation in comparison with the applied image motion perturbations $\mathbf{p}_{\text{dist}}(t)$ – the effectiveness of compensation is clearly visible. The averaged perturbations suppression factor was 40 at 72 Hz and 16 at 43 Hz.

E. Simulation results - residual image motion instability after compensation of perturbations

The effectiveness of the image motion stabilization has been estimated with four geometrical image quality criteria.

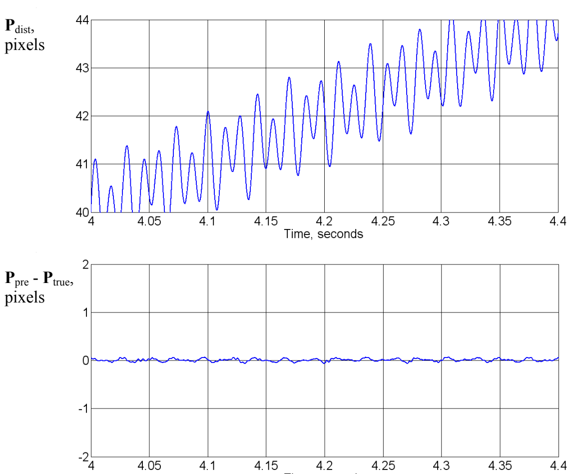

Fig. 11. Simulated image motion disturbances $\mathbf{p}_{\text{dist}}$ (top) and residual image motion disturbances ($\mathbf{p}_{\text{pre}}-\mathbf{p}_{\text{true}}$) after compensation (bottom).

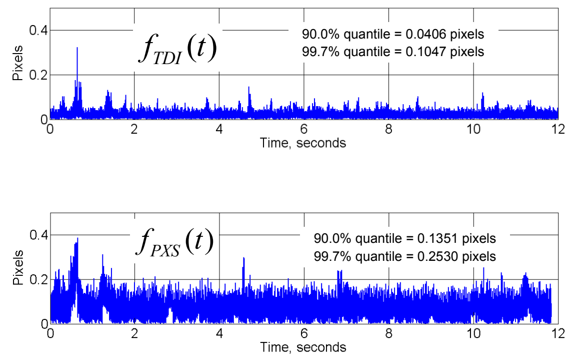

Fig. 12. Short term (f_{TDI}) and long term (f_{PXS}) image motion stability criterion.

The *Local consistency criterion* characterizes the image motion instability during one line integration time (0.1 ms),

$$f_{LOC}(\Delta\mathbf{p},t,\tau)=\sqrt{\left(\Delta p_x(t+\tau)-\Delta p_x(t)\right)^2+\left(\Delta p_y(t+\tau)-\Delta p_y(t)\right)^2} \quad (4)$$

where $\Delta\mathbf{p}=\begin{pmatrix}\Delta p_x & \Delta p_y\end{pmatrix}^T=\mathbf{p}_{\text{true}}-\mathbf{p}_{\text{exp}}$ (image motion error); t = 0…12 s; τ = 0.1 ms (one line integration time).

To avoid the image quality degradation, the magnitude of local consistency criterion should be below 0.1 pixels (99.7% quantile).

The *Dynamic MTF criterion* $f_{TDI}(\Delta\mathbf{p},t,\tau)$ characterizes the image motion instability during 10 TDI lines integration time, with $\Delta\mathbf{p}=\mathbf{p}_{\text{true}}-\mathbf{p}_{\text{pre}}$ (image motion error); t = 0…12 s; τ = 1.0 ms (10 TDI lines integration time)

To avoid the image quality degradation, the magnitude of dynamic MTF criterion should be below 0.1 pixels (99.7% quantile, see Fig. 12, top).

The *Superposition criterion* $f_{PXS}(\Delta\mathbf{p},t,\tau)$ characterizes the error of superposition of panchromatic and color images, with $\Delta\mathbf{p}=\mathbf{p}_{\text{est}}-\mathbf{p}_{\text{true}}$ (error of image motion estimation); t = 0…12 s; τ = 159 ms (PAN/XS distance)

To ensure the proper superposition of panchromatic and color images, the magnitude of the local superposition criterion should be below 1 pixel (99.7% quantile, see Fig. 12, bottom).

The *Stability criterion* $f_{STAB}(\Delta\mathbf{p},t,\tau)$ characterizes the residual error of image motion estimation after bias and linear/low frequency errors suppression, with $\Delta\mathbf{p}=\mathbf{p}_{\text{est}}-\mathbf{p}_{\text{true}}$ (error of image motion estimation); t = 0…12 s; τ = 0.1 ms

The magnitude of local superposition criterion should be below 0.5 pixels (99.7% quantile).

The results of criteria calculation are summarized in Table II. The obtained values of geometrical image quality criteria are generally within the required limits.

The results from this performance analysis and the previous hardware test results with optical correlators allow

TABLE II
GEOMETRICAL IMAGE QUALITY CRITERIA CALCULATED FOR 12 S OF SIMULATED SYSTEM OPERATION

	Acceptable value (99.7% quantile)	Obtained values (90.0% quantile)	Obtained values (99.7% quantile)
Local Consistency criterion	0.1 pixels	0.0056 pixels	0.0168 pixels
Dynamic MTF criterion	0.1 pixels	0.0406 pixels	0.1047 pixels
Superposition criterion	1.0 pixels	0.0786 pixels	0.2294 pixels
Stability criterion	0.5 pixels	0.0312 pixels	0.1026 pixels

concluding, that the proposed focal plane stabilization with visual feedback is feasible even for high resolution pushbroom scan cameras.

VII. CONCLUSIONS

The paper has presented a new approach for active image stabilization of a pushbroom scan space camera. It is based on the in-situ measurement of the image motion in the focal plane, which directly senses the image disturbance motion. The image motion processing is performed in real-time with an onboard optical correlator, which allows using the image motion data as visual feedback signal to control the optical path via a tilt mirror piezo-actuator. It has also been shown, how the image motion record can be used advantageously for a further image quality improvement by a deconvolution procedure to remove image blurring. The proposed solution allows building smart imaging systems in the sense, that the cameras can be kept compact with small aperture optics and no additional camera platforms are needed. Such imaging systems can accept even moderate attitude stability and in consequence less costly attitude control of the host satellite. Therefore these smart imaging systems may help to decrease the cost of many remote sensing applications considerably.

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