A Visual Feedback Approach for Focal Plane Stabilization of a High Resolution Space Camera

Ein Ansatz zur Bildgestützten Regelung für die Fokalebenenstabilisierung einer Hochauflösenden Satellitenkamera

Klaus Janschek, Valerij Tchernykh, Serguei Dyblenko, and Grégory Flandin

In this article a new concept of a smart satellite pushbroom imaging system with internal compensation of attitude instability effects is presented. 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. The real-time image motion measurement is derived from an auxiliary matrix image sensor and an onboard optical correlator. In this way the effects of attitude instability, vibrations and micro shocks can be neutralized, the image quality is improved and the requirements to the satellite attitude stability can be reduced considerably. 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.

Dieser Beitrag behandelt ein neues Konzept für eine kompakte Fernerkundungskamera mit interner Kompensation von Lagestörungen. Die Kompensation erfolgt über einen bildgestützten, opto-mechatronischen Regelkreis, womit eine Stabilisierung der Bildbewegung in der Fokalebene erreicht wird. Zur in-situ Messung der Bildbewegung werden ein Matrix-Bildsensor und ein optischer Korrelator verwendet. Mit dieser Anordnung können die Effekte von Lagestörungen und Vibrationen unterdrückt werden und gleichzeitig die Bildqualität bei reduzierter Lagegenauigkeit des Satelliten verbessert werden. Der Beitrag beschreibt die grundlegenden Funktionsprinzipien, die wesentlichen Systemelemente und präsentiert detaillierte Leistungsmerkmale auf der Basis eines speziellen Verhaltensmodells.

Keywords: Image motion stabilization, optical correlator, opto-mechatronics, pushbroom camera, remote sensing, visual feedback

Schlagwörter: Bildgestützte Regelung, Bildbewegungsstabilisierung, Fernerkundung, optischer Korrelator, Opto-Mechatronik, Zeilenkamera

1 Introduction

Attitude stability is critical for high resolution satellite cameras. For an optimal image quality pushbroom 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, three general principles can be applied.

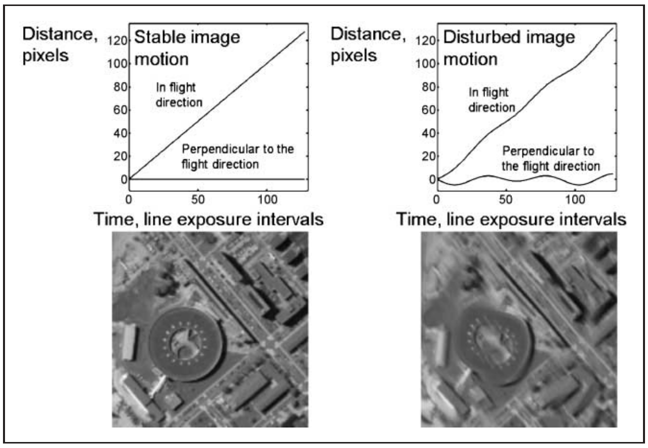

Figure 1: Image distortion due to camera pointing instability.

The first and most common principle is to improve the attitude stability of the satellite body and to minimize the vibrations, produced by momentum and reaction wheels and other moving elements of the satellite (Fig. 2, left). 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, middle). 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, right). 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 image sensor. Second it is not required to move 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 existing [4].

The three basic principles of active motion compensation introduced above 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 control of head/body motion (coarse control) paired with the fine retina control [6; 7]. Mechatronic systems use commonly two realization variants. 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 [8]. 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 [9].

The advantage of the second variant results mainly from the fact, that in general only smaller masses have to be moved for the actual fine-pointing. This allows the application of high-precision actuators such as piezo-drives. The actual achievable overall control accuracy, however, depends in any case on the performance of the motion measurement.

Laser inter-satellite link communication systems use a laser beacon signal from a remote laser terminal to determine relative orientation measurements [4]. Such a solution is not adequate at all for a remote sensing camera, which must be operated autonomously without any external aids.

The best suitable motion sensor for camera focal plane stabilization is an image sensor. This allows autonomous image motion estimation by analyzing the temporal-spatial dynamics of image blocks. Commonly used feature based tracking methods basically use computationally efficient edge detection techniques, but they rely on structured en-

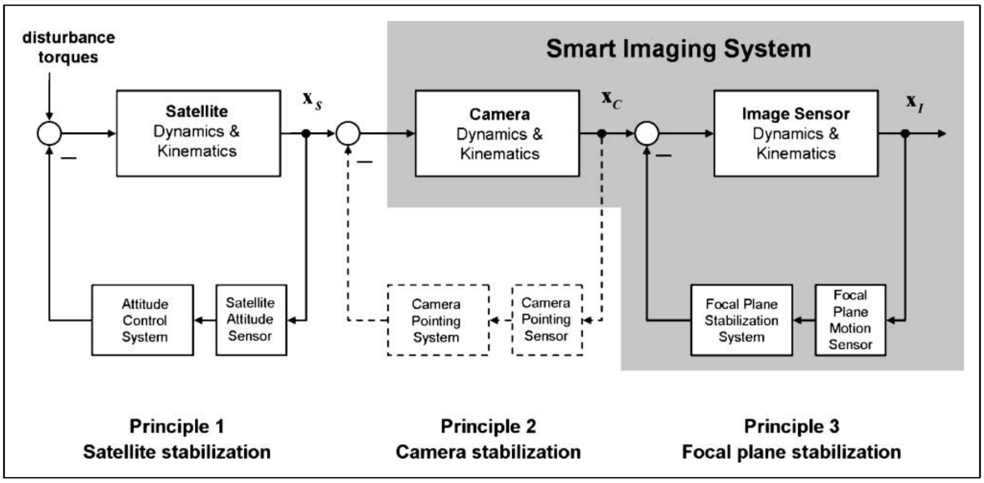

Figure 2: Simplified block diagram of a satellite remote sensing system.

vironment with specific patterns [10], which is not the case in most remote sensing applications.

Alternative methods based on 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 applied approach is the area correlation, developed originally for image registration [11]. Area correlation uses the fundamental property of the cross-correlation function of two mutually shifted images, that the location of the correlation peak is a direct measure of the displacement vector of the mutual image shift. Different correlation schemes are known beside the standard cross correlation, e. g. phase correlation [12] or the Joint Transform Correlation [13].

If these image based motion measurements are available in real-time, they can by used directly as “visual” feedback signals within the motion control loop. Such structures are known as visual servoing [10]. A wide variety of visual servoing applications has been developed so far in macro-robotics [14] 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 submicrometer accuracies and the actuation principles applied, e. g. MEMS micro-assembly [12; 15].

A solution for in-situ focal plane image motion measurement based on area correlation has been proposed by the authors (TU Dresden) and proved by detailed investigations and experimental airborne testing [16–18]. 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. This real-time image motion record allows a further posteriori correction of the distorted images of the linear sensor by an off-line post-processing in a ground station.

A first variant of an embedded opto-mechatronic focal plane assembly with visual feedback has been proposed in [19; 20]. This solution uses 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 an alternative opto-mechatronic variant of an actively stabilized focal plane assembly is investigated. Again visual feedback from area correlation image data is used to derive motion compensation signals, but in this new variant the optical path is controlled directly by actuating one of the telescope imaging mirrors. This solution offers several advantages for high resolution multi-spectral pushbroom cameras, but requires extremely high-speed correlation processing with minimum delay time. To cope with these demanding onboard processing requirements, a special embedded optical correlator technology is used, which has been developed and tested in several applications during the last years at the Institute of Automation at the Technische Universität Dresden.

2 Principle of 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).

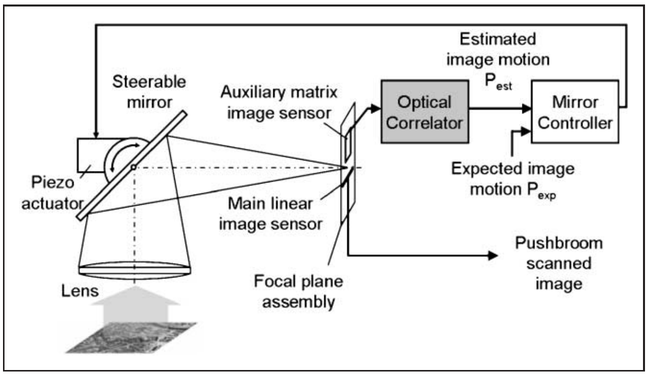

Figure 3: Stabilization of the focal plane image motion with visual feedback.

3 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/frame (one sigma), also in presence of large image noise and with different image texture.

Image motion is considered as a time discrete motion of small image parts 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 characterized by a large amount of processed image information and it requires high reli-

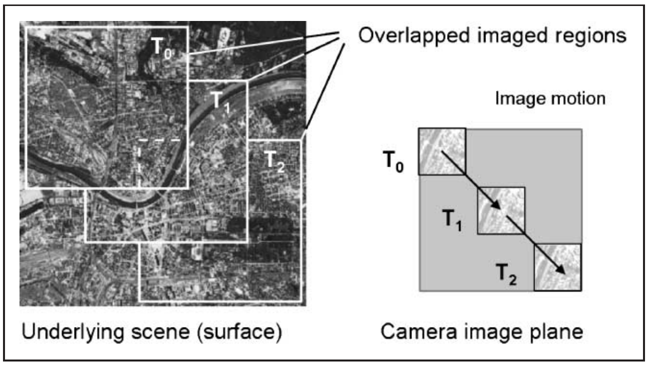

Figure 4: Image motion tracking principle.

ability and robustness to noise and distortions. The most powerful methods used today are 2D-Fourier analysis and 2D-correlation.

The basic step for image motion tracking is the measurement of the shift between two overlapped images. Normally they are taken with a single image sensor at two close time moments during camera motion. The second image will be shifted with respect to the first by a shift vector. This vector is defined by the size and position of overlapped parts for both images. The shift can be effectively determined by two dimensional (2D) correlation of the images. The 2D-correlation function represents the location (offset) of the second image with respect to the first image. This location is normally given by a distinctive peak in the correlation function. The detection of the correlation peak and measurement of its coordinates in the correlation plane allows determining the mutual shift 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 [13] (Fig. 6).

As a result, the vector of mutual shift of the images can be determined by locating the bright correlation peaks in the correlation image. 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. Practically it is sufficient to have some flat texture within the correlated images for successful image motion determination.

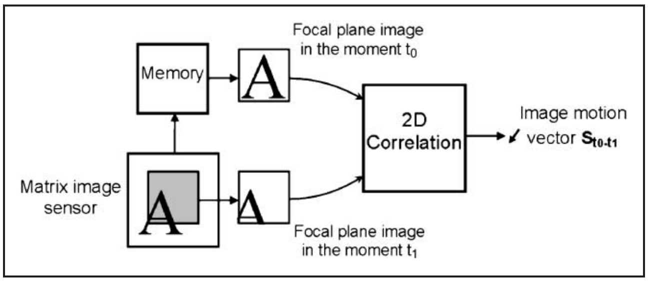

Figure 5: Image motion determination with matrix image sensor and correlator.

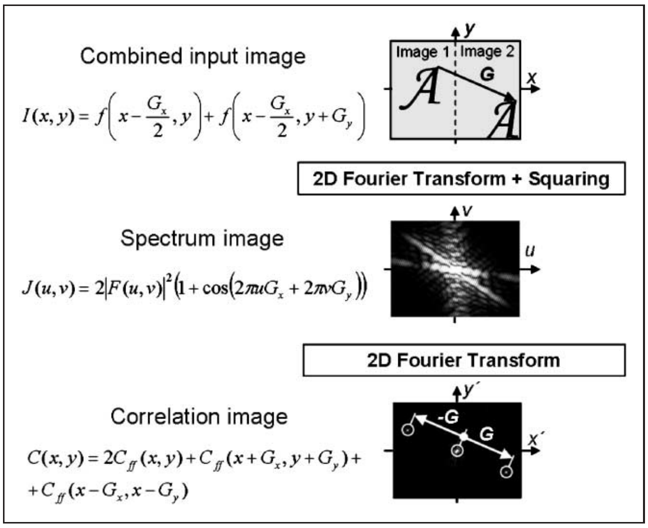

Figure 6: Principle of joint transform correlation.

The correlation approach, however, has one significant drawback – a huge amount of calculations are 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.

4 Real-time 2D-correlation with an optical correlator

For the correlation technique under consideration a special opto-electronic scheme, known as *Joint Transform Optical Correlator* (JTOC), can be used [13]. A Joint Transform Optical Correlator possesses two identical opto-electronic modules – Optical Fourier Processors (OFP), as sketched in Fig. 7.

Each of these Optical Fourier Processors computes the power spectrum of the digital input image with the speed of

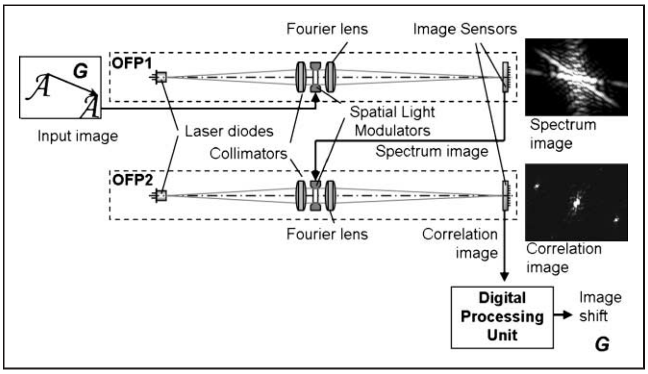

Figure 7: Joint Transform Optical Correlator.

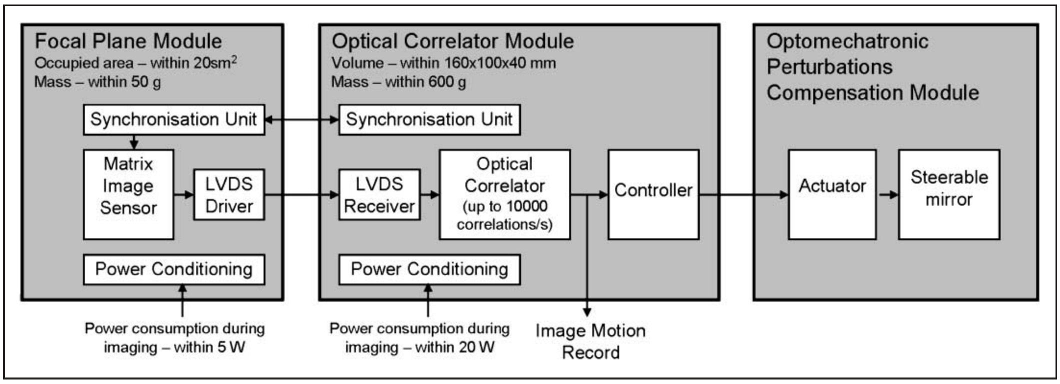

Figure 8: Focal plane stabilization system layout – additional modules to be included in a satellite remote sensing camera.

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. As the actual 2D-Fourier transform is performed with the speed of light, the end-to-end processing speed is limited only by the data transfer of the opto-electronic input and output devices (SLM, CCD/CMOS). Optical processing thus allows a unique real time processing of high frame rate video streams.

To build a Joint Transform Optical Correlator, the two digital images to be compared are entered as the combined input image (see Fig. 6, top) into the optical system of the first OFP by a SLM. After optical Fourier transformation, the joint power spectrum (JPS, see Fig. 6, middle) is sensed by an image sensor in the focal plane of the first OFP and loaded to the SLM of the second OFP. A second optical Fourier transformation generates the correlation image (see Fig. 6, bottom), which can be acquired again by an image sensor in the focal plane of the second OFP. The position of the peaks on the correlation image and the shift value can be measured with sub-pixel accuracy using standard algorithms for centre of mass calculation, as already mentioned above.

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

Due to special design solutions the devices are very robust to mechanical loads and do not require precise assembling and adjustment [21; 22]. 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 10 000 correlations per second (correlated images of 128×128 pixels) with the processing delay of 0.2 ms. Thus, the performance of the optical correlator fulfills well with the requirements on an image motion sensor in the visual feedback loop in all respects.

5 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 operation of the steerable mirror in order to compensate for the deviation from the ideal image motion.

6 Performance analysis

6.1 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 1.

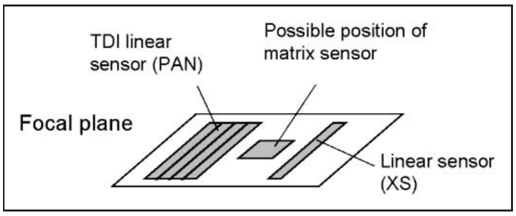

Figure 9: Focal plane assembly for reference mission.

Table 1: Reference mission parameters.

Mission parameters	
Altitude	695 km
Attitude perturbations	72 Hz, Ax = 0.76 µrad, Ay = 1.14 µrad 43 Hz, Ax = 0.38 µrad, Ay = 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

6.2 Analysis goals

The following goals have to be achieved by the performance analysis:

- demonstration of the feasibility of image motion stabilization in the focal plane of a satellite camera with visual feedback under simulation experiment conditions
- estimation of the accuracy of image motion determination with an optical correlator and the robustness to image texture
- estimation of the effectiveness of compensation of the image motion perturbations
- evaluation of the resulting image quality with geometrical image quality criteria.

6.3 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: 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).

The *expected image motion* 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* are added to the expected motion to simulate the effect of attitude disturbances. The *realized image motion* represents the result of perturbation compensation by light deflecting with the tilt mirror. With ideal compensation, the realized motion should be equal to the expected one. The *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.

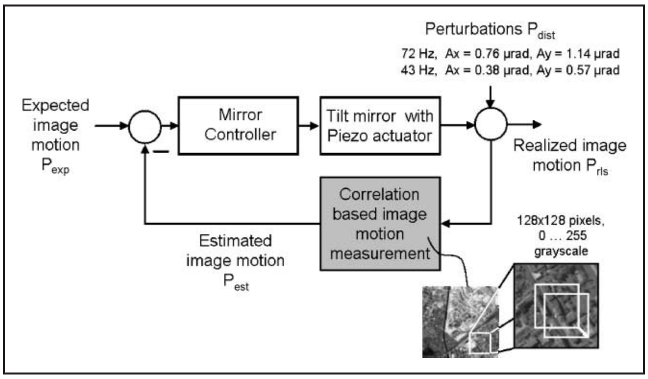

Figure 10: Performance model structure.

The model of the *image motion sensor* (Fig. 11) includes an image generator and a software model of the optical correlator.

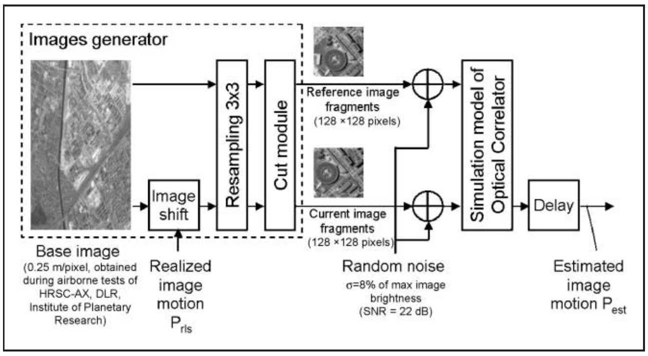

Figure 11: Model of image motion sensor.

The image generator produces the current and reference image fragments for the correlation according to the realized image motion P_{rls}. 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 testing the system operation with different image content.

The mirror controller is represented by the following transfer function:

$$R(s) = \frac{U(s)}{E(s)} = \frac{K_r\left(\frac{1}{\omega_r^2}s^2 + 2\frac{D_r}{\omega_r}s + 1\right)}{s\left(\frac{1}{\omega_n}s + 1\right)} \cdot$$

$$\cdot \frac{\left(\frac{1}{\omega_p^2}s^2 + 2\frac{D_p}{\omega_p}s + 1\right)}{\left(\frac{1}{1.5\cdot\omega_p^2}s^2 + 2\frac{0.8}{1.5\cdot\omega_p}s + 1\right)} \cdot \frac{\left(\frac{1}{\omega_s^2}s^2 + 2\frac{1}{\omega_s}s + 1\right)}{\left(\frac{1}{\omega_s^2}s^2 + 2\frac{0.1}{\omega_s}s + 1\right)}$$

with

$$K_r = 2000\,;\ D_r = 0.5\,;\ \omega_r = 2\cdot\pi\cdot 600\,\mathrm{s}^{-1}\,;$$
$$\omega_n = 2\cdot\pi\cdot 600\,\mathrm{s}^{-1}\,;\ D_p = 0.35\,;\ \omega_p = 2\cdot\pi\cdot 1000\,\mathrm{s}^{-1}\,;$$
$$\omega_s = 2\cdot\pi\cdot 72\,\mathrm{s}^{-1}\,.$$

The first term forms a PID controller, the second term represents a supplementary filter for suppression of the gain at

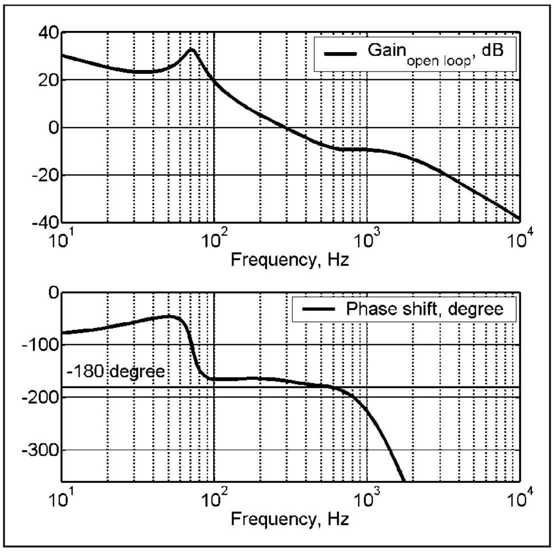

Figure 12: Mirror controller frequency response.

the resonant frequency of the actuator and the third term gives a supplementary filter for increasing the gain on frequencies of the perturbations. The frequency response of the controller is shown in Fig. 12.

6.4 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 10 000 samples/s altogether 120 000 image fragments have been generated and 120 000 correlations performed per simulation run.

6.5 Simulation results – suppression of image motion perturbations

As a direct result of the simulation experiments, a record of the realized image motion P_{rls} 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. P_{rls} should be equal to the expected image motion for an ideal (full) compensation. Fig. 13 shows for the focal plane x-axis the residual deviation of P_{rls} from the expected motion after compensation in comparison with the applied image motion perturbations P_{dist} – the effectiveness of compensation is clearly visible. The averaged perturbations suppression factor was 40 at 72 Hz and 16 at 43 Hz.

6.6 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.

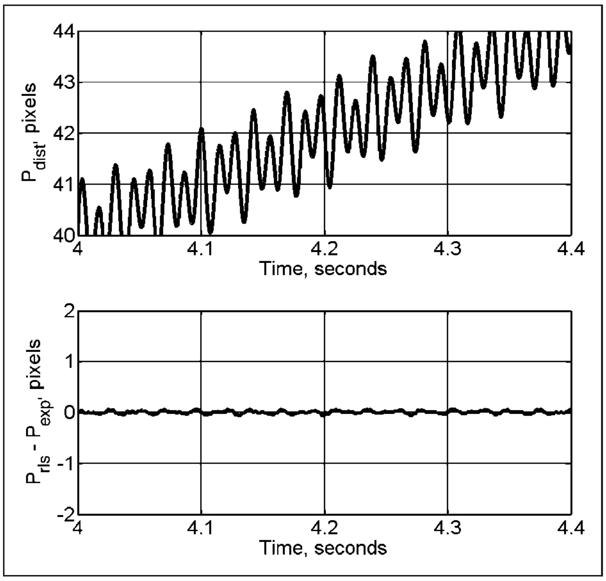

Figure 13: Simulated image motion disturbances P_{dist} and residual disturbances after compensation ($P_{\text{rls}} - P_{\text{exp}}$) for the focal plane x-axis.

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

$$f_{LOC}(\Delta\mathbf{P},t,\tau) = \\ = \sqrt{\left(\Delta P_x(t+\tau)-\Delta P_x(t)\right)^2+\left(\Delta P_y(t+\tau)-\Delta P_y(t)\right)^2}$$

with $\Delta\mathbf{P} = \left(\Delta P_x \Delta P_y\right)^T = \mathbf{P}_{\text{rls}} - \mathbf{P}_{\text{exp}}$ (image motion error); $t = 0\ldots 12\,\text{s}$; $\tau = 0.1\,\text{ms}$ (one line integration time).

To avoid 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 $\Delta\mathbf{P} = \mathbf{P}_{\text{rls}} - \mathbf{P}_{\text{exp}}$ (image motion error); $t = 0\ldots 12\,\text{s}$; $\tau = 1.0\,\text{ms}$ (10 TDI lines integration time)

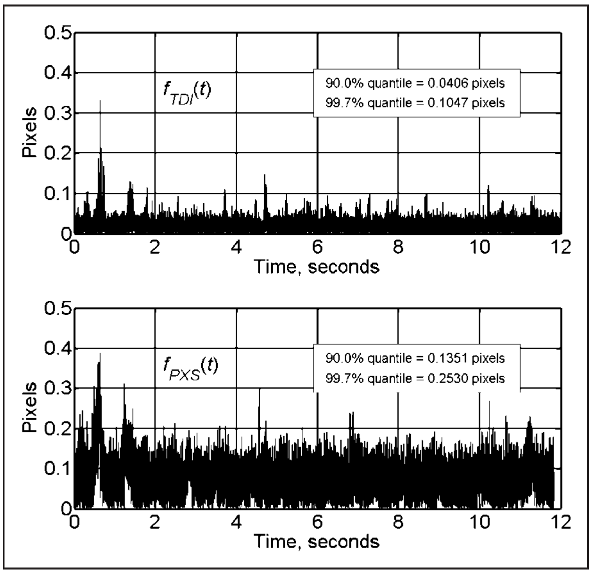

Figure 14: Short term (f_{TDI}) and long term (f_{PXS}) image motion stability criterion.

Table 2: 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

To avoid image quality degradation, the magnitude of dynamic MTF criterion should be below 0.1 pixels (99.7% quantile, see Fig. 14, top).

The *superposition criterion* $f_{PXS}(\Delta\mathbf{P}, t, \tau)$ characterizes the error of superposition of panchromatic and color images, with $\Delta\mathbf{P} = \mathbf{P}_{\text{est}} - \mathbf{P}_{\text{rls}}$ (error of image motion estimation); $t = 0 \ldots 12$ s; $\tau = 159$ 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. 14, 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 error suppression, with $\Delta\mathbf{P} = \mathbf{P}_{\text{est}} - \mathbf{P}_{\text{rls}}$ (error of image motion estimation); $t = 0 \ldots 12$ s; $\tau = 0.1$ ms

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

The results of criteria calculation are summarized in Table 2. 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 concluding, that the proposed focal plane stabilization with visual feedback is feasible even for high resolution pushbroom scan cameras.

7 Conclusions

A new approach for active image stabilization of a pushbroom scan space camera has been presented in this paper. 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 the use of the image motion data as visual feedback signal to control the optical path via a tilt mirror piezo-actuator.

The basic working principles and the overall system concept have been presented. Feasibility of the proposed concept has been proved by a detailed performance analysis on the basis of the simulation of a high-end reference remote sensing mission.

In general the focal plane stabilization principle 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. Moreover such imaging systems can accept even moderate camera attitude stability and needs in consequence less costly attitude control of the host satellite.

The key element of the proposed solution is the embedded optical correlator for real-time image motion measurement. The applicability of this technology for smart imaging applications has been demonstrated by the authors up to now successfully on the basis of laboratory and airborne flight experiments. With the positive results of focal plane stabilization shown in this paper, the interest of both European Space Agency and space industry is now to qualify the optical processor technology for the harsh space environment, so that this smart imaging concept can be used in future space projects.

Acknowledgements

This research was supported by European Space Agency (ESA) Contract No. 1752/03/NL/SFe.

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Manuscript received: 16th February 2005.

Prof. Dr. techn. Klaus Janschek is managing director of the Institute of Automation and holds the chair of Automation Engineering in the Department Electrical Engineering and Information Technology at Technische Universität Dresden. Main research topics: automation systems design, teleautomation, mobile robotics, navigation, optical data processing.

Address: Institut für Automatisierungstechnik, Technische Universität Dresden, 01062 Dresden, Tel.: +49-351-463-34025,
E-Mail: klaus.janschek@tu-dresden.de

Dr.-Ing. Valerij Tchernykh is scientific staff member of the chair of Automation Engineering in the Department Electrical Engineering and Information Technology at Technische Universität Dresden. Main research topics: visual navigation, optical image processing.

Address: Institut für Automatisierungstechnik, Technische Universität Dresden, 01062 Dresden, Tel.: +49-351-463-32134,
E-Mail: chernykh@ifa.et.tu-dresden.de

Dr.-Ing. Serguei Dyblenko is scientific staff member of the chair of Automation Engineering in the Department Electrical Engineering and Information Technology at Technische Universität Dresden. Main research topics: visual navigation, optical image processing.

Address: Institut für Automatisierungstechnik, Technische Universität Dresden, 01062 Dresden, Tel.: +49-351-463-32134,
E-Mail: dyblenko@ifa.et.tu-dresden.de

Dr. Grégory Flandin is research engineer with EADS Astrium, Toulouse, where he is in charge of image processing R&D activities with space applications. Main research topics: registration and tracking, fusion and super-resolution, simulation and restoration.

Address: EADS Astrium, 31 Avenue des Cosmonautes, 31402 Toulouse, FRANCE, Tel.: +33 562 19 6123,
E-Mail: gregory.flandin@astrium.eads.net