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IMAGE BASED ATTITUDE DETERMINATION USING AN OPTICAL CORRELATOR

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ABSTRACT

The paper discusses a spacecraft attitude determination system based on image data provided by an onboard observation camera. The attitude is measured by the observed image motion which can be registered by an appropriate allocation of additional navigational area sensors in the focal plane of the onboard imaging system. An advantageous feature of this concept is the possibility to use the payload observation camera without changes in the optics as attitude sensor. The real-time image processing is performed by a hybrid opto-electronic system based on a Joint Transform Optical Correlator. With up to-date opto-electronic components the correlator can have a size of 20x40x220 mm, a mass within 0.5 kg and a power consumption less than 5 W. The paper presents a system layout of a laboratory prototype and gives the performance estimations in terms of data processing rate, accuracy, sensitivity to noise and distortions and response time under disturbing conditions.

1. INTRODUCTION

The accurate determination of the spacecraft attitude respectively the attitude of the imaging device (observation camera) itself is of particular interest for spacecraft missions. The orientation of the camera relative to the observed planet surface can be revealed from analysis of surface image motion in its focal plane [Ref.1]. Using only the onboard camera and a fast processing circuit makes onboard attitude determination fully autonomous and real-time. This is especially important for missions suffering from lack of accurate and reliable attitude information sources. Most of such systems are equipped with imaging payloads which can be used for attitude determination under nominal and/or backup operational conditions.

The attitude determination system based on image motion analysis can be inserted in a spacecraft AOCS as add-on or backup equipment using the existing payload observation camera without altering the main imaging task. As the attitude measurements in the given case are based on images, taken from the underlying planet surface, it is more suitable for determination of spacecraft orientation in a tangent roll-pitch-yaw or a Local-Horizontal-Local-Vertical (LVLH) coordinate frame (see Figure 1).

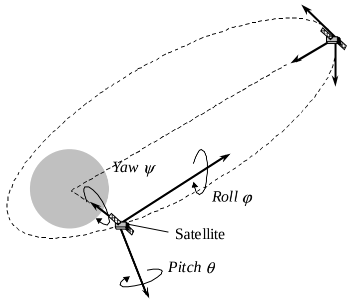

Figure 1: Definition of the reference coordinate frame for attitude measurements.

This frame is fixed to the orbit, yaw axis is headed to nadir – centre of planet, pitch axis is perpendicular to nadir and velocity vectors, that means to the plane of the orbit, roll axis is orthogonal complementary to others and lies into the plane of the orbit. Attitude data in this frame are usually used for observation and attitude manoeuvres.

Assuming that the observation camera is rigidly mounted on the spacecraft and their relative orientation is well known, the attitude of camera itself in the reference frame can be easily recalculated into attitude of the spacecraft (equivalent to standard AOCS sensors).

The instantaneous camera orientation is derived from an analysis of image motion in the focal plane of camera. A single cycle of attitude determination consists of two image shoots and a following image processing phase in which the motion of points on the images is analysed to estimate the camera orientation parameters – pitch, roll, yaw angles. In case of repeated measurements the adjacent cycles can be tied and the second image of the previous cycle is interpreted as the first for the next cycle. In such a way, at each moment of image exposure, the attitude of the camera with respect to the LVLH frame can be found .

2. MATHEMATICAL BACKGROUND

For attitude closed loop control the instantaneous stream of attitude measurements is required. This can be achieved by a repeated acquisition of surface images with the camera sensor. At each acquisition the attitude data are pushed up after some delay for processing. The basis for each measurement is a pair of overlapping images.

An attitude measurement cycle consists of three stages.

1. Taking the first image at moment of time *t*´;
2. Taking the second image at moment of time *t*´´;
3. Processing the images in order to find the orientation angles of camera at moment *t*´´.

The adjacent cycles are overlapping in terms of usage of the second image from the first cycle as the first image for the next cycle.

The geometrical representation of the problem is presented on Figure 2. In order to solve the attitude determination problem in a more easy way, the spherical surface, from which images are taken, is approximated by a plane. The feasibility of this approximation is considered in chapter 5.

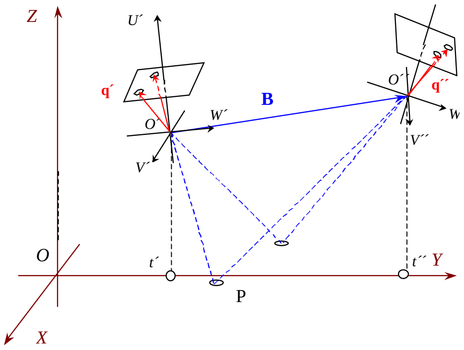

Figure 2: Geometrical representation of the problem of attitude determination from image motion.

Here the orientation in the absolute sense is considered. That means the attitude of the camera at each moment of time is given in the reference frame *XYZ*. Plane *XY* belongs to the surface from which the images are taken. Plane *YZ* is aligned with the orbital plane and is close to flight direction. All attitude angles obtained for *XYZ* frame can be accepted in LVLH coordinates, only yaw is to be taken with opposite sign.

The camera is placed in the coordinate frame *VWU* such, that the centre of the frame corresponds to the centre of the lens, the focal plane is aparted from the centre by focal length *f* and is coplanar to plane *UV*. Internal geometry (focal length, aberrations) of the camera is assumed to be known.

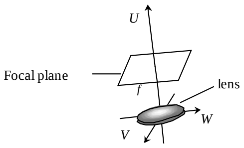

Figure 3: Internal camera geometry.

Relationships between frames *XYZ*, *V´W´U´* and *V´´W´´U´´* are given by transformation matrices **M´** and **M´´** correspondingly. Matrix **M´** describes the attitude of the camera w.r.t. frame *XYZ* at *t*´ and gives for this moment of time - θ´ pitch, φ´ roll, ψ´ yaw. Matrix **M´´** describes the attitude of camera w.r.t. frame *XYZ* at *t*´´ and gives θ´´, φ´´, ψ´´. Here the camera is assumed to rotate about *v*-axis at the angle θ first, about *w*-axis at the angle φ second and then about *u*-axis at the angle ψ.

The motion of the camera in *XYZ* is given by the base vector $\mathbf{B} = \left(b_x, b_y, b_z\right)^T$.

The motion of the image in camera focal plane is described by a set of pairs of focal vectors $\left\{\mathbf{q}'_i, \mathbf{q}''_i\right\}$ derived from two overlapping images with correlation matching (Figure 2 shows two pairs).

This set is then used to build a system of coplanarity equations,

$$\left\{\begin{array}{c} \mathbf{B}_n \cdot \left[\left(\mathbf{M}'\mathbf{q}'_1\right)\times\left(\mathbf{M}''\mathbf{q}''_1\right)\right] = 0 \\ \dots \\ \mathbf{B}_n \cdot \left[\left(\mathbf{M}'\mathbf{q}'_N\right)\times\left(\mathbf{M}''\mathbf{q}''_N\right)\right] = 0 \end{array}\right. , \qquad (1)$$

where $\mathbf{B}_n = \left(b_x/b_y, 1, b_z/b_y\right)^T$, $\{\times\}$ - vector cross product, $\{\cdot\}$ - vector dot product. The origin of this method is discussed in more detail in [Ref. 2].

The system (1) can be solved for θ´´, φ´´, ψ´´ under known $\mathbf{B}_n$ and first attitude (θ´, φ´, ψ´) with some optimisation technique – in our experiments the simple direct simplex search method was employed. Note, that only the direction of the base vector might be known (i.e. no knowledge of the length of the base vector). If the orbit is non-equatorial and/or elliptical, the vector **B** is declined from the orbital plane due to planet rotation and becomes no more parallel to plane *XY*. If there is no possibility to have its coordinates, they can be obtained with the same optimisation of system of equations (1). Two additional parameters, ρ-diverting angle and β-elevation angle, are given as

$$\rho = \tan^{-1} b_x/b_y, \quad \beta = \tan^{-1} b_z/b_y .$$

If these angles are expected to approach to zero (e.g. a low circular orbit close to the equator), the vector $\mathbf{B}_n$ could be taken for (1) as $\mathbf{B}_n = (0, 1, 0)^T$.

3. IMAGE MOTION MEASUREMENT

The motion of the image points is defined by matching of image patterns from the first image with respective patterns from predicted locations on the second image. Some tracking techniques extract certain local features on the first image (cross lines, spots, etc.) and define the locations of these features on the next images. Disadvantages are: high noise sensitivity and complexity of processing algorithms. Another approach consists of tracking the patches or blocks of the image. The matching is performed in this case by a standard correlation procedure for two 2D arrays. It is very robust to noise and the initial images for tracking can be taken from any parts of the image, whereas the features are texture specific.

If the *observation camera* is equipped with an *area scan sensor*, the same sensor can be used for attitude determination, e.g. CCD sensor with 1024x1024 pixels, pixel size of 12 µm (CA-D4-1024 from DALSA Inc). Initial blocks for tracking are chosen at fixed locations on the sensor and tracking is performed by correlation of each block with block read from the fixed location on the same sensor but shifted respectively to the initial one (see Figure 4).

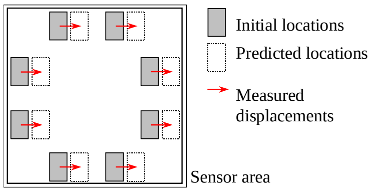

Figure 4: Block tracking with single sensor.

If the onboard camera is equipped with a linear (line) sensor only, a set of small additional navigational area sensors can be arranged in the focal plane of the camera without increasing the field of view and therefore without significantly changing the optics [Ref. 3]. Some appropriate configuration is shown in Figure 5 with CCDs of 659x494 pixels and pixel size of 7.4 µm (ICX084AL from SONY). On each sensor a pair of blocks can be tracked.

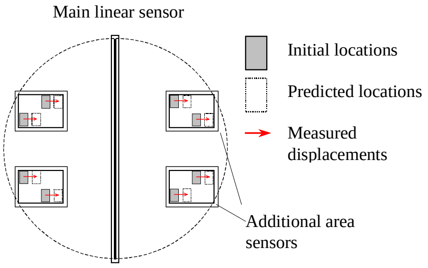

Figure 5: Block tracking with four additional navigational area sensors.

4. TRACKING WITH OPTICAL CORRELATOR

The velocity of image motion in the focal plane of the camera defines the attitude update rate. The update time has a low boundary, determined by the time that is required for the block to pass the overall sensor length. The accuracy of attitude determination is better, if the focal vectors to initial/predicted blocks are widely spread, therefore the shift between successive images must be chosen as small as possible. The minimum value of this shift is mainly restricted by the frame rate provided by the CCD and the processing power of the correlator. Figure 6 shows a plot of the attitude update rate vs. ground resolution for a single sensor camera for an Earth observation mission with an altitude of 800 km. This plot was generated with equal image shift in order to provide the same accuracy.

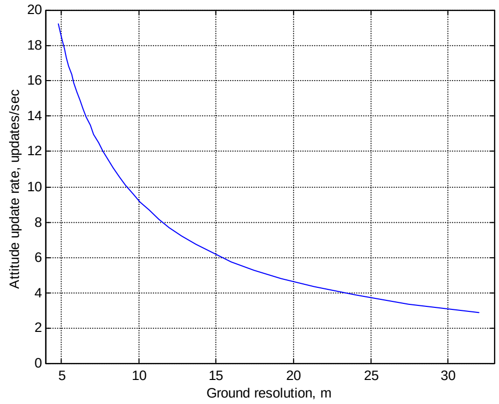

Figure 6: Typical attitude update rate vs. ground resolution – altitude 800 km, Earth orbiter.

For each attitude measurement eight correlation procedures must be performed. The required speed for the correlator is shown in Figure 7.

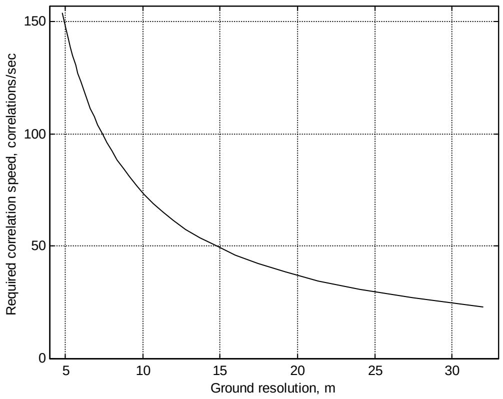

Figure 7: Required processing speed for the correlation operations.

The size of blocks is chosen as 240x160 pixels. Correlation could be performed with FFT calculations. One correlation matching of two images 240x160 on up-to-date digital Fourier processors will take approximately 60 ms, that gives 16 correlations per second [Ref. 4]. Figure 7 shows that such a processing performance is not sufficient even for medium ground resolution. For systems with high and medium spatial resolution and high attitude update rate more powerful correlators are required. The required processing speed can be achieved with an optical processing device – optical correlator. This device uses the feature of a simple lens to produce the Fourier pattern at a speed of light and the processing rate is limited only by the read/write operations of the opto-electronic components. Figure 8 shows the comparison of optical and digital correlator performances.

This figure assumes that all devices produce the results with equal accuracy and the optical correlator consists only of one optical processor (see Figure 9).

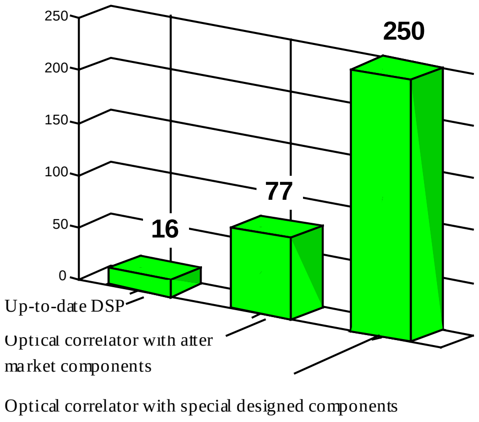

Figure 8: Comparison of processing speed for optical and digital correlator – number of correlations per second.

Even with commercial of the shelf components an optical correlator can work with high resolution cameras. With a correlator built with specially designed multi-output elements the attitude determination rate is defined mainly by frame rate of observation camera.

From two main schemes of optical correlators – Van-der-Lugt and Joint Transform for image tracking the *Joint Transform Correlator* is more preferable due to its simplicity and reliability [Ref. 5,6,7]. Here one processor scheme is proposed (Figure 9), as it can provide robustness to mechanical deformation without additional processing and it does not require precise assembling and exact knowledge of sizes of pixels for the opto-electronic components.

During one cycle of matching an initial block (=reference image) and a block from the predicted location (=current image) are *simultaneously* entered into the optical system of the optical Fourier processor (OFP) by a special device – *spatial light modulator* (SLM).

In the focal plane of the lens, the image of *the Joint Power Fourier Spectrum* (JPS) is formed, which is detected by a square-law image sensor (usually CCD) and entered into the same SLM during read out of the CCD. Then in the focal plane the image of the correlation function is formed with two symmetric bright points – correlation peaks – if that current image contains even a part of the reference one. The position of the peak corresponds to the mutual shift of the current and reference images (Figure 10). The correlation image is processed by digital processing unit (DPU) in order to detect the correlation peaks and calculate their position. The amount of processed information from the correlation image is reduced by recording only the pixels, whose brightness exceeds certain level. For this quite simple image processing task a fast video DSP can be used.

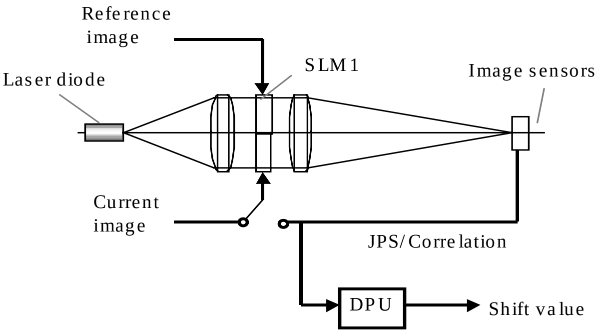

Figure 9: General scheme of Joint Transform Correlator with one processor

SLM – spatial light modulator, DPU – digital processing unit, JPS – joint power spectrum.

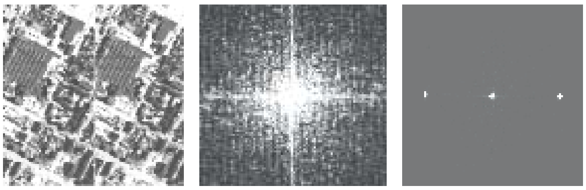
a b c

Figure 10: Images in a Joint Transform Correlator,
a – input image, b – joint power spectrum,
c – correlation image.

All complex Fourier processing is therefore performed optically. Digital resources are required only for locating the correlation peak (by threshold comparison) and calculating the mass centre. The position of correlation peaks together with the predicted shift allows to find the overall displacement for the tracked block.

The small size of available SLM pixel (15 µm) [Ref. 8] makes it possible to develope a JTC with overall length of the optical system within 220 mm.

The main performances of the image tracker based on the *Joint Transform Correlator* are summarised in Table 1. Data were obtained through a series of computer experiments with a mathematical model of the Joint Transform Optical Correlator. Input parameters are: altitude 800 km, focal length 0.96 m, sensors layout as mentioned in chapter 3, measurement rate 9 times per second. Numerical simulation results (accuracy) were proved with a hardware model of the Joint Transform Optical Correlator (Figure 11). This model has one optical Fourier processor implemented with standard commercial liquid crystal display and CCD camera. On this model the algorithms for measurement of shift between two images have been tested.

Figure 11: Laboratory model of Joint Transform Correlator (JTC).

The processing rate of a JTC with multi-input SLM and multi-output CCD is estimated to reach 250 correlation per second with the same accuracy and noise robustness.

The correlator can also work under some scale and perspective distortions between compared images. The influence of distortion depends on camera parameters and SLM size.

Table 1. Estimated performances of JTC image tracker with commercial of the shelf SLM and CCD.

	Value
Matching accuracy, pixel	0.20
Correlation rate, corr./s	77
# of tracked blocks	8
Minimal input SNR, dB	15
Off-nadir declination, degree	± 25
Acceptable altitude change, km	6.4 km (0.08%)
Maximum angular rate, degree/correlation	0.05 – yaw 1.0 – pitch, roll

5. ATTITUDE DETERMINATION PERFORMANCES

Real conditions, under which the system works, differ from ideal mathematical assumptions. Therefore the performance of system, namely accuracy, will suffer from disturbances and degrade. In order to define the level of robustness of attitude determination series of computer simulations were carried out. With some amount of deviation from ideal conditions (chapter 2) the accuracy of the system was estimated at given camera parameters and motion.

The accuracy is affected mainly by:

Sphericity of the planet. It means the deviation from plane surface and would cause a systematic error, if the image motion is measured with ideal accuracy. But with errors of tracking provided by the correlator the optimisation procedure reduces the systematic component. The degree of reduction also depends on camera altitude, planet radius, measurement rate and camera parameters – focal length, tracking arrangement. For Earth and low planetary orbits this error is significantly lower for high resolution cameras.

Change of the altitude. It means the elevation of the satellite relative to the surface due to a non-circular orbit or relief changes. This also disturbs the apparent picture of image motion. From mathematical analysis in chapter 5 this change can be directly included in the method by a priori defining the direction of the base vector. In practice it could be done only for orbit altitude on the base of position information from a navigation system. Unpredictable relief changes cause error in attitude data - mainly in pitch angle. However, from simulation this error was shown to depend mainly on predicted image shift - measurement rate. For a small value of the shift the system is fairly tolerant to elevation in term of attitude accuracy. There is also a possibility to build the optimisation of coplanarity equations system (1) with an additional parameter – elevation of satellite. With accurate focal vectors determination it is possible to define both attitude and elevation precisely.

Relief roughness. That means unknown local heights of surface plots from which small image blocks are taken during tracking. The distribution of these heights is assumed to be random and can also be accommodated by the error of the image matching.

Planet rotation. Due to this, the axis *OY* of reference coordinate frame deviates from orbit plane, that causes a systematic error in attitude. As in the case with altitude change, the previously estimated value of deviation can be included in the processing. With high accuracy correlation matching both elevation and diverting can be determined.

Planet oblateness. As the camera attitude is defined respectively to the underlying surface, the reference system *XYZ* follows the plane touching the planet in place of measurements. If the planet is not an ideal sphere, the additional systematic error appears. This inclination of *XYZ* from LVLH frame can be corrected on the base of knowledge of the planet shape and position of satellite. This inclination changes vary slowly and even without correction the data produced by the system can be used for attitude control of the satellite.

Clouds. The main problem here is the cloud motion. The correlation tracking of images obtained from surface covered by clouds is possible, as any cloud field has a texture, that is constant for short time between images. Deviation angle from clouds motion can reach 0.25..0.50 degree/second for low orbit observation. This value lies under the accommodation level.

Water surface. In principle wave pattern changes during time, but not so large for small time between two successive images acquisitions. The only problem is to have a ground resolution less than typical wave length. The high resolution systems are assumed to be able to work over ocean and sea.

The main performances of the attitude determination system with a given camera, tracking and mission parameters are summarised in Table 2. These data were obtained through computer simulation using the following input parameters: single/four sensors arrangement (chapter 3), focal length 0.96, ground resolution 10m, altitude 800 km, planet – Earth.

Table 2: Estimated performances of the attitude determination system.

	Four sensors system	**Single sensor system**
Update rate, update/sec	6.6	
Response time, sec	0.150	
Accuracy (RMS + bias), degree		
yaw	0.006	0.02
roll	0.005	0.005
pitch	0.3	0.4
Attitude range, degree	±18	±20
Angular rate, degree/sec	0.12	0.33

Data in the performance analysis were obtained at the disturbing conditions levels as defined in Table 3.

Table 3: Disturbing conditions – acceptable levels

Condition	**Value**
Acceptable altitude change, m	±100
Maximal relief roughness (RMS), m	100
Maximal deviation angle (from orbital plane), degree	±4

6. DISCUSSION OF PERFORMANCES

Attitude data update rate is limited mainly by the read out time of the area sensors of the camera, processing time of the correlator and the time for determination the attitude from the measured image motion. It can be significantly increased by employing multi-output CCD sensors and more fast correlator with 4 optical processors.

Response time is the time between exposure of image and updating the attitude data and it is given as the reciprocal value of the update rate.

Measured attitude range and angular rate for attitude changes are the maximum values at which the system gives the accurate results. The attitude range is defined by the correlation tolerance to geometrical distortions of compared images and the capability of the system to work accurately over a sphere surface. The angular rates are also defined by the field of view of the camera and the size of tracked blocks on the sensor plane. An increasing is possible with more complex prediction of the image motion, taking into account the attitude of the camera from the previous step.

Accuracy of attitude determination mainly is subject of image shift and therefore update rate. The more often images are taken, the more accurate attitude is derived from these images. In case of the pitch inclination the image motion changes less, than for roll or yaw. Therefore under noisy measurements with correlator the accuracy of pitch angle determination is worse. There are two ways to improve the accuracy: 1) make the imaging sensor longer in the flight direction and 2) reduce the measurement error of the correlator.

Tolerance of attitude determination to disturbing conditions also depends on image shift and will be higher for high rate systems.

With multi-output CCD sensors and a faster correlator with 4 optical processors the update rate can reach 35 times per second, that results in smaller response time and higher operational angular rate.

7. CONCLUSION

The problem of attitude determination based on onboard camera images attracts the efforts of researchers for years. But the practical implementation of a real-time system met difficulties due to the lack of small image processing devices capable to perform correlation of two images with speed of a few hundred times per second and lacking suitable onboard hardware installations. The last achievements in the field of imaging sensors and liquid crystal matrices opened the way for implementation of optical correlators having small size, mass and power consumption. Even with commercially available components these devices can provide processing speeds up to several tens correlations per second. The devices are modular and with parallel arrangement the operation speed rises by order of ten. The high processing speed of optical correlators makes these devices more attractive than digital ones.

An attitude determination system using an image tracker on the base of the joint transform optical correlator can provide high measurement rate, small response time and good accuracy. The system can be added to a payload observation camera without serious reconstruction. Even a linear scan camera can be used with small auxiliary area sensors in the same focal plane without significant changes in the optics.

The employing of optical correlator is reasonable, as at high frame rates of the main camera the best accuracy of attitude determination and high level of tolerance to disturbing conditions can be obtained.

The described attitude determination system is particularly useful for the mapping planetary missions Such missions are already equipped with imaging payloads. The system permits autonomous attitude determination directly in relation to the mapped surface.

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