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SATELLITE AUTONOMOUS NAVIGATION BASED ON IMAGE MOTION ANALYSIS

K. Janschek, S. Dyblenko

Technische Universität Dresden, D-01062 Dresden, Germany
Institute of Automation, Department of Electrical Engineering
Tel.: ++49-351-463-34025
Fax: ++49-351-463-37039

Abstract: A novel approach for autonomous navigation of satellites is presented. The proposed navigation concept uses robust image motion tracking for acquisition of navigational data and requires minimum a priori information. The system incorporates a single compact image sensor and a high speed optical image processing unit to provide real-time performances. With the possibility of determination of both position and attitude estimates this system could be a basis for full autonomous operation of a satellite. This can be of particular interest in context with missions to other planets: Mars, Europa, etc. *Copyright©2001 IFAC*

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1. INTRODUCTION

Autonomous navigation in terms of "real-time provision of precise satellite orbit and attitude with sole onboard means" is a prerequisite function for (semi-) autonomous satellite operations such as payload scheduling, payload data referencing, payload pointing or satellite orbit maintenance.

For some missions autonomous satellite operations are required simply because of the nature of the missions itself. This is the case for planetary flybys or missions to far distant planets where either the spacecraft is out of contact or the communication delay is too long for normal ground control.

For satellite constellations at any altitude, the overall process of orbit determination and control represents a major operational cost. It also represents a significant risk element in which any operational error or failure of the ground system could damage or destroy the constellation. Autonomous operations could therefore considerably reduce operations cost.
For Earth-oriented missions the most appropriate onboard navigational sources are GNSS-services provided by existing systems like GPS or Glonass (Janschek *et al.*, 1999a; Porter *et al.*, 1984) or future systems like Galileo. But it should be emphasized that such concepts will *not* be fully autonomous systems, because they rely on the availability of co-operative navigation satellites. Moreover GNSS services are not available at all in interplanetary space.

So the best fully autonomous navigational sources are natural objects in the solar system – sun, planets, etc. For *orbiting satellites*, which are subject of this paper, the use of the nearest object – the *surface* of the *target planet* is therefore the most promising solution.

The traditional approach for surface based navigation is *landmark navigation* (Janschek *et al*., 1999a; Markley, 1981). It uses an onboard camera to take surface images, an onboard image processing system for recognition and determination of the landmarks positions on the taken image and a computer to process the results of measurements. The position and attitude of the satellite in some inertial frame can be determined with appropriate algorithms using the information about planet geometry and rotation as well as coordinate positions of all detected landmarks on the planet. Normally, landmarks information is collected at the stage of mission preparation and is existing onboard as a landmark database, which includes images (in raster or vector form) of the landmarks together with their coordinates.

The effective use of such systems depends on the following principal factors:

- content of the onboard landmark database;
- accuracy of reference data, i.e. landmarks coordinates;
- robustness of landmark recognition algorithms to varying appearance of landmarks.

The first factor plays a significant role in the length of orbit propagation periods and convergence time of the navigation algorithms. Large orbit propagation periods require also high accuracy of pre-definition of landmarks positions. Collecting high quality image data and their precise referencing is not a trivial task even for the planet Earth and will become much more difficult for other planets. Increasing the landmark database results in large efforts for the data preparation stage and requires large onboard memory capacity and effective processing means.

The robust and accurate measurement of landmark positions becomes a nontrivial problem under changes of observation conditions (different illumination angles, clouds) and changes of the surface (seasonal changes for image landmarks, high/low tides for coastal vector landmarks, etc).

To overcome this problem either special onboard image correction algorithms using some a-priori information or an extended set of landmarks for different situations must be introduced. The complexity of image processing increases the system realisation cost and the risk of non-proper or erroneous results.

The necessity of having a lot of precise a priori information about landmarks and reliable, robust image processing is the main hindrance for cost effective landmark navigation solutions .

2. NOVEL NAVIGATION CONCEPT BASED ON SURFACE IMAGE MOTION TRACKING

This paper introduces an *alternative concept* to landmark navigation employing a novel approach of *opto-electronic navigation* using *image motion tracking* instead of landmark tracking. This concept requires also the observation of the planet surface with an onboard camera but uses different and more general type of data.

The navigation principle is based on the fact that the image motion in the focal plane of an onboard (planet looking) camera maps the mutual motion of the satellite and the observed planetary surface. The instantaneous image motion in the focal plane is defined by the satellite's position and attitude relative to the planet's surface motion defined by the planet's size and rotation. This allows to extract both *attitude and orbit information* from a track of observed images with *minimum a-priori information*.

The proposed navigation concept does in particular *not require* a *pre-stored landmark database*. The simple matching of concurrent images taken in short time intervals does moreover *not depend* on *lighting* and *seasonal changes*.

Image motion tracking is based on *2-D correlation analysis* and allows correlation accuracies at sub-pixel level. The particular advantage of spectral image information processing is known to be independent of single image features, but relying only on the overall image texture (in contrary to landmark tracking). Thus correlation methods are extremely robust against uncertainties and noise and they are most appropriate if complex image textures are available (as it is the case for satellite images). *Optical Fourier processor* technology is introduced for image motion processing in order to achieve the required high measurement/update rate for real-time navigation (Janschek *et al*., 2000; Jutamulia, 1992; Tchernykh *et al*., 2000; Dyblenko *et al*., 2000). Due to the high update rate the navigation system can provide accurate orbit and attitude information in autonomous mode within the *first orbital revolutions*.

The application of the proposed autonomous navigation system can be of particular interest in context with:

- back-up navigation for remote sensing satellites using the nominal remotes sensing payload as imaging device
- smart cameras as navigation and attitude sensors for small satellites;
- data fusion or back-up navigation systems for planetary missions.

3. NAVIGATION PRINCIPLES

The navigation approach uses the dependency of image motion in the focal plane of an onboard camera from the relative motion of the satellite and planet surface. In the general case, this motion does not remain constant due to changing satellites altitude (elliptical orbits) or different surface motion at different latitudes due to planet rotation. The onboard satellite camera will map the mutual motion of the satellite and the planet in a focal plane projected surface image. This image motion also does not remain constant and depends in addition on the instantaneous satellite attitude.

If the camera takes images at definite time intervals in a specific way, such that the subsequent images have common overlapping parts (Figure 1), then the image motion can be observed as paths of some image parts (blocks) across the focal plane of the camera. Figure 2 shows a geometrical interpretation of such observations.

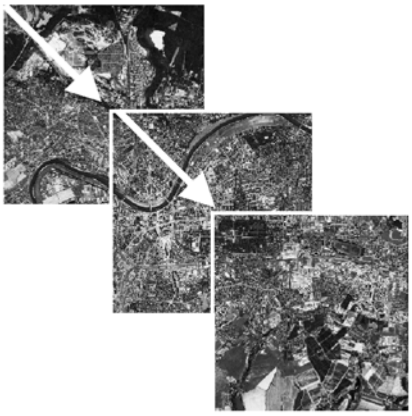

Fig. 1. Overlapped subsequent images – image motion

Here the camera fields of view from subsequent observations are overlapped (light cones). Due to planet rotation the mapped areas (dark circles on the planet surface) move constantly in the corresponding direction. This causes the images to have different overlapped parts as it were without the planet rotation. It is evident, that for a given observation scheduling and a given planet the overlapped images parts could be different for different corresponding satellite orbit positions. The most important fact is, that the overlapping is defined solely by the *mutual orientation* of the images, but *not* by *images content*.

The measured overlapping of subsequent images together with some minimum a-priori information can be used for determination of the satellite path around the planet. This *a-priori information* is restricted to:

- *planet parameters* – gravitational and rotational models, rough shape description for attitude determination;
- *camera imaging properties* – focal length, sensor pixel size and image sensor arrangement, coefficients of geometrical calibration.

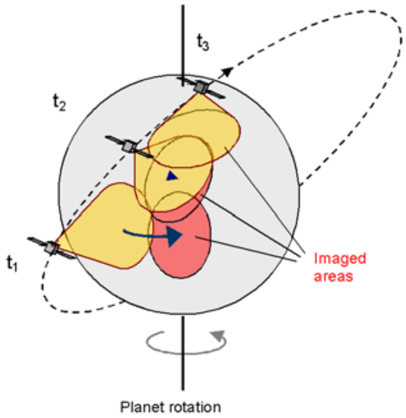

Fig. 2. Satellite and surface motion – basic geometrical interpretation

4.STRUCTURE OF THE ONBOARD NAVIGATION SYSTEM

The navigation system has *three functional layers*. The *first* represents the *image motion measurements.* Each two subsequent images go through a special image processing function, that chooses the predefined locations of image parts (blocks) on the first image, then defines the locations of these blocks on the second image.

On the *second* functional layer these locations are used for determining some parameters related to the position of the satellite at the observation time instants. As the image processing from a single camera cannot produce distance information, such position related data are derived from *navigation angles*. These intermediate processing results allow already the determination of the raw attitude (Janschek *et al.*, 1999b).

The *third* layer contains the actual *navigational functions*. As the instantaneous measurements do not allow to derive directly orbit estimates, some filtering techniques must be applied (e.g. Extended Kalman Filter). For this a measurements model is established, which relates the estimated orbit parameters to measurements of navigation angles. On this level the raw attitude can be transformed to the attitude in the Roll-Pitch-Yaw (RPY) reference frame.

A general structure of the navigation system realizing these functions is shown in Figure 3. An onboard area camera generates images of the surface at definite time instants. These images are processed in pairs by a special high speed processing device – *Optical Fourier Processor*. Image motion measurements are then forwarded to a digital computer, which performs the determination of navigation angles, estimation of orbit parameters and the attitude of satellite. All camera observations are performed under control of an onboard reference clock. Registered time marks and intervals are then used by the orbit estimator.

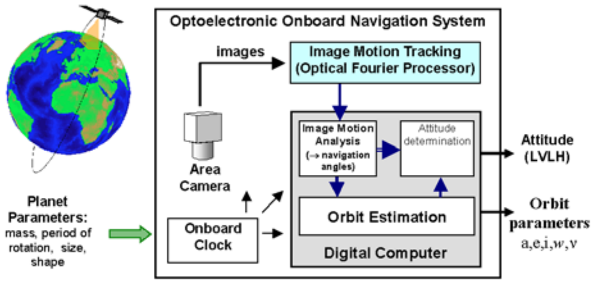

Fig. 3. General structure of opto-electronic navigation system

The system hardware consists of a standard design onboard camera, a high performance real-time image processing device and a standard digital computer. If a remote sensing payload is available, it could be used with some constraints for imaging.

This navigation system can provide the estimation of *five orbit elements* (except right ascension of ascending node Ω) and *attitude* in *Roll-Pitch-Yaw* (RPY) reference frame. These data alone are sufficient for:

- autonomous orbit control and maintenance (e.g. overcoming secular altitude perturbations for LEO satellites - station keeping);
- for nadir pointing of onboard instruments.

A synthesis of this concept with conventional landmark navigation is also possible. This can increase the accuracy, significantly reducing the size of onboard landmark database and therefore the costs. The landmark measurements will moreover support the determination the *sixth orbit parameter* Ω. The high speed of the Optical Fourier Processor allows the implementation of landmark tracking, which can improve the navigation performances, because several orbit updates can be made as a landmarks set passes the camera field of view. With the full set of orbit elements estimated autonomously, the *attitude* in the RPY frame can be transformed in *inertial frame*. Therefore the joint concept allows even a full autonomous navigation and attitude determination in inertial reference frame.

The navigation and attitude data provided by the image motion analysis system can be used for improvement of performances of an existing onboard navigation and attitude determination system working with other sensors.

5. PERFORMANCES RESULTS

A comprehensive performance analysis was performed by computer simulations incorporating the study of the influence of different factors on algorithms performances and to define system limitations and constraints - the ranges of internal parameters and external conditions/factors within which the system is operable without significant performance degradations.

The results of this analysis will be the basis for further activities on the optimal design of the system and its components for specific mission conditions.

The following operational factors have been investigated in detail: parameters of image motion tracking: number and size of tracked image blocks; parameters of the camera: FOV and IFOV; orbit filter update time; dynamic of satellite attitude; orbit parameters: semi-major axis, eccentricity, inclination; level of uncertainty of initial knowledge of satellite position. It was found that the most critical orbit parameters are altitude and inclination: lower altitude provides worse accuracy and the system is not operable in equatorial orbits. A camera with wider field of view (FOV) and smaller instantaneous field of view (IFOV) could be more suitable. Larger number and smaller size of tracked image blocks and smaller orbit filter update cycles can improve the system performances. The level of uncertainty of initial knowledge of satellite position is tolerated by the navigation algorithm up to 250..300 km without change of performances.

Another analysed in detail subject is the influence of imperfections of models and a priori information, namely:

- inaccurate model of the satellite orbit motion, e.g. caused by inaccurate knowledge of the planet gravity model;
- inaccurate knowledge of the geometrical model of planet;
- inaccurate knowledge of the rotation model for the planet.

It was found, that the proposed navigation approach can provide good accuracy under wide range of real conditions.

The unknown planet surface relief is the most critical item for RPY attitude determination. The ideal accuracy (on an ideally spherical planet) could be very high - 0.001..0.003 degree (rms), but in real conditions the degradation of accuracy by a factor of 30..60 must be expected.

The inaccuracy in orbit motion model for satellite has very low effect on attitude accuracy degradation (by factor of 1.5..3 within the range of position error of several kilometres).

The inaccuracy in planet rotation model is negligible small for the known planets and does not practically produce additional navigation and attitude errors.

The analysis of the system behaviour under unpredictable interruptions of observations, caused by low distinctive texture of observed regions (including also clouds on the Earth) or degraded lighting conditions (on the night side flight path) shows, that the effect of such observation pauses is proportional to the square root of reduction of number of filter updates for an orbit. With such pauses the orbit estimator reduces the convergence speed. The consequence is a larger navigation error at the same time after start of estimation. For night side pause this means a degradation of accuracy by a factor of 2..3. The effect of these disturbances can be eliminated by choosing a higher rate of measurement and filter updates.

Figure 4 presents the accuracy of navigation results obtained by simulation for an Earth orbit without observation pauses.

Orbit parameters: altitude 1500 km, eccentricity 0.02, inclination 65 degree. Camera parameters: FOV 96 degree, IFOV 0.01 degree. Number of tracked blocks 600. One orbit contains 140 updates of the orbit parameters (50 sec interval).

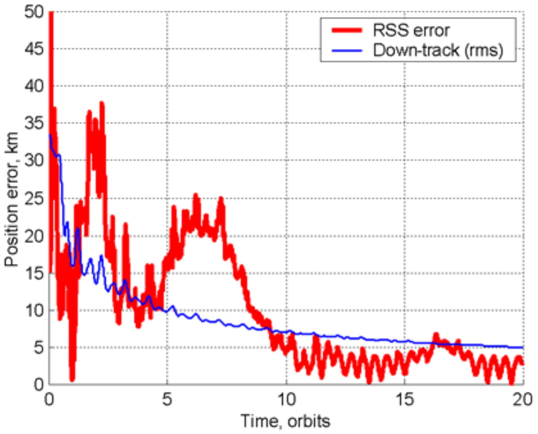

Fig. 4. Position error, simulation results

The down-track error is the largest component. Table 1 presents the values of error components, calculated from instant covariance matrix of orbit parameters of the 20th orbit.

Table 1. Position error components, simulation results

	Radial	Cross-track	Down-track
RMS position error, [km]	0.05	0.6	5.0

The RSS error of attitude determination was 0.08 degree. The required frame rate for the camera is estimated as 0.7 frame per second, the required processing rate for Optical Fourier Processor is 2300 correlations per second at a correlated image size of 160x120 pixel.

6. SYSTEM LIMITATIONS AND CONSTRAINTS

The main system limitations are:

- there must be a distinctive and stable image texture;
- maximal focal length of the camera is limited, large focal plane sensor assembly is required for better performances;
- working range of satellite attitude (RPY-frame) is limited by a few degrees;
- working range of satellite altitude and orbit eccentricity for given camera FOV is limited.

The system is applicable for a considerable number of planets in the solar system: Earth, Mars, Europa, etc (total 18 bodies). A dedicated navigation camera is more preferable, as it can provide better performances.

For the Earth the maximal allowable altitude for attitude determination is 6000 km (semi-major axis 12378 km) at a diagonal camera FOV of 50 degrees. The navigation algorithm works up to 12000 km (semi-major axis 18378 km) with a diagonal camera FOV of 29 degrees. It was found, that the selection of the maximal possible camera FOV allows to keep equal navigation accuracy for a wide working range of orbit altitudes. For low altitude orbits the performances are limited by a maximal feasible camera FOV for large focal plane assembly (~108 degree, diagonal).

For a target mission the system should be equipped with a camera having specific FOV. The allowable variations of orbit parameters for the system are also limited (Figure 5).

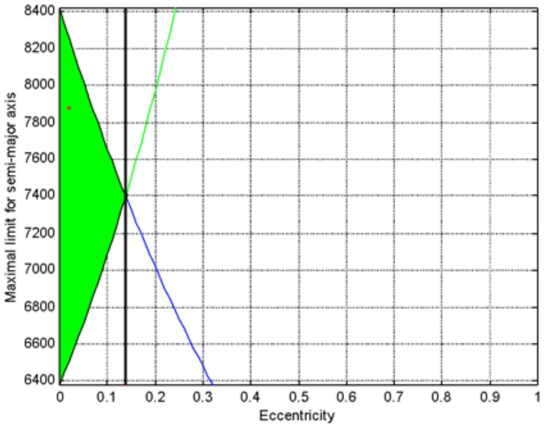

Fig. 5. Working range for semi-major axis and eccentricity for a camera FOV of 96 degree and attitude dynamics range ±3 degree

The descending line shows the maximal limit for semi-major axis, the uprising line shows the minimal limit for semi-major axis at a given eccentricity. The bold vertical line corresponds to maximal limit for eccentricity. The working range of the system is defined by grey shaded area.
For larger attitude motion the working area becomes smaller. Choosing a smaller camera FOV enlarges the working area, but reduces the system performances.

7. POSSIBLE VARIANT OF SYSTEM REALISATION

The navigation system basically consists of three units:

- wide-angle camera with baffle;
- electronic unit;
- optical Fourier processor unit.

The camera includes a wide angle optics and multi-sensor focal plane. The sensors are mounted in a specific way to cover the motion of image blocks. The electronic unit contains an image buffer, a reference timer and a medium power onboard computer. The optical Fourier processor unit has a number of processing modules according to required processing speed.

The system considered in the simulations has the following parameters (without housing):

Envelope size:	310x300x300 mm
Average/peak power	36/66 W
Mass	4.4 kg

This system can provide the following performances for some planetary missions in the solar system. Table 2 presents the radial, cross-track, down-track rms error components, calculated from the instantaneous covariance matrix of orbit parameters of the 20th orbit.

Table 2. Performance result for planetary missions, simulation results

	Earth	Mars	Europa
Altitude, [km]	1500	800	400
Radial, [km]	0.06	0.03	0.01
Cross-track, [km]	0.6	0.3	0.3
Down-track, [km]	6.2	2.5	6.1

8. CONCLUSION

A novel approach for the autonomous navigation of satellites based on camera sole image data and minimum a priori data has been developed and studied. The navigation system can provide accurate results after a few revolutions. The application of the proposed autonomous navigation system can be of particular interest in context with back-up navigation for remote sensing satellites using the nominal remotes sensing payload as imaging device, smart cameras as navigation and attitude sensors for small satellites and data fusion or back-up navigation systems for planetary missions. With the possibility of determination of both position and attitude the system provides a basis for full autonomous operation of a satellite.

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