Visual Navigation System for Pin-Point Landing
ESTEC/Contract No 18692/04/NL/MU

Summary Report

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Dresden, 28 November 2005
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1. Introduction

This document summarizes the results of the proof of concept study *Visual Navigation System for Pin-Point Landing*, funded by ESA/ESTEC (Contract No. 18692/04/NL/MV) within the frame of Innovation Triangle Initiative. The study has been performed from December 2004 until October 2005 by TU Dresden (Germany) and EADS Astrium Toulouse (France). Main goal of the study was to prove the feasibility of the concept of visual navigation system for planetary lander.

2. List of acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
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<tr>
<td>CF</td>
<td>Camera-fixed coordinate Frame</td>
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<tr>
<td>DEM</td>
<td>Digital Elevations Model</td>
</tr>
<tr>
<td>INS</td>
<td>Inertial Navigation System</td>
</tr>
<tr>
<td>MTF</td>
<td>Modulation Transfer Function</td>
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<tr>
<td>OF</td>
<td>Optical Flow</td>
</tr>
<tr>
<td>PRNU</td>
<td>Pixel Response Non Uniformity</td>
</tr>
<tr>
<td>RMF</td>
<td>Reference Model-fixed coordinate Frame</td>
</tr>
<tr>
<td>RMS</td>
<td>Root Mean Square (error)</td>
</tr>
<tr>
<td>RSS</td>
<td>Root Sum Square (distance)</td>
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<tr>
<td>VGP</td>
<td>Visual Guidance Phase</td>
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</table>
3. Background

3.1. Problem description

Future Solar System Exploration missions will require the capability to perform precision autonomous guidance and navigation to the selected landing site. Pinpoint landing capability will allow to reach landing sites which may lie in areas containing hazardous terrain features (such as escarpments, craters, rocks or slopes) or to land accurately at the selected landing sites of high science value.

To make such a precision landing possible, a fast and accurate navigation system is required, capable of real time determination of the spacecraft position and attitude with respect to the planet surface during descent.

State of the art planetary landers are mainly navigated on the base of initial position knowledge at the start of descent phase by propagation of position data with the help of an inertial navigation system. The initial lander position (before starting the deorbit burn) is usually determined by Earth-based observation with limited accuracy due to the large observation distance. The accuracy is further degrading during the inertial navigation phase due to error accumulation. As a result, the landing accuracy is considerably poor with the landing error about 30 - 300 km for planets with atmosphere and about 1 – 10 km for airless bodies [1].

Much better accuracy, especially for the final part of the landing trajectory, can be obtained by visual navigation with respect to the surface. A number of concepts of visual navigation systems for planetary landing missions have been already developed and partially tested [1-4]. Their operation is generally based on the motion estimation by feature tracking and/or landmark matching. These approaches however have certain disadvantages. Navigation data determination by feature tracking is subject to error accumulation (results in accuracy degradation for the final part of the landing trajectory). Landmark matching requires the presence of specific features, suitable to be used as landmarks, within the field of view of navigation camera during the whole landing trajectory. Matching of 2D images of landmarks is also strongly affected by perspective distortions and changing illumination conditions.

3.2. Proposed solution

To obtain the required accuracy and reliability of navigation data determination, we have proposed a concept of visual navigation system, based on matching not the 2D images, but the 3D models of planet surface, produced by optical flow processing of images from a single navigation monocular camera. Currently obtained 3D models of visible surface will be matched with the reference model of landing site. Position and attitude of the lander with respect to the surface will be determined from the results of the matching.

Matching of 3D models instead of 2D images is not sensitive to the perspective distortions and is therefore especially suitable for inclined descent trajectories. The method does not require any specific features/object/landmarks on the planet surface and is not affected by illumination variations. The redundancy of matching the whole surface instead of the individual reference points ensures a high reliability of matching and a high accuracy of the obtained navigation data: generally, the errors of lander position determination are expected to be few times smaller, than the resolution of the reference model.

To reach the required real time performance together with high accuracy of 3D models, optical flow fields will be determined by multipoint 2D correlation of sequential images with an onboard optical correlator.
3.3. Optical flow background

Optical flow field is the vector field representing the image motion pattern from frame to frame. Figure 1 shows an example of the optical flow (OF) field calculated for the pair of images, taken by moving camera.

Image 1

Image 2

Optical Flow field

OF field with image overlayed

Fig. 1. Optical flow example

If camera has moved between the moments of images acquisition, each optical flow vector contains the information about local distance to the imaged surface: this information can be extracted from the length of the vector, considering also its position with respect to the flight direction, camera displacement and camera parameters.
3.4. Optical correlator background

A Joint Transform Optical Correlator is an optoelectronic device, capable of extremely fast image processing due to application of high parallel optical computing technology. Its operation is based on the natural feature of the lens to produce a 2D Fourier transform of the image. This diffraction-based phenomenon is used to perform 2D correlation of two images by two sequential optical Fourier transforms (Fig. 2), according to the Joint Transform Correlation principle [5].

![Fig. 2. Optical correlator principle](image)

This advanced technology and its applications have been studied during last years at the Institute of Automation of the Technische Universität Dresden [6, 7]. Different hardware models have been manufactured, e.g. under ESA contract (Figure 3).

![Fig. 3. Hardware model of optical correlator](image)

Due to special design solutions these devices are very robust against mechanical loads and do not require precise assembling and adjustment [8, 9]. The results of airborne flight test, performed with one of the models during summer 2002 showed very promising performances [10]. Recent research has given solutions for a very compact realization of such a device, suitable for onboard installation.
4. Concept of visual navigation system

4.1. General navigation principle

Proposed visual navigation system (Fig. 4) is intended to produce high accuracy navigation data (position, attitude and velocity) with respect to the preselected landing site during descent of the planetary lander. The lander should be equipped with a planet-oriented navigation camera. The system uses also the reference 3D model of landing site. This model can be produced during the orbital phase or obtained from the results of another mission.

For optimal performance the system can work in parallel with an Inertial Navigation System (INS), which allows coarse orientation of the lander and provides initial rough estimates of navigation data at the initialization of the visual navigation phase. During operation, the system can also benefit from real time acceleration information from INS and provide it with the navigation data update.

A totally autonomous operation is possible in principle, at the cost of considerably long start-up time and some degradation of performances. A certain degree of attitude stabilization prior to start of system operation is required also in this case: navigation camera should see the planet surface; rotation velocity of the spacecraft should be within $5 \ldots 25^\circ/s$ (depending on the mission parameters).

For each two sequential images from the navigation camera the optical flow field is determined and processed to reconstruct the 3D model of visible surface in camera-fixed coordinate frame CF. 3D model reconstruction is performed using the estimated velocity of the lander/camera. To make possible matching with the reference model of landing site, OF-derived model should be represented in the same coordinate frame (Reference Model-fixed Frame - RMF), so it is subjected to coordinates transformation. Transformation matrix is generated using the estimated position and attitude of the camera in RMF. Navigation data (position, attitude and velocity of the camera in RMF) are extracted from results of the matching.

Initial rough estimates of the position, attitude and velocity for the first cycle of navigation data determination should be taken from other navigation data source, for example, from INS. These estimates can have considerably large errors – they will be compensated after first few matches and will not affect subsequent operation of the system. After start of system operation, navigation data estimates for each new cycle are taken from results of previous one.

Fig. 4. General navigation principle
4.2. Optical flow determination

4.2.1. Optical flow determination with multipoint 2D correlation

For each pair of sequential images the optical flow field is determined by subdividing both images into the small fragments and 2D correlation of corresponding fragments. As a result of each correlation the local shift vector at the specific location is determined; a whole set of local shift vectors forms an optical flow field (Figure 5).

![Fig. 5. Principle of the optical flow determination](image)

Optical flow determination method, based on 2D correlation of the image fragments, offers a number of advantages:

- high (subpixel) accuracy;
- direct determination of large (multi-pixel) image shifts (suitable for measuring fast image motion);
- low dependency on image texture properties (no specific texture features required);
- high robustness to image noise (suitable for short exposures and/or poor illumination conditions).

In the same time this method requires performing a very large amount of computations which makes practically impossible its real time realization with conventional digital processors onboard the planetary lander. To reach the real time performance we propose to perform the correlations with an onboard optical correlator.
4.2.2. Detection and correction of the optical flow errors

Within the navigation images, there can be locations with very bad illumination conditions (dark shadows) or very poor texture. Correlation of corresponding image fragments can result in erroneous determination of the OF vectors. Large OF errors can also result from correlation of fragments, positioned at the edges of occlusions (different parts of such fragment can be positioned at very different distances from camera). As the obtained OF field will be used for producing the model of visible surface, these errors should be corrected before this operation (large OF errors can result in false peaks and holes in the DEM, making difficult the matching of OF-derived and reference models).

Detected invalid vectors are replaced by results of standard 2D interpolation of surrounding valid OF vectors. Figure 6 shows an example of the OF errors correction.

![Planet surface image](image1)
![Raw optical flow](image2)
![Detected optical flow errors](image3)
![Corrected optical flow](image4)

Fig. 6. Example of optical flow errors correction

Interpolation works also if large continuous areas (occupying significant part of the image) contains no valid OF vectors – such areas will be filled with smooth averaged surface. Follow-on procedures of reconstruction of the 3D surface model and matching it with reference model of landing site will also work (to some extend) with OF fields with large averaged textureless areas. Such situations, however, are not expected to occur often. Even within large shadows (large crater directly under the lander, very low sun angle) there is some reflected light which, at least at some locations within the shadow, can provide enough image content for correlation.
4.3. 3D model reconstruction

The 3D surface model is produced from the matrix of optical flow vectors, determined for two sequential camera images. Each vector represents the motion of the corresponding object (surface point) projection in the focal plane of the camera during the time interval between the images (Figure 7).

\[
\begin{pmatrix}
v_{1,x} \\ v_{1,y} \\ 1
\end{pmatrix}
- \begin{pmatrix}
v_{2,x} \\ v_{2,y} \\ 1
\end{pmatrix}
\begin{pmatrix}
z_1 \\ z_2 \\ 1
\end{pmatrix} = \begin{pmatrix}
t_{x2} \\ t_{y2} \\ t_{z2}
\end{pmatrix}
\]

(1)

with

\(v_{1,x}, v_{1,y}, v_{2,x}, v_{2,y}\) are the coordinates of the optical flow vector measured in the focal plane of navigation camera;

\(x_1, y_1, z_1\) are the surface point coordinates in camera-fixed coordinate frame at the moment of the first image acquisition CF1 (z axis coincides with optical axis);

\(x_2, y_2, z_2\) are the surface point coordinates in camera-fixed coordinate frame at the moment of the second image acquisition CF2.

\(v_{1,x} = x_1/z_1; v_{1,y} = y_1/z_1; v_{2,x} = x_2/z_2; v_{2,y} = y_2/z_2;\)

\(R^{CF_1,CF_2}\) is the rotation matrix which aligns the attitudes of coordinate frames CF1 and CF2; this matrix is determined from the optical flow;

\(\vec{t}\) is the vector of camera motion in CF2 between the moments of images acquisition; direction of \(\vec{t}\) is determined from optical flow, magnitude is estimated on base of previous measurements or data from another navigation systems.

As a result of solving of the equations system, the surface point coordinates in CF1 and CF2 are determined. A whole set of surface points coordinates, determined for all optical flow vectors, forms the 3D model of the visible surface in a camera-fixed coordinate frame. Figure 6 shows an example of the obtained model.
4.4. Matching of 3D models and navigation data extraction

To determine the actual position, attitude and velocity of the lander, the optical flow-derived 3D model of the visible surface is matched with the reference model of the landing site. For matching, the OF-derived model in camera-fixed coordinate frame CF should be represented in the same coordinate frame, as the reference model. This is done by a coordinate transformation, using the estimated (propagated) position $r_{Est}$, attitude $R_{Est}$ and velocity $v_{Est}$ of the lander in reference model-fixed frame RMF. With ideal (accurate) estimates, the obtained OF-derived model in RMF should exactly coincide with reference model. In the real case, the estimation errors result in some misalignment of the models (Fig. 6).

Figure 7 shows an example of the OF-derived model after transformation in a form of Digital Elevation Model DEM (local height is represented with pixel brightness: brighter areas are higher), in comparison with corresponding fragment of reference DEM of landing site.
Fig. 7. Example of the OF-derived and reference DEMs of planet surface.

Matching of the models is understood as finding the geometrical transformation, which aligns the obtained and reference surfaces. As a result of the matching, 3D shift (translation) $t$, scaling $\alpha$ and rotation matrix $R$ of the OF-derived DEM with respect to the reference one are determined. These parameters of aligning transformation are then used to update previously estimated navigation data.

Camera attitude update:

$$ R_{Updated} = R^{-1} R_{Est} $$

Camera position update:

$$ r_{Updated} = R^{-1} (r_{Est} - \hat{t}) $$

Camera velocity (magnitude) update:

$$ v_{Updated} = \frac{v_{Est}}{\alpha} $$

After navigation data update the whole procedure of reconstruction of the OF-derived DEM, matching it with reference one and navigation data extraction can be repeated to improve accuracy.
5. Simulation test description

5.1. Reference mission description

The simulation experiment has been performed considering the reference mission scenario, based on one of the Mercury lander concepts (originally planned as a part of Bepi Colombo mission). It includes the inclined landing trajectory (Fig. 8) with Visual Guidance Phase (VGP) starting at altitude of 8.46 km (ground distance to landing site 20.1 km, velocity 746 m/s) and ending at an altitude 142 m (ground distance 40 m, velocity 36 m/s).

![Reference landing trajectory](image)

Fig. 8. Reference landing trajectory.

Position, attitude and velocity of the lander at the start of VGP are known roughly, with following errors (one sigma)

- position error: 500 m;
- attitude error: 5°;
- velocity error: 10 m/s.
5.2. Test setup

To prove the feasibility of the proposed visual navigation concept and to estimate the expected navigation performances, a software model of proposed visual navigation system has been developed and an open-loop simulation of navigation data determination has been performed. Configuration of software modules and main data flows are shown in Figure 9.

For simulation test first a 3D model of landing site has been generated on base of random relief, with craters added according to typical law of craters distribution. The model has been used then to generate the simulated navigation camera images. The images have been rendered with standard software, observing the reference landing trajectory. To make possible separate optical flow determination tests, rendering software has been also used to produce an ideal (reference) optical flow field (based on real local distances, calculated from 3D model and reference trajectory data).

The test has been performed with software model of Visual Navigation System. It includes the detailed software model of the optical correlator. The correlator model has been developed to process the pairs of simulated navigation camera images and to produce the optical flow fields with required density. Image processing algorithms simulate the operation of the planned hardware realization of the optical correlator (optical diffraction effects, dynamic range limitation and squaring of the output images by image sensor, scaling of the output images according to focal length value, etc.). As a result of correlation, optical flow vector fields have been determined. They were further processed to reconstruct the 3D models of visible surface. Obtained OF fields have been also compared with ideal (reference) OF to estimate the OF determination errors.

3D models of visible surface from optical flow have been matched with reference models; navigation data have been extracted from results of the matching and compared with the reference trajectory data to determine the navigation errors.

For start, the system has been provided with the initial values of navigation data, taken from reference trajectory. To consider the effect of errors of initial navigation data estimation, simulated errors have been added to reference trajectory data. During operation, the system used the results of previous cycle of navigation data determination as an initial estimation for next cycle. Except for this, no filtering of navigation data has been performed.
5.3. Test images generation

3D model generation of the landing site has been performed in a form of a Digital Elevation Model (DEM). Such model can be represented by a 2D pseudo image, with brightness of each pixel corresponding to the local height over the base plane. The model has been generated on base of a random relief field. To produce the naturally looking landscape, a radial distribution of the energy in the spatial frequencies spectrum of the generated relief has been adjusted to match with that of the typical relief of the target planet. Craters have been added to the generated relief considering typical density/size dependence and morphology. Overlapping and partial destruction of the old craters by younger ones have been simulated. To provide the required resolution for the whole descent trajectory, the model has been produced as a combination of 12 embedded layers, each containing 4096x4096 pixels. Figure 10 shows one of the layers.

Simulated images generation has been performed using the 3D model of the landing site. Rendering of simulated images have been made using standard ray tracing software (Pov-Ray, version 3.6), taking into account the lander trajectory and camera parameters. Resolution of the rendered images was set to 4096x4096 pixels, what is 4 times higher, then the assumed resolution of navigation camera (1024x1024 pixels). A higher resolution of the rendered images has been used later for simulation of the MTF of the optics and image sensor.

Rendering has been performed assuming uniform texture of planet surface with constant albedo and Lambertian light scattering. The surface has been illuminated by a point light source, positioned at infinite distance (parallel light) with elevation 30° over horizon and azimuth -110° with respect to the flight direction.

MTF of the optics (0.7 at Nyquist frequency) has been applied in Fourier plane. For this purpose a 2D Fourier transform of the image (4096x4096 pixels) has been performed, the obtained spectrum was multiplied by the desired MTF envelope and reversely transformed to obtain the filtered image. The MTF of the image sensor has been simulated by down sampling (binning) of the large rendered image. Each pixel of the down sampled image (1024x1024 pixels) has been produced by averaging of the corresponding group of 4x4 pixels of the large (4096x4096 pixels) image.

Photonic noise has been simulated by adding the random noise with standard deviation equal to square root of pixel brightness, measured in electrons (average brightness of the image has been assumed to be 13000 electrons).

Readout noise has been simulated by adding the random noise with $\sigma = 40$ electrons.
Pixel response non-uniformity has been simulated by multiplication of the pixel brightness by 1 plus random value with $\sigma_{PRNU} = 2\%$.
Discretization has been simulated by rounding of the pixel brightness to 10 bits. Figure 11 shows an example of generated image.

Figure 11. Simulated image example

5.4. Estimation of effect of correlated fragments size on optical flow accuracy

5.4.1. Test goals
Main goal of this test was the determination of the optimal size of navigation image fragments to be correlated for optical flow determination.
Dimensions of correlated fragments determine the accuracy and reliability of correlation. Larger size of correlated fragments improves the reliability of the optical flow determination in the poor textured image areas and reduces the errors of the obtained OF vectors. In the same time, increasing of the correlated fragments size smoothes the obtained OF field, suppressing the small details and producing additional errors in areas with fast variations of local depth.
During the tests the optimal fragment size has been determined, making the best compromise between the accuracy/reliability of correlation and preservation of the small details.

5.4.2. Test conditions
The test has been performed with the software model of optical flow processor, using two neighbouring images from the sequence of simulated navigation camera images. To find the optimal size of correlated fragment, OF field has been determined with correlated fragments size changing in the range from 8x8 to 64x64 pixels. Obtained OF fields have been compared with a reference (ideal) one to determine the errors. Reference (ideal) OF field has been produced directly from reference trajectory data and 3D model of landing site.

5.4.3. Test results
Figure 12 shows the results of the optical flow fields determination with different correlated fragment sizes. Images in the left column represent the 2D patterns of the OF vectors magnitudes, middle row contains the errors patterns, determined as a difference between the reference (ideal) and test OF fields. RMS error values are also shown in the graphic at bottom right corner.
Fig. 12. Results of the optical flow determination

According to the graphics, minimal OF errors correspond to the fragment size of 24x24 pixels. In the same time, practically the same errors have been obtained for the fragment size 16x16 pixels. Taking into account fast increase of computational load with fragment dimensions, 16x16 pixels has been finally selected as optimal correlated fragment size.
5.5. Estimation of the requirements to the correlator performances

**Correlated fragment size.** As a result of test, described in previous chapter, 16x16 pixels is found to be optimal correlated fragment size for given 3D environment.

**Optical flow sampling distance.**
A side effect of the optical flow field determination by correlation of image fragments is the smoothing of the obtained OF field equivalent to 2D filtering (convolution) with window having the same size, as correlated fragment. Figure 13 represents the frequency response of such filtering, corresponding to correlated fragment size of 16x16 pixels. Main lobe of the filter characteristic is limited by spatial frequency 1/16 pixel\(^{-1}\). According to the sampling theorem, such frequency range requires sampling frequency of 1/8 pixels\(^{-1}\) or sampling distance of 8 pixels.

![Figure 13. OF field filtering with correlated fragment size 16x16 pixels](image)

Based on these considerations, optical flow sampling distance of 8 pixels (1/2 of correlated fragment size) can be selected as optimal for the OF field, produced with correlated fragment size 16x16 pixels. In the same time, smaller sampling distance significantly enlarges the possibilities of the OF field filtering, false vectors detection and correction, so, in the case of limited requirements to processing rate or large computational resources available, sampling distance of 4 pixels can be also recommended.

**Correlations rate:** considering the image processing rate 10 frames per second, camera frame size 1024x1024 pixels and OF sampling distance 8 pixels, 127x127=16129 OF vectors per frame and 161290 correlations per second are required.

5.6. Estimation of the effect of image noise on correlation accuracy

5.6.1. Test goals
Main goal of this test was to estimate the optical correlator sensitivity to additive and multiplicative input images noise.

5.6.2. Test conditions
To determine the correlator error dependency on the input image noise, random noise pattern has been added to the input images (additive noise simulation) or input images have been multiplied by 1 plus random noise pattern (simulation of multiplicative noise or pixel response non-uniformity - PRNU). Optical flow field has been determined with correlated fragments size 16x16 pixels and sampling distance 8 pixels. Obtained OF fields has been compared with a reference (ideal) one to determine the errors. Reference OF field has been produced directly from reference trajectory data and 3D model of landing site.
5.6.3. Test results

Figures 14 and 15 show the results of the optical flow field determination obtained with additive (figure 14) and multiplicative (figure 15) noise added to the input images. The noise value changed from $\sigma = 1\%$ to $\sigma = 16\%$ of average image brightness. Images in the left column represent the 2D patterns of the OF vectors magnitudes, middle column contains the errors patterns, determined as a difference between the reference (ideal) and test OF fields. RMS error values are also shown in the graphic at bottom left corner.

![Magnified errors (reference OF – test OF)](image)

Fig. 14. Results of the optical flow determination with different values of additive image noise

The graphics show, that additive noise with standard deviation within 8% of average image brightness has little influence on the OF field accuracy. Starting from $\sigma = 8\%$, however, the effect of image noise rapidly increases. According to these results, the limit of acceptable additive image noise for optical flow determination with fragments size 16x16 can be set at $\sigma = 8\%$ of average image brightness.
The effect of multiplicative noise is very similar to that of the additive one. According to the graphics, the limit of acceptable multiplicative image noise (PRNU) for optical flow determination with fragments size 16x16 can be set at $\sigma = 6\%$ of average image brightness.
5.7. Navigation errors estimation (end-to-end test)

5.7.1. Test goals
Main goals of this test were to prove the feasibility of proposed visual navigation system concept and to estimate the expected performances of such system.

5.7.2. Test conditions
The test has been performed with software model of visual navigation system using the simulated navigation camera images and reference 3D model of landing site. Resolution of the reference 3D model has been limited to 4 m. Initial estimation of navigation data, required for starting of navigation system operation, have been obtained as a sum of ideal navigation data (from reference trajectory) and following simulated errors:

- position error: 500 m on each axis (860 m deviation from correct position – 4% of distance to landing site);
- attitude error: 1.4° for each angle;
- velocity error: 20 m/s on each axis (35 m/s or 5% deviation from correct velocity).

After start, navigation data, obtained in a previous measurement, have been used as initial estimation for the next one. Except for this, no filtering has been applied to navigation data. Navigation errors have been determined as a difference between the position/attitude/velocity obtained from the optical flow and the reference trajectory data.

5.7.3. Test results
As the result of this test, feasibility of proposed navigation system concept has been proved at simulation level. The system demonstrated stable operation during whole Visual Guidance Phase of reference landing trajectory. Graphics of navigation errors are shown in Fig. 16-20.

![Fig. 16. Attitude errors (3 angles, whole Visual Guidance Phase)](image-url)
Fig. 17. Position errors (3 axes, whole Visual Guidance Phase)

Fig. 18. Position errors (last 16 seconds of VGP)

Fig. 19. Velocity errors (3 axes, whole Visual Guidance Phase)
Local increase of errors around 13-14th second of VGP has been caused by a large crater passing through the field of view. Occasionally, this crater was very new; therefore it had very smooth surface and practically no later-on small crates inside, what caused large optical flow errors. Nevertheless, the system was stable and has returned to low error as soon as the disturbance finished. The effect of such occasions will be significantly reduced in the next version of correlation algorithms.

Averaged errors values for the whole Visual Guidance Phase are summarized in Table 1.

Table 1. Navigation data errors

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>RMS attitude error</td>
<td>0.54 degrees</td>
</tr>
<tr>
<td>RMS position error (relative, with respect to distance to landing site)</td>
<td>0.92%</td>
</tr>
<tr>
<td>Position error at the end of Visual Guidance Phase (RSS for all axes)</td>
<td>1.8 m</td>
</tr>
<tr>
<td>RMS velocity error (relative)</td>
<td>1.06%</td>
</tr>
<tr>
<td>Velocity error at the end of Visual Guidance Phase (RSS for all axes)</td>
<td>0.10 m/s</td>
</tr>
</tbody>
</table>

The results above have been obtained practically without filtering (except for the using the results of previous measurements as an initial estimation). The accuracy can be significantly improved with appropriate filtering of navigation data.
5.8. Effect of reference DEM resolution

5.8.1. Test goals
Main goal of this test was to estimate the effect of the resolution (sampling distance) of reference 3D model (DEM) of landing site on navigation data accuracy.

5.8.2. Test conditions
Test has been performed with resolution of the reference DEM changing from 4 to 64 m. Other conditions were identical to the previous test (chapter 5.7.2).

5.8.3. Test results
Errors of obtained navigation data (root sum square for three axes) are shown in Fig. 21-25.

Fig. 21. RSS position errors (whole Visual Guidance Phase)

Fig. 22. RSS position errors (last 16 seconds of VGP)
Limiting the resolution of the reference DEM has practically no effect during the first half of the Visual Guidance Phase. Only at the end of VGP increase of errors and (for reference DEM resolution 16 and 64 m) some instability were observed. For reference DEM resolution 4 m RSS position error in the end of VGP was within one half of the DEM resolution.
5.9. Effect of errors of initial navigation data estimation

5.9.1. Test goals
Main goals of this test were to estimate the effect of the errors of initial navigation data estimation on visual navigation system operation and to determine the limits of acceptable values of these errors.

5.9.2. Test conditions
As the errors of initial navigation data estimation only affect few first cycles of navigation data determination (the system uses the results from the previous cycle as initial estimation for the next one), this test has been performed only for the beginning part of VGP (first 9 measurements). Three experiment have been performed: in each of them one of errors of initial navigation data estimation (position, attitude or velocity estimation error) has been changed, the rest two errors were identical to previous test (chapter 5.7.2). The errors have been changed within the following limits:

- position error: from 500 to 4000 m on each axis (RSS from 870 m to 6900 m or from 4% to 32% of the distance to landing site);
- velocity error: from 56 to 280 m/s on each axis (RSS from 97 m/s to 485 m/s or from 13% to 65% of the initial velocity);
- attitude error: from 2.0 to 11.3 degrees for each angle (RSS from 3.5 to 19.5 degrees).

5.9.3. Test results
Errors of obtained navigation data (root sum square for 3 axes) are shown in Fig. 26-28.

![Fig. 26. Effect of the error of initial position estimation on navigation data errors](image-url)
As a result of the test a good estimation convergence has been obtained, when the initial estimation errors were within certain limits. In this case the effect of initial errors was practically compensated after 3 to 4 measurements. Acceptable limits of initial estimation errors (root mean sum on all axes) can be estimated as:

- position estimation error – 4800 m (22% of the initial distance to landing site);
- attitude estimation error – 14 degrees;
- velocity estimation error – 340 m/s (45% of initial velocity).
6. Conclusions

1. The feasibility of proposed concept of visual navigation system for planetary lander has been proved in open-loop simulation experiment, considering the Mercury landing scenario as a reference mission.

2. During simulated Visual Guidance Phase, RMS error of position determination has been determined to be within 1% of distance to landing site; RMS attitude error – about 0.5 degrees and RMS velocity error – about 1%.

3. Obtained accuracy can be further improved by appropriate filtering of navigation data.

4. The practical realization of the proposed visual navigation system will allow performing precision autonomous guidance and navigation to the selected landing site, also for high inclined landing trajectories.

7. References


