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OPTICAL FLOW NAVIGATION FOR AN OUTDOOR UAV USING A WIDE ANGLE MONO CAMERA AND DEM MATCHING

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ABSTRACT

Visual navigation for low altitude unmanned aerial vehicles (UAV) shows many scientific and technical challenges in terms of navigation performances, complex 3D environment, high computational requirements for real-time image processing and very limited onboard mass and power resources.

The current paper presents a concept of a visual navigation system, based on a wide angle mono camera as vision sensor and matching of the recovered and reference 3D environment, modeled by a digital elevation map (DEM). The recovered 3D models are being produced by real-time optical flow processing of the navigation camera images. An embedded optical correlator is introduced, which allows a robust and ultra high-speed optical flow processing under different and even unfavorable illumination conditions. The proposed concept can be augmented by any state-of-the art navigation aids, e.g. GPS, IMU, magnetometers. The current paper discusses the general principles and structure of the navigation system as a vision only system, i.e. without any additional navigation aids, and with instantaneous determination of the vehicle state, i.e. without time filtering. The paper gives also detailed end-to-end visual navigation performance results, based on a detailed software simulation model of the visual navigation system, including the optical correlator as the key component for ultra-high speed image processing. *Copyright © 2002 IFAC*

Keywords: visual navigation, optical flow, optical correlator, digital elevation map, DEM matching

1. INTRODUCTION

The use of vision for the navigation of compact unmanned aerial robots can lead to a high degree of autonomy, but it involves many scientific and technical challenges in terms of navigation performances, complex 3D environment, high computational requirements for real-time image processing and very limited onboard mass and power resources. In particular unstructured outdoor environment is most challenging due to weak and changing illumination conditions. The general approaches can be categorized in *map-based* navigation, *map-building-based* navigation and *mapless* navigation (Desouza et al., 2002). Map-based approaches using metric maps allow a purposive and rather precise (depending on the map accuracy) relative navigation with respect to a given reference coordinate system. A very common approach is to use landmark based maps, which however have well known drawbacks for unstructured environments with weak illumination conditions. A more favourable approach for outdoor environments is the use of the terrain topography in terms of Digital Elevation Maps (DEM). A Digital Elevation Map (or sometimes called 2.5D-Map) represents the local height over the surface planar coordinates. By matching of a previously generated reference DEM with an on-the-fly generated navigation DEM it is possible to derive navigation information for the flying vehicle (Sim et al., 2002). The most simple configuration for navigation imaging is to use a mono camera mounted rigidly to the vehicle. The egomotion of the vehicle with respect to the terrain surface is then mapped to the optical (or image) flow vector field in the camera image plane (Prazdny 1980). Since more than two decades the evaluation of the optical flow for navigation purposes has been investigated by many researchers, e.g. some recent results are found in (Green et al., 2004), (Hrabar & Sukhatme, 2003), (Hrabar & Sukhatme, 2004). As the optical flow field contains depth information of the underlying scene, it can be used comfortably in context with DEM based navigation, e.g. (Lerner et al., 2004). In particular for UAVs operating in low altitudes, the operational envelope as well as the navigational performances can be improved using wide-angle optics, such as fish-eye or omni-directional lenses, e.g. (Baker et al., 2004) , (Pless 2004).

The current paper presents a mono camera concept which was adapted from a recently introduced visual navigation concept for planetary landing (Janschek et al. 2005b). The key features of this concept involve a correlation based optical flow approach for vehicle egomotion estimation and 3D map generation. The demanding processing requirements for real-time optical flow computation can be met by an embedded optical correlator, which allows a robust and ultra high-speed optical flow processing under different and even unfavorable illumination conditions. This optical processor technology has been developed in the last years at the Institute of Automation, Technische Universität Dresden. First investigations considering realistic performance properties of the optical correlator hardware and dimensioning landing trajectory properties have proved the feasibility of the proposed concept for a planetary landing application (Janschek et al. 2005b).

An adaptation of this concept for low altitude unmanned aerial vehicles is presented in the current paper. New elements for the UAV application are the use of a wide angle mono camera which needs some different approach for navigation data processing including the handling of the DEM models.

2. VISUAL NAVIGATION PRINCIPLES

The proposed visual navigation principle is based on the matching of 3D surface models instead of 2D images. A 3D model of the visible surface in the camera-fixed coordinate frame is reconstructed from the images taken by an onboard camera. This model is matched with the reference 3D model with known position/attitude (pose) in a surface-fixed coordinate frame. As a result of the matching, the reconstructed model pose in the surface-fixed frame is determined. With position and attitude of the reconstructed model known in both camera-fixed and surface-fixed frames, the position and attitude of the camera can be calculated in the surface-fixed frame.

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

2.1. Reconstruction of a 3D model by optical flow processing of navigation camera images

Stereo vision or 3D laser scan, commonly used for creation of 3D environment models, are not suitable for UAVs. Due to limited size of the vehicles, the possible stereo base is very small in comparison with the flight altitude, which makes stereo vision-based distance measurements unreliable and inaccurate. 3D laser scanners are generally too large and heavy for UAVs. Being active devices, they also consume a lot of power and have a limited range of operation. Under these conditions and constraints a very promising solution is an optical flow based 3D terrain model reconstruction.

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

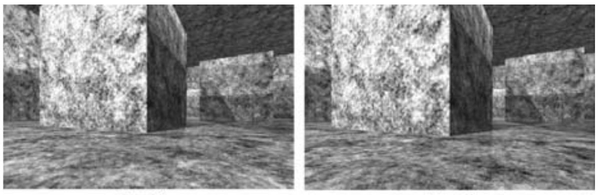


Image 1 Image 2

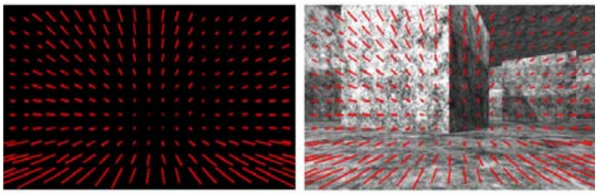

Optical Flow field OF field with image overlayed

Fig. 1. Optical flow example

If the camera has moved between the moments of images acquisition, each optical flow vector contains the information about the 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. Processing of all optical flow vectors allows a determination of a 3D model of the visible surface in a camera-fixed coordinate frame (Janschek et al. 2005b).

2.2. Optical flow determination by 2D correlation of image fragments

For each pair of sequential navigation camera 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 matrix (Figure 2).

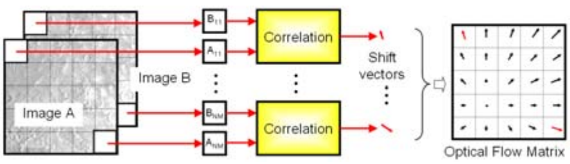


Fig. 2. Principle of the optical flow determination

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

- high subpixel accuracy (error of image shift determination can be within 0.1 pixel , 1σ);
- 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).

These operational advantages have been paid however with a very large amount of computations which makes it practically impossible to get a compact real time realization with conventional digital processors onboard a flying robot. To reach the real time performance we propose to perform the correlations with an onboard optical correlator.

3. OPTICAL CORRELATOR TECHNOLOGY

The key component for real-time optical flow processing is the Joint Transform Optical correlator. This 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 (Figure 3), according to the Joint Transform Correlation principle (Jutamulia, 1992).

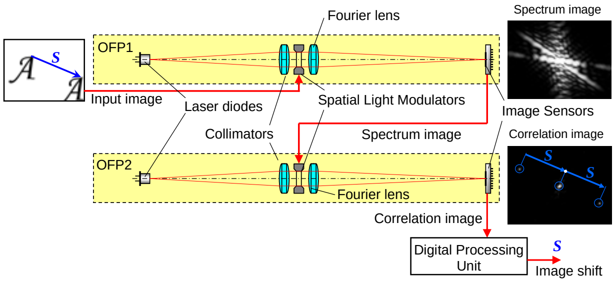


Fig. 3. Optical correlator principle

This advanced technology and its applications have been studied during last years at the Institute of Automation of the Technische Universität Dresden (Janschek, et al., 2001 and Janschek, et al., 2003). Different hardware models have been manufactured, e.g. under European Space Agency (ESA) contracts (Figure 4).

Fig. 4. Hardware model of an optical correlator

Due to special design solutions these devices are very robust against mechanical loads and do not require precise assembling and adjustment (Tchernykh, et al., 2000 and Janschek, et al., 2005a). The results of airborne flight test showed very promising performances (Tchernykh, et al., 2004). Recent research has given solutions for a very compact realization of such a device, suitable for onboard installation. Using advanced opto-electronics technology it is possible to get a compact correlator with a processing rate of up to 50000 correlations per second, which allows real time optical flow determination on mobile vehicles (Tchernykh, et al., 2006).

4. NAVIGATION SYSTEM CONCEPT

The main goal of the visual navigation system is the fast determination of high accuracy navigation data (position, attitude and velocity) in a surface-fixed coordinate frame (SF) onboard an autonomous unmanned aerial vehicle. The primary navigation sensor shall be a surface-oriented navigation camera. The general structure of the system is presented in Figure 5.

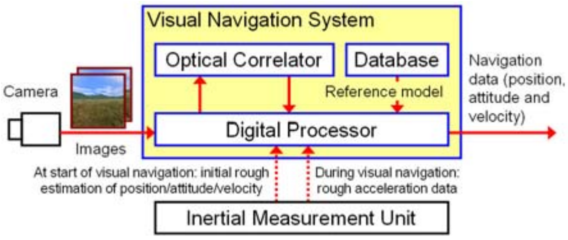


Fig. 5. General structure of visual navigation system

Navigation data will be determined by processing the surface images, taken by the onboard camera. Different camera types can be used for visual navigation, however, high resolution cameras with wide angle optics are preferable. To reach the real-time performance, an onboard optical correlator is foreseen for images processing. Position and attitude of the vehicle will be determined with respect to the reference 3D terrain model of the area. The reference model can be obtained from a topographic map database or produced from high resolution aerial stereo images of the terrain. For optimal performance the system can be augmented with an inertial navigation unit or GPS receiver, which allows coarse orientation of the robot and provides rough initial estimates of navigation data at the initialization of the visual navigation phase. During operation, the system can also benefit from real time acceleration information. A totally autonomous operation (vision only) is also possible in case of shadowing of GPS signals or unavailability of IMU, at the cost of a considerably long start-up time (initial acquisition of position/attitude) and some degradation of navigation performances.

5. SIMULATION EXPERIMENT DESCRIPTION

To prove the feasibility of the proposed visual navigation concept and to estimate the expected navigation performances, a software model of the proposed visual navigation system has been developed and an open-loop simulation of navigation data determination has been performed.

A simulation environment has been produced using the landscape generation software (Vue 5 Infinity from e-on software) on the base of 3D relief, obtained by filtering of the random 2D pattern. Natural soil textures and vegetation have been simulated (with 2D patterns and 3D models of trees and grass), as well as natural illumination and atmospheric effects (Figure 6).

Fig. 6. Simulation environment with UAV trajectory

A simulation reference mission scenario has been set up, which includes the flight along a predetermined trajectory (the loop with the length of 38 m – Figure 6, 7) at a height about 10 m over the simulation terrain.

Fig. 7. Top view of simulation environment with UAV trajectory

Simulation navigation camera images (Figure 8) have been rendered for a single nadir-looking camera (Table 1) considering the simulated UAV trajectory.

Table 1. Navigation camera parameters.

Lens type	fisheye
Field of view	220°
Sensor resolution (pixels)	792x792
MTF of the optics @ Nyquist frequency	0.6
Full well capacity (electrons)	10000
Pixel response non-uniformity	$\sigma = 2\%$
Readout noise (electrons)	$\sigma = 20$
Quantization	8 bits

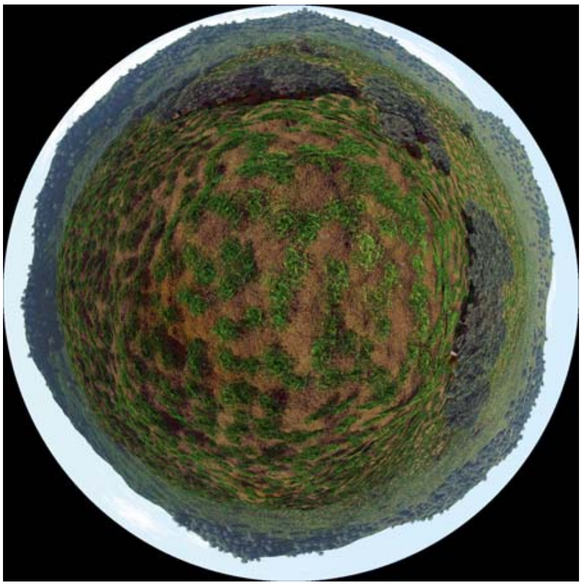
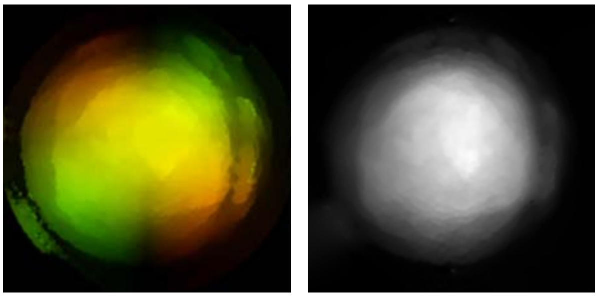


Fig. 8. Example of simulated navigation camera image

To produce the reference 3D model of the terrain two high altitude images of the simulation environment have been produced and stereo processed (simulating the standard aerial mapping). A reference model has been produced in a form of Digital Elevation Model (DEM). Such model can be represented by a 2D pseudo image with the brightness of each pixel corresponding to the local height over the base plane.

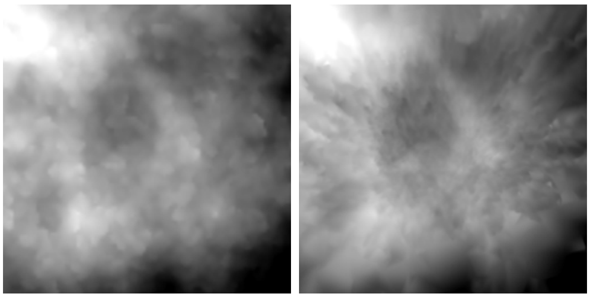
The optical flow determination has been performed with a detailed simulation model of the optical correlator. The correlator model produces the optical flow fields (matrices) with the required density for each pair of simulated navigation camera images, simulating the operation of the real optical hardware. Figure 9 shows an example of the optical flow field. 3D surface models have been first reconstructed as local distance maps in a camera-fixed coordinate frame (Figure 9), then converted into DEMs in a surface-fixed frame using the estimated position and attitude of the vehicle. Figure 10 shows an example of both the reconstructed and reference DEMs.



Optical flow field (magnitude of vectors coded by brightness, direction – by color)

Distance map (local distance coded by brightness)

Fig. 9. Example of an optical flow field and corresponding distance map.



Reference DEM

Reconstructed DEM

Fig. 10. Reference and reconstructed DEMs.

The matching of the reconstructed and reference model has been performed by multi-point 2D correlation of the DEMs (which actually can be performed also by the onboard optical correlator). The correlation results have been further processed to determine scaling, 3D shift and rotation of the reconstructed model with respect to the reference one. From those values have been determined the errors of the initial estimate of camera position, attitude and velocity. With these errors known, the initial estimation of navigation data has been updated and accurate estimates of camera position, attitude and velocity in surface frame have been determined.

6. SIMULATION EXPERIMENT RESULTS

As a result of the simulation, position and attitude have been determined for 56 locations along the UAV trajectory, using the reference DEM with horizontal sampling distance of 0.4 m. The obtained values have been compared with reference trajectory data and the corresponding navigation errors have been calculated (Table 2, Figure 11).

Table 2. Navigation errors

	RMS	Mean			Std		
		x	y	z	x	y	z
Position error, whole trajectory (m)	0.36	0.03	-0.03	-0.08	0.17	0.16	0.25
Position error, pure translation (m)	0.20	-0.01	-0.01	-0.06	0.12	0.09	0.12
Attitude error, whole trajectory (degrees)	0.70	-0.16	-0.03	-0.07	0.35	0.30	0.49
Attitude error, pure translation (degrees)	0.45	-0.06	-0.05	0.03	0.15	0.19	0.36

The simulation results show a significant degradation of navigation accuracy during turns of the UAV. (Figure 11). The reason for it is the dominance of the rotation component of the optical flow during turns.

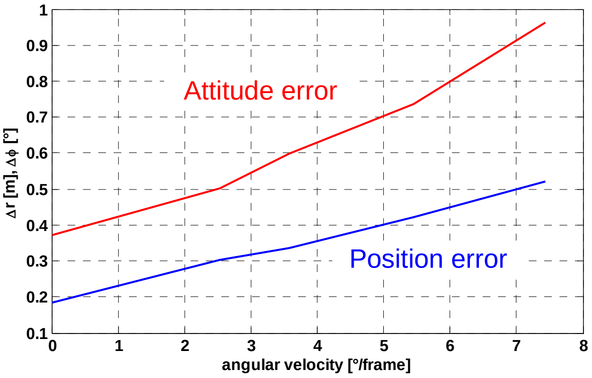


Fig. 11. Navigation errors dependence on the angular velocity

To evaluate the requirements to the reference DEM, the error dependency on DEM sampling distance and accuracy have been determined (Figs. 12, 13).

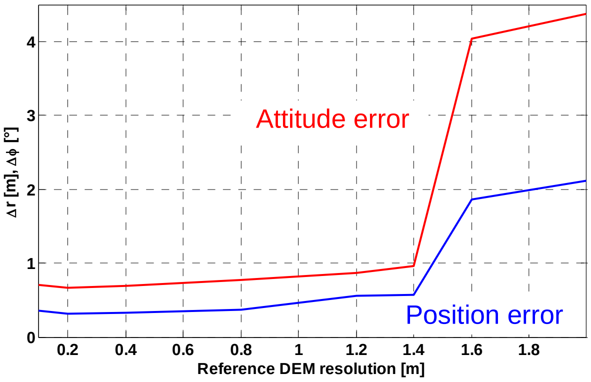


Fig. 12. Navigation error dependency on DEM sampling distance

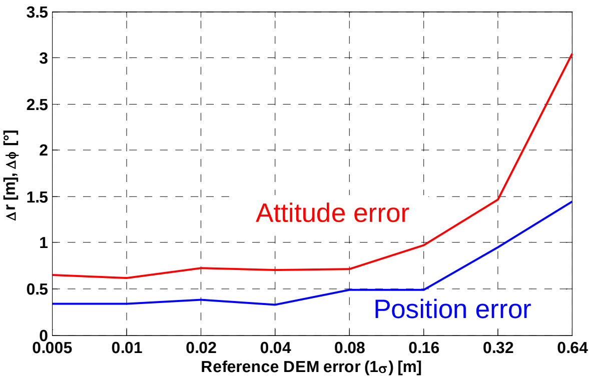


Fig. 13. Navigation error dependency on DEM errors

Figure 12 shows, that the navigation errors practically do not depend on the reference DEM sampling distance below a certain threshold (1.4 m in Figure 12), after which the DEM matching becomes unstable what results in fast growth of navigation errors. Below the threshold the position error tends to be generally smaller then the sampling distance of the reference DEM. The value of the threshold should be linked with the ground resolution of the navigation camera (0.05 m/pixel simulated UAV trajectory). A similar situation has been observed with reference DEM errors (Figure 13), where the threshold error value has been observed to be about 0.2 m (one sigma). Simulation results show, that position and attitude errors have a strong dependency.

7. CONCLUSIONS

A visual navigation concept for low altitude unmanned aerial vehicles has been proposed, based on real time processing of the surface images with onboard optical correlator and suitable for varying illumination conditions.

The practical realization of the proposed navigation system will allow performing precision autonomous guidance and navigation of UAVs over a natural terrain. A detailed performance analysis based on simulation studies with synthetic images and detailed models of the navigation system has shown very promising results.

The current results have been obtained by instantaneous processing of the optical flow data, i.e. without any time filtering, and without any additional navigation aids (except the DEM reference map). The navigation accuracy may be improved by some filtering, which is currently under investigation. The existing algorithms are currently tested with real camera images from a (slow dynamics) blimp and processing on a laptop. A further development line at the Institute of Automation is devoted to the development of an advanced opto-electronic optical flow processor, which is applicable both for terrestrial and space applications.

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