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OPTICAL FLOW BASED NAVIGATION FOR MOBILE ROBOTS USING AN EMBEDDED OPTICAL CORRELATOR

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Abstract: The proposed navigation concept solves the problem of autonomous real time navigation of mobile robots with a single wide angle camera as primary perception sensor and a standard odometry as auxiliary navigation sensor. The key feature of this navigation concept is the synergetic combination of the optical flow concept and a special computer hardware technology on the base of photonic computing using an advanced embedded optical correlator. The navigation information derived from the optical flow measurements is used for a high rate continuous trajectory estimation using auxiliary odometry data as well as for a periodic absolute navigation with sole optical flow data. The paper presents the general system layout, describes the key components and discusses performance and simulation results.

Keywords: optical flow, optical computing, localisation, navigation, mobile robotics

1. INTRODUCTION

One key function for autonomous mobile robots is the precise and reliable determination of the robots position and orientation (= robot pose) with respect to a 3D world model. This problem has been widely studied for a long time and many solutions have been proposed on the base of different perceptional capabilities. Among these the minimum hardware systems are of particular interest in order to minimise the robots mass, power and volume budgets. The most promising candidate for single perception concepts are vision sensors. The inherent advantage of visual data in terms of huge information content is paired with the inherent disadvantage of extreme processing requirements in terms of appropriate algorithms and hardware. Many of the proposed solutions use feature based image processing concepts, e.g. landmark navigation with natural or artificial landmarks. The drawback of these methods is mainly the necessity to have precise a-priori information on the environment and to be relying on the existence of these specific navigation targets. Moreover the feature based methods are mostly sensitive to image noise, which is a standard problem in mobile robotics for low illumination conditions. Other methods, which do not rely on specific features, seem therefore to be suited much better for mobile robotic applications.

Among these the concept of optical flow is of particular interest, because it works in principle content free. An optical flow can be defined as the projection of velocities of 3D surface points onto the imaging plane of a visual sensor. It is usually determined as a matrix of local image velocity vectors. As the 3D relative motion of a robot mounted camera with respect to its environment is mapped on the camera 2D focal plane, the 2D optical flow information can be used for extracting information on the motion of the camera and in consequence to derive navigational information for the robot.

This principle has been studied and investigated in detail by several groups (Giachetti et.al. 1994), (Winters et.al. 2001). The main limitation for a standard implementation on mobile vehicles is the real-time determination of the optical flow field, which requires very high number chrunching capabilities on embedded technology. The current paper proposes a solution to this problem by a synergetic combination of the optical flow concept and a special computer hardware technology on the base of photonic computing using an advanced embedded optical correlator.

2. SYSTEM CONCEPT

The proposed navigation concept solves the problem of autonomous real time navigation of mobile robots with a single *wide angle camera* as primary perception sensor and a standard odometry as auxiliary navigation sensor.

The underlying method for motion measurement is based on the *optical flow* concept. This incorporates the analysis of image motion vectors determined by real time processing of a sequence of local surroundings images from a wide angle camera. The image motion vectors are derived from 2D-correlation of individual image segments. For this purpose an advanced embedded *optical correlator* is used, which offers unique processing power which is required for real-time operation. Auxiliary odometry data allows a basic continuous coarse trajectory estimation which is augmented with navigation data derived from the vision based optical flow measurements.

Two basic modes of operation are proposed:

- *propagated pose estimation* by continuous integration of the travelled path (with some error accumulation) and periodical (high update rate) heading measurement from optical flow data
- *absolute pose estimation* by periodical (low update rate) 3D matching of visible environment with an internal 3D model (to eliminate the accumulated error) and to provide an autonomous initialisation capability.

In a separate mode (not addressed in this paper) the optical flow measurements could be used also for a vision based 3D mapping of the environment.

The key feature of this navigation concept is the synergy of the *optical flow* concept with the unique processing power of an *optical correlator*.

Optical flow in general and in combination with the proposed 2D-correlation approach in particular needs no a-priori information on the 3D environment, it works for any distinct textures and is extremely robust to image noise (critical for low illumination conditions). The optical correlator technology offers unique processing power by using photonic data processing at the speed of light. The proposed embedded optical correlator technology has been developed at the TU Dresden Institute of Automation in the frame of previous space projects (Tchernykh et.al. 2002). The proved performances show subpixel image shift determination and high mechanical robustness to mechanical deformations (Tchernykh et.al. 2000).

Thus the key components *optical flow & optical correlation* makes the proposed navigation concept in particular suitable for mobile robotic applications in harsh and unstructured environments.

3. OPTICAL FLOW DETERMINATION

Optical flow represents a vector field which describes the apparent motion of the brightness pattern of an image. For the calculation of the two-dimensional optical flow, a variety of methods have been studied (Galvin et.al. 1998), (McCane et.al. 1998) (Barrows et.al. 2000), (Bruhn et.al. 2003). In any case it requires a large computational effort, which is hindering the implementation in real-time and embedded environments. The approach which is followed in this paper uses sequences of digital images, image segmentation and motion tracking of image segments by 2D-correlation. To overcome the high computational load for the 2D-correlation an embedded optical correlator hardware is introduced, which allows for real-time operation on mobile vehicles.

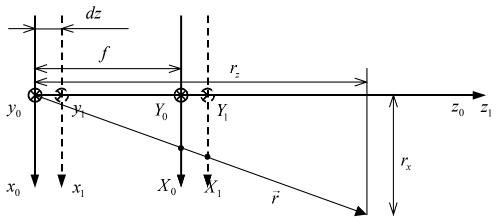

Fig. 2 Coordinate frames for linear motion along z-axis

The optical flow can be computed as linear superposition from elementary flow fields under the assumption, that only small camera pose changes occur between two subsequent image recordings.

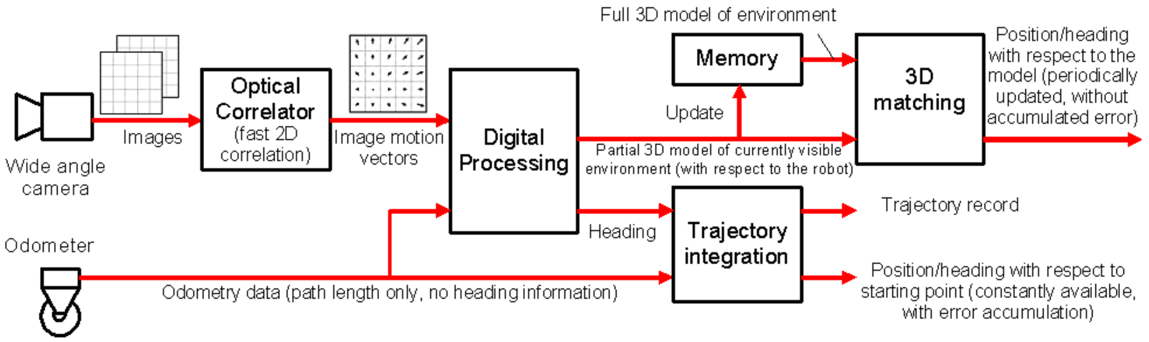

Fig. 1 Optical flow based navigation system – block diagram

With the definition

$$\vec{v} = \frac{1}{f}\begin{pmatrix} X \\ Y \end{pmatrix} = \frac{1}{r_z}\begin{pmatrix} r_x \\ r_y \end{pmatrix} \qquad (1)$$

it follows for the elementary flow gradients for translation (x/y/z) and rotation $(\varphi_x / \varphi_y / \varphi_z)$ (see Figure 2)

$$\vec{F}_x^t(\vec{v}) = \begin{pmatrix} -1/r_z(\vec{v}) \\ 0 \end{pmatrix} ;\ \vec{F}_y^t(\vec{v}) = \begin{pmatrix} 0 \\ -1/r_z(\vec{v}) \end{pmatrix} ;\ \vec{F}_z^t(\vec{v}) = \frac{1}{r_z(\vec{v})}\begin{pmatrix} v_x \\ v_y \end{pmatrix} \qquad (2)$$

$$\vec{F}_x^r(\vec{v}) = \begin{pmatrix} v_x v_y \\ v_y{}^2 + 1 \end{pmatrix} ;\ \vec{F}_y^r(\vec{v}) = -\begin{pmatrix} v_x{}^2 + 1 \\ v_x v_y \end{pmatrix} ;\ \vec{F}_z^r(\vec{v}) = \begin{pmatrix} -v_y \\ v_x \end{pmatrix} \qquad (3)$$

The incremental optical flow under perspective projection is then given by linear superposition as

$$\begin{pmatrix} \Delta v_x \\ \Delta v_y \end{pmatrix} = \Delta\varphi_x \cdot \vec{F}_x^r(\vec{v}) + \Delta\varphi_y \cdot \vec{F}_y^r(\vec{v}) + \Delta\varphi_z \cdot \vec{F}_z^r(\vec{v}) + \qquad (4)$$
$$+ \Delta x \cdot \vec{F}_x^t(\vec{v}) + \Delta y \cdot \vec{F}_y^t(\vec{v}) + \Delta z \cdot \vec{F}_z^t(\vec{v})$$

A pixel based computation of the optical flow requires a huge computational effort and is moreover very sensitive to image noise (in particular for mobile robots under low illumination conditions).

Therefore a segmentation of the images is proposed. For these segments a discretised flow field can be generated in form of an image flow matrix.

As an example the discretised flow field (image flow matrix) resulting from image segmentation is shown in Figure 4 for a linear approach trajectory to an object (wall) as sketched in Figure 3.

The discretized flow vectors for each image segment can be computed by comparing the respective segments of an image sequence and by determining the shift of the image contents, called image motion tracking (Figure 5). Instead of using feature based tracking methods, a correlation approach is proposed, which offers much higher robustness to image noise. The overall scheme for image flow matrix computation is sketched in Figure 6.

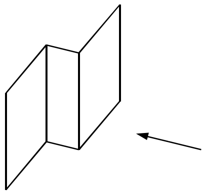

Fig. 3 Linear motion - wall approach

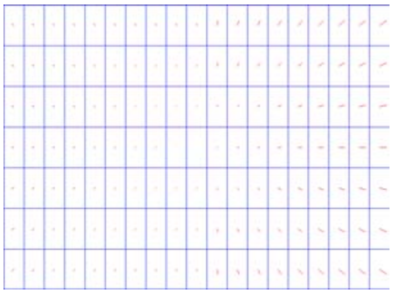

Fig. 4 Optical flow matrix for linear motion along z-axis (wall approach)

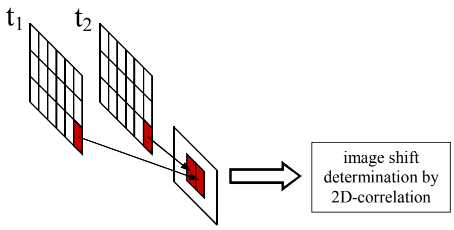

Fig. 5 Image segmentation

4. IMAGE MOTION TRACKING BY 2D-CORRELATION

The basic step for optical flow determination is the image motion tracking of each segment of the segmented camera image. This image motion tracking requires the accurate measurement of the shift between two overlapped images.

The so-called *joint transform correlation* scheme is used to minimise the overall computational effort. It makes use of two subsequent 2D-Fourier transforms without using phase information (this is beneficial for hardware realisation by optical Fourier processors, see next paragraph).

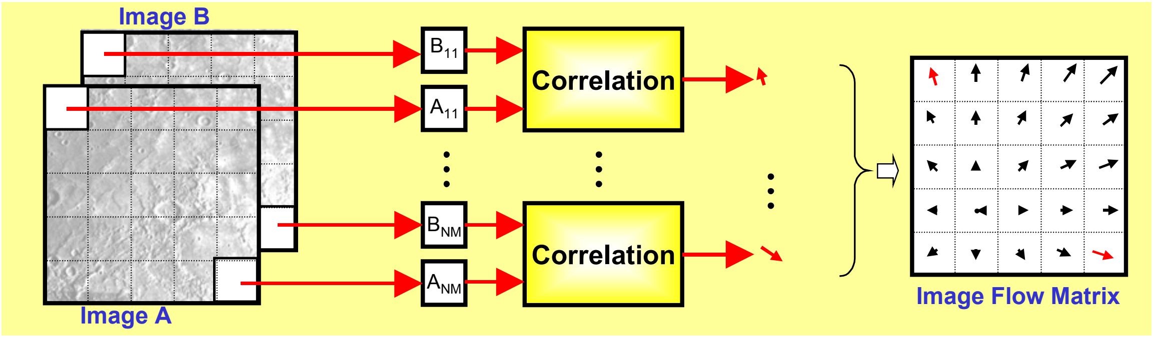

Fig. 6 Optical flow matrix of two successive images

The two images $f_1(x,y)$ and $f_2(x,y)$ to be compared are being combined to an overall image $I(x,y)$ as shown in Figure 7 (top). A first Fourier transform results in the joint power spectrum $S(u,v)=\mathbf{F}\{I(x,y)\}$. Its magnitude contains the spectrum $F(u,v)$ of the common image contents augmented by some periodic components which are originating from the spatial shift $\vec{G}$ of f_1 and f_2 in the overall image I (Figure 7 center).

A second Fourier transform of the squared joint spectrum $J(u,v)=S(u,v)^2$ results in four correlation functions (Figure 7 bottom). The centered correlation function $C_{ff}(x,y)$ represents the auto-correlation function of each input image, whereas the two spatially shifted correlation functions $C_{ff}(x \pm G_x, y \pm G_y)$ represent the cross-correlation functions of the input images. The shift vector $\vec{G}$ contains both the technological shift according to the construction of the overall image $I(x,y)$ and the shift of the image contents according to the image motion. If the two input images f_1 and f_2 contain identical (but shifted) image contents, the cross-correlation peaks will be present and their mutual spatial shift $\vec{\Delta}=\vec{G}-\left(-\vec{G}\right)$ allows to determine the original image shift in a straightforward way.

Several advantages of this approach compared to feature based image motion tracking are evident. The correlation approach is much more robust against image noise. Moreover it requires no a-priori information on the image contents and it works well as long as “enough” image texture is existent. The determination of the actual image shift is reduced to the comparable simple task of determining the bright spot of the correlation peak within a certain region of the correlation image.

The main drawback of the correlation approach however is the high computational effort for the two 2D-Fourier transforms, which limits its applicability for real-time solutions. A very promising solution to this problem is given by using optical computers, as outlined in the next paragraph.

5. REAL-TIME OPTICAL CORRELATOR

The 2-dimensional correlation uses data sources organized in matrices (e.g. digital images). A digital computation in real-time is feasible only for rather small images or at a low processing frequency.

An interesting alternative is offered by so-called optical processors. Optical Fourier processors are based on special opto-electronic assemblies, which make use of optical defraction phenomena at the benefit of parallel processing at speed of light. The latest achievements in the development and manufacturing of opto-electronic components allow to build compact embedded optical processors, which are much faster than available digital FFT processors.

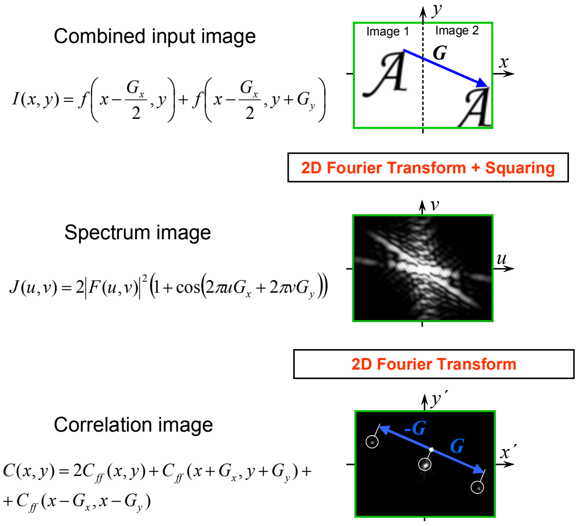

Fig. 7 Principle of joint transform correlation

For image motion correlation, the *Joint Transform Optical Correlator (JTC)* scheme is used, which includes two identical optoelectronic modules – Optical Fourier Processors (OFP) - as sketched in Figure 8.

The two digital input images are entered side by side into the optical system of the first OFP by a special opto-electronic component, a transparent spatial light modulator (SLM). After a first optical Fourier transformation, the joint power spectrum (JPS) is read by the image sensor (CCD, CMOS) and loaded to the SLM of the second OFP. A second optical Fourier transformation forms the joint transform correlation image, which is recorded by the second image sensor.

The correlation image contains the joint transform correlation peaks, which map uniquely the spatial shift of the input images, as outlined in the previous paragraph.

The position of peaks on the correlation image can be measured with sub-pixel accuracy using standard algorithms for centre of mass calculation. A standard digital signal processor can be used for this task.

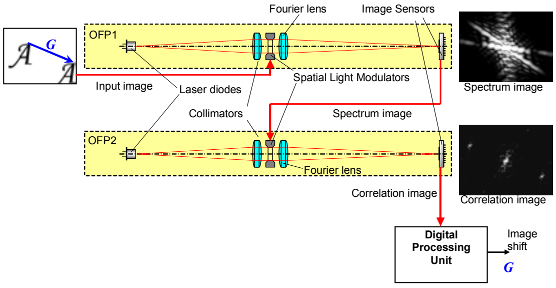

Fig. 8 Joint Transform Optical Correlator (JTC)

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

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). Recent airborne test flight results showed very promising performances (Tchernykh et.al.2002).

The typical optical correlator accuracy of shift determination errors is below 0.2 pixel (1σ) even for extremely noisy images with SNR less then 0 dB. Processing rates up to 3200 correlations per second are possible. This makes an optical correlator particularly suitable for the determination of the motion of dark and fast moving images in mobile robot applications under weak illumination conditions.

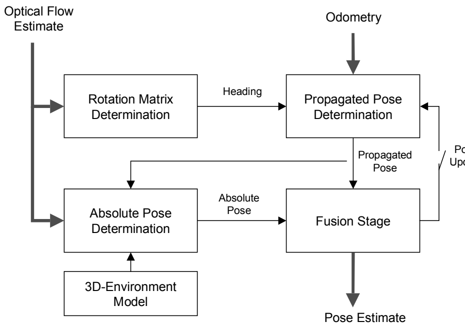

Fig. 9 Navigation functional overview

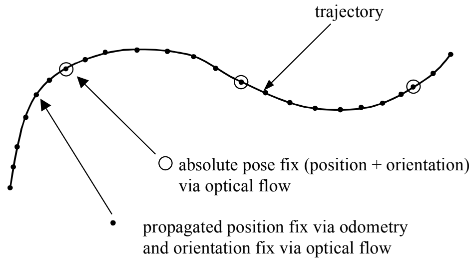

Fig. 10 Navigation scheduling scheme

6. NAVIGATION SOLUTION

A functional overview on the navigation scheme is sketched in Figure 9, the scheduling scheme is shown in Figure 10.
It is assumed that standard odometry data (path length without heading information) is available continuously. Optical flow measurements are available frequently in the sense, that image movements are fitting to the acceptable shift limits for 2D-correlation. This allows a frequent determination of *propagated pose* estimates (position and full heading) on the base of integrated odometry data and heading information derived from optical flow measurements. These propagated pose estimates are corrupted by the unknown odometry errors and will drift off with time from the true values. Therefore with some lower update frequency an *absolute pose* estimate can be derived from the optical flow measurements taking into account some a-priori data on the 3D-environment. In a *fusion stage* the propagated and absolute pose estimates are being combined by an appropriate data fusion algorithm to form a best estimate. This best estimate is used further to reset the propagated pose filter.

This navigation scheme contains two non-standard functions, which should be explained briefly.

- **Rotation Matrix Determination**

For a translational motion with a primary component in z-direction it follows $\Delta x = \Delta y = 0$ which simplifies (4) to

$$\begin{aligned}\begin{pmatrix}\Delta v_x \\ \Delta v_y\end{pmatrix} &= \Delta\varphi_x \cdot \vec{F}_x^r\left(\vec{v}\right) + \Delta\varphi_y \cdot \vec{F}_y^r\left(\vec{v}\right) + \\ &+ \Delta\varphi_z \cdot \vec{F}_z^r\left(\vec{v}\right) + \Delta z \cdot \vec{F}_z^t\left(\vec{v}\right)\end{aligned} \tag{5}$$

The rotation angles $\Delta\varphi_x, \Delta\varphi_y, \Delta\varphi_z$ can be determined from (5) by minimising numerically the measure

$$\begin{aligned}&M\left(\vec{v}, \Delta\varphi_x, \Delta\varphi_y, \Delta\varphi_z\right) = \\ &= \left\| \left[\begin{pmatrix}\Delta v_x \\ \Delta v_y\end{pmatrix} - \Delta\varphi_x \cdot \vec{F}_x^r\left(\vec{v}\right) - \Delta\varphi_y \cdot \vec{F}_y^r\left(\vec{v}\right) - \Delta\varphi_z \cdot \vec{F}_z^r\left(\vec{v}\right) \right] \cdot \frac{1}{\left|\vec{v}\right|} \begin{pmatrix} v_y \\ -v_x \end{pmatrix} \right\|\end{aligned} \tag{6}$$

$$\sum_{\vec{v}} M\left(\vec{v}, \Delta\varphi_x, \Delta\varphi_y, \Delta\varphi_z\right) \Rightarrow \min \tag{7}$$

- **Absolute Pose Determination**

The absolute pose determination uses a matching approach on the basis of optical flow estimates resulting from the actual measurement and the 3D environment model. This leads finally to an optimization problem, which tries to find the unknown $Pose^*$ which is consistent with the measured optical flow $\vec{F}(\vec{v})$ and the supposed flow $\vec{F}^*(\vec{v})$ from the environment model, i.e.

$$\Delta\vec{F}(\vec{v}) = \vec{F}^*(\vec{v}) - \vec{F}(\vec{v}) \tag{8}$$

$$M(Pose^*) = \sqrt{\frac{1}{n}\sum_{i=1}^{n} \Delta\vec{F}^2(\vec{v}_i)} \Rightarrow \min \tag{9}$$

The search space can be reduced considerably, if some a-priori infomation on the pose is available. For this purpose the propagated pose estimate from odometry data can be used advantageously.
It should be noted, that the absolute pose algorithm works in principle also without any a-priori pose estimate (needs only a longer search) and is therefore suited for an *autonomous initialisation*.

7. SIMULATION RESULTS

The complete navigation scheme including the correlation based optical flow computation has been implemented in a software model (Matlab, C) together with an advanced software simulation model of the optical correlator (Beck 2004). A synthetic scene generation has been performed using the public domain software POV-Ray 3.5 (www.povray.org). The synthetic planar room contains cube-type obstacles distributed over the room. The image sequences for a reference robot trajectory consists of 1006 single images with a resolution of 760x560 pixels (Figures 11 and 12).

An example for the optical flow measurement is given in Figure 12. It can be seen that for some segments the correlation was not successful (marks "▪"). This can be overcome by adapting the windows or improving the image contrast by pre-filtering.

Preliminary simulation studies have demonstrated the feasibility of the proposed navigation approach.

A typical navigation results for sole *propagated pose determination* (odometry + heading from optical flow) is shown in Figure 13 (position error). It can be clearly seen the increase of the estimation error with time (decrease at the end is due to the selected trajectory), but yet an overall acceptable good behaviour. A considerable improvement can be achieved by using the *absolute pose determination* from optical flow, which is shown in Figure 14. It can be clearly seen, that the estimation error (position) is no more diverging and kept within certain limits.

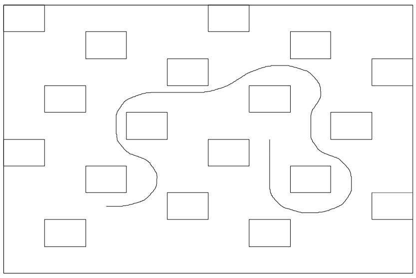

Fig. 11 Test trajectory in synthetic room

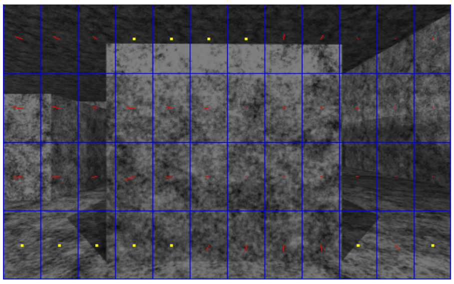

Fig. 12 Computed image flow matrix from synthetic scene

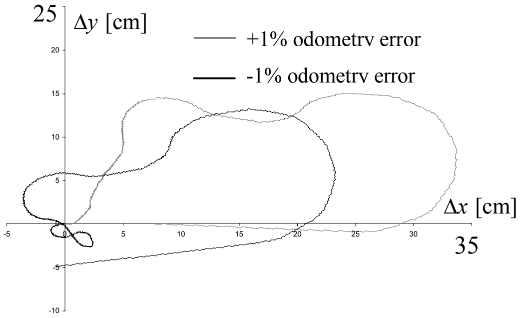

Fig. 13 Localisation error for propagated pose estimates

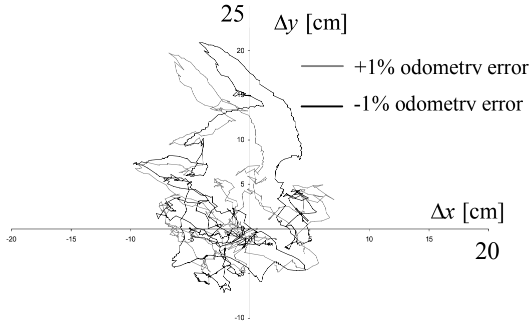

Fig. 14 Localisation error for fusion of propagated pose and absolute pose estimates

8. CONCLUSIONS

This paper presented a navigation approach combining optical flow methods and optical computing technology. A first performance assessment at simulation level has proved the feasibiliy of the concept. Current investigations are directed towards a more detailed performance analysis and improvement in terms of efficiency and accuracy of 3D-matching and data fusion. Complementary tests with real images and the integration of the existing optical correlator hardware are currently under preparation.

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