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An Embedded Optical Flow Processor for Visual Navigation using Optical Correlator Technology

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Abstract – **The conceptual design of an embedded high performance opto-electronic optical flow processor is presented, which is designed for navigation applications in the field of robotics (ground, aerial, marine) and space (satellites, landing vehicles). It is based on 2D fragment image motion determination by 2D correlation. To meet the real-time performance requirements the principle of joint transform correlation (JTC) and advanced optical correlator technology is used. The paper recalls briefly the underlying principles of optical flow computation and optical correlation, it shows the system layout and the conceptual design for the optical flow processor and it gives preliminary performance results based on a high fidelity simulation of the complete optical processing chain.**

Index Terms – optical flow, optical correlator, joint transform correlation, visual navigation.

I. INTRODUCTION

The egomotion of a camera rigidly mounted on a vehicle is mapped into the motion of image pixels in the cameras focal plane. This image motion is commonly understood as image flow or optical flow [1]. This vector field of 2D image motion can be used efficiently for navigation purposes such as localization, mapping, obstacle avoidance or visual servoing. The big challenge for using the optical flow in real applications is its computability in terms of its density (sparse vs. dense optical flow), accuracy, robustness to dark and noisy images and its real-time determination. The general problem of optical flow determination can be formulated as the extraction of the two-dimensional (2D) projection of the 3D relative motion into the image plane in form of a field of correspondences (motion vectors) between points in consecutive image frames. Many methods for optical flow computation have been developed in the last two decades [2,3,4,5,6]. All these methods have in common, that rather dense and accurate optical flow needs low noise images and requires high computational power, which is hardly realizable with embedded processors [6]. Existing pure digital high performance solutions based on conventional PC or FPGA technology [3,21,22] additionally consume a lot of power, mass and volume which does not fit the requirements of advanced mobile robotics and space applications. The recently developed and currently very popular SIFT approach [7,8] allows a computationally efficient determination of more or less sparse optical flow fields in well structured environments. Some specialized very high speed optical flow sensors on hybrid analogue-digital technology [9,10] provide even super real-time performances but are suffering from the required accuracy of optical flow vectors for navigation purposes.

In particular the navigation in unstructured environments with dark and noisy images due to small camera aperture or fast vehicle dynamics requires a robust determination of the apparent image motion. For practical applications the so called block or window based approach using area methods has been proved to be very robust. The underlying methods exploit the temporal consistency over a series of images, i.e. they assume the appearance of a small region in an image sequence changes little.

The classical and most widely used approach is the area correlation, applied originally for image registration [11]. Area correlation uses the fundamental property of the cross-correlation function of two images, which gives the location of the correlation peak directly proportional to the displacement vector of the original image shift. A very efficient method requiring only double Fourier transform without phase information is given by the Joint Transform Correlation (JTC) principle [12]. The high robustness of area based methods to weakly structured image texture and small signal-to-noise ratio has to be paid by a considerable high computational effort. As the complete image area content has to be processed pixel-wise, the real-time application is restricted to rather small image blocks in the range 8x8 to 16x16 pixels. This limits the accuracy, which is known to be poor when the block size gets too small.

This paper addresses a real-time solution for high precision optical flow computation based on 2D correlation of image fragments on the basis of an optical correlator. It exploits the principle of Joint Transform Correlation (JTC) in an optoelectronic setup using the Optical Fourier Transform [13]. Based on the experience of the authors with different successful optical processor developments [14,15,16,17] a new optical processor design is presented, which makes use of advanced optoelectronic technology. The proposed opto-electronic optical flow processor (OE-OFP) shows to be very compact with low mass and low power consumption and provides the high performance needed for navigation applications in the field of robotics (ground, aerial, marine) and space flight (satellites, landing vehicles). The paper recalls briefly the underlying principles of optical flow computation and optical correlation, it shows the system layout and the conceptual design for the opto-electronic optical flow processor and it gives preliminary performance results based

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on a high fidelity simulation of the complete optical processing chain.

II. PRINCIPLE OF OPTICAL FLOW COMPUTATION

For each pair of sequential navigation camera images the optical flow field is determined by subdividing both images into 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 1).

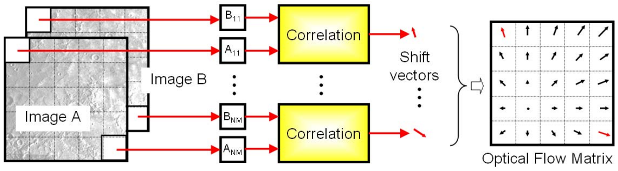

Fig. 1. Principle of correlation based optical flow determination

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

- high subpixel accuracy (error of image shift determination can be within 0.1 pixel , 1);
- 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)
- direct determination of large (multi-pixel) image shifts (suitable for measuring fast image motion).

The capability of large shift determination can be further increased by hierarchical (pyramidal) flow determination which overturns the limitation of the maximum shift by the size of the correlation window. Additionally errors are reduced because the resulting shifts are close to zero.

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 a flying robot. To reach the real time performance we propose to perform the correlations with an onboard optical correlator.

III. OPTICAL CORRELATOR TECHNOLOGY

The key component for proposed real-time optical flow processing is the Joint Transform Optical Correlator (JTOC). This is an opto-electronic device, capable of extremely fast image processing due to application of high parallel optical computing technology. Its operation is based on the principle of Optical Fourier Transform [13], which produces a 2D Fourier transform of an input image with speed of light. This diffraction-based phenomenon is used to perform a 2D correlation of two images by two sequential optical Fourier transforms (Figure 2), according to the Joint Transform Correlation principle [12].

This advanced technology and its applications have been studied during last years at the Institute of Automation of the Technische Universität Dresden [14,15]. Different hardware models have been manufactured, e.g. under European Space Agency (ESA) contracts (Figure 3). Due to special design solutions these devices are very robust against mechanical loads and do not require precise assembly and adjustment [16,17].

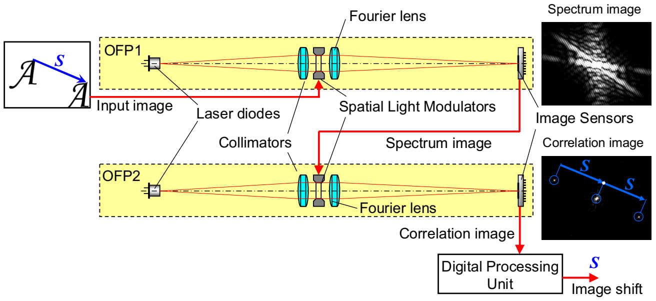

Fig. 2. Joint Transform Optical Correlator (JTOC) principle

The results of airborne flight tests showed very promising performances [14]. A conceptual design for a very compact high performance optical correlator is presented in the next chapter.

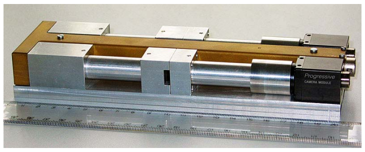

Fig. 3. Hardware model of an optical correlator (60 corr/sec, standard optoelectronic components)

IV. OPTICAL FLOW PROCESSOR CONCEPT

The main purpose of the Optical Flow (OF) processor is the real time determination of the optical flow field for the visible surrounding environment. An OF processor with a standard image sensor includes the following main components as shown in Figure 4.

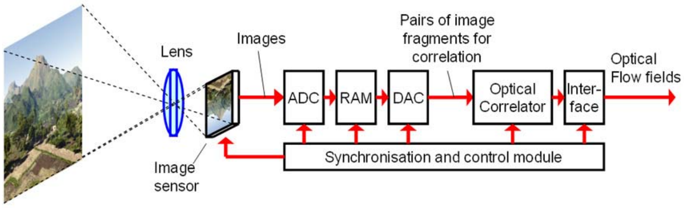

Fig. 4. Optical Flow processor with standard image sensor

A lens is used to produce the images of the environment. The lens is interchangeable – different lens types (i.e. normal, wide angle or fisheye) can be used depending on the application. The images are read by the standard image sensor, digitized by an Analog to Digital Converter (ADC) and stored in the Random Access Memory (RAM). The memory always contains the last two images. The stored images are read in a special order to form the combined pairs of fragments for the joint transform correlation. The combined fragments are converted by the Digital to Analog Converter (DAC) and sent to the optical correlator in analogue form. The optical flow vectors, determined as a result of correlation, are sent to the interface module. The operation of all modules is controlled by a Synchronization and Control Unit. This unit, as well as the interface module, is realized on a FPGA chip.

The key component of the OF processor is the optical correlator. The concept of the optical correlator module based on advanced customized miniature optoelectronic components is shown in Figure 5. A reflective Spatial Light Modulator (SLM) and a Spectrum/Correlation Image Sensor (SCIS) are configured in a folded optical system design on the base of small block of glass or optical plastic to reduce the overall processor size.

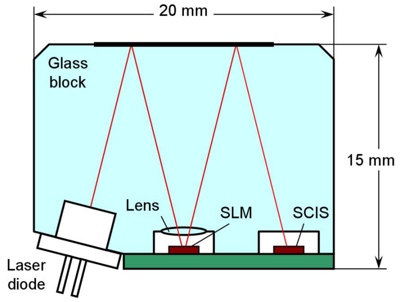

Fig. 5. Optical correlator layout

The operation differs slightly from the standard JTOC design as sketched in Figure 2. In the folded design the coherent light, emitted by a laser diode, reflects from the aluminized side of the block and illuminates the SLM surface via the embedded lens (can be formed as a spherical bulb on the surface of the block). The phase of the wave front reflected from the SLM, is modulated by the input image. It is focused by the same lens and forms (after intermediate reflection) the amplitude image of the Fourier spectrum of input image on the SCIS surface. After a second optical Fourier transform, the correlation image is obtained. The optical flow vector (equal to the shift between the correlated fragments) is calculated from the correlation peaks positions within the correlation image. This operation can be performed directly inside the SCIS chip. Using unpackaged optoelectronic components and Chip On Board (COB) mounting technology, the whole optical system can be realized within the volume of 6 x15 x 20 mm.

The optical correlator module will be mounted together with the input image sensor (unpackaged) and FPGA chip (compact BGA package) on a single printed board in the aluminum housing. The external dimensions of the housing (without lens mount protrusion) will be within 40 x 25 x 15 mm, the total mass of the OF sensor (without lens) will be within 30 g. Dimensions and mass can be further reduced by using an unpackaged FPGA chip. Power consumption during operation is expected to be below 1 W.

V. SIMULATION EXPERIMENTS

A. Test setup

To prove the feasibility of the proposed optical flow processor and to estimate the expected performances, a high fidelity software model of the proposed optical flow processor has been developed and tested. It includes the detailed model of the complete processing chain of the optical correlator. The correlator simulation model has been developed to process pairs of simulated navigation camera images and to produce the optical flow fields with required density. Image processing algorithms simulate all relevant operations of the opto-electronic 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.).

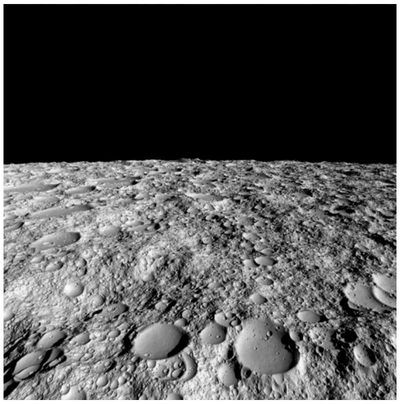

Fig. 6. Synthetic 3D scene for testing and performance evaluation

Testing has been performed using simulated images from synthetic 3D scenes of a planetary surface generated during an ESA study on the visual navigation of a planetary landing vehicle [19]. The images contain parts of rich texture as well as flat low texture regions and dark shadows. The image sequence of an inclined landing trajectory (example image see Figure 6) has been generated on base of a 3D model of the landing site using standard ray tracing software considering the following parameters of the navigation camera:

1. Modulation Transfer Function (MTF) of the optics: 0.6 at Nyquist frequency
2. MTF of the image sensor has been simulated by down sampling (binning) of the large initially rendered image
3. Photonic noise has been simulated assuming the average brightness of the image to be 13000 electrons
4. Readout noise: $\sigma = 40$ electrons
5. Pixel response non-uniformity: $\sigma_{PRNU} = 2\%$
6. Discretization: 10 bits.

B. Estimation of effect of correlation window size on optical flow accuracy

The main goal of this test was the determination of the optimal window size of navigation image fragments to be correlated for optical flow determination.

The dimensions of correlated fragments determine the accuracy and reliability of correlation. Larger window size improves the reliability of the optical flow determination in poorly textured image areas and reduces the errors of the obtained OF vectors. At the same time, increasing the correlated fragments size will smooth the obtained OF field, it will suppress small details and it will produce additional errors in areas with large variations of local depth.

During the tests the window size has been determined, making the best compromise between the accuracy/reliability of correlation and preservation of small details of the underlying 3D scene.

The OF field has been determined with correlated fragments size varying in the range from 8x8 to 64x64 pixels and was compared with a reference (ideal) OF field to determine the correlation errors. The reference OF field has been produced directly from reference trajectory data and the known 3D model of the landing site.

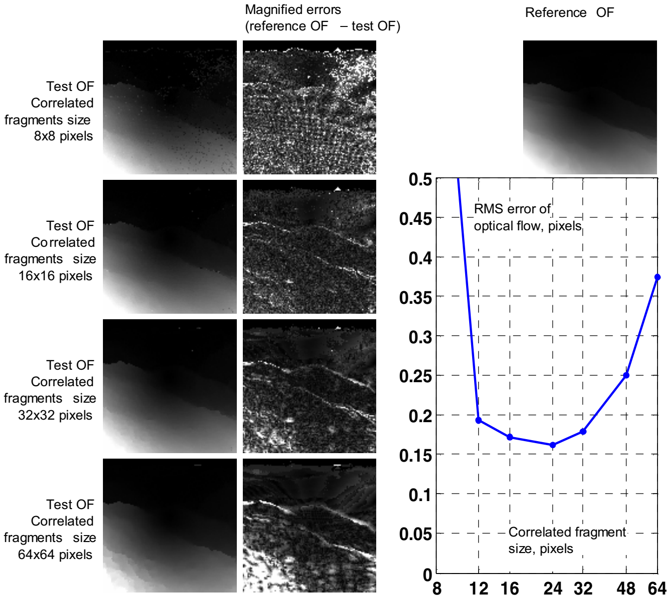

Fig. 7. Results of the optical flow sensitivity w.r.t. correlation window size

Figure 7 shows the results of the optical flow accuracy sensitivity with different correlation window sizes. Images in the left column represent the 2D patterns of the OF vectors magnitudes, the middle row contains the errors patterns, determined as a difference between the reference (ideal) and test OF fields. RMS error values are shown in the diagram at the bottom right corner.

According to this sensitivity analysis, minimal OF errors correspond to a window size of 24x24 pixels.

C. Estimation of correlator performance requirements

1) Optical flow sampling distance – density of OF field: 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 a window having the same size as the correlated fragment. Figure 8 shows the frequency response of such filtering, corresponding to a correlated fragment size of 24x24 pixels. The main lobe of the filter characteristic is limited by the spatial frequency 1/24 pixel^{-1}. According to the sampling theorem, such frequency range requires a sampling frequency of 1/12 pixels^{-1} or sampling distance of 12 pixels.

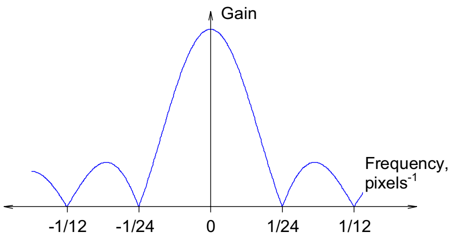

Fig. 8. OF field filtering with correlation window size 24x24 pixels

Based on these considerations, the optical flow sampling distance of 12 pixels (1/2 of correlated fragment size) has been selected as optimal for the OF field, produced with correlation window size of 24x24 pixels. This allows to produce a rather dense OF field even for image regions with flat texture.

2) Correlations rate: Considering the image processing rate of 10 frames per second, camera frame size of 792x792 pixels and OF sampling distance of 12 pixels, as a result 64x64 = 4096 OF vectors per frame and 40960 correlations per second are required.

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

The main goal of this test was to estimate the optical correlator sensitivity to additive and multiplicative input image noise.

To determine the correlator error dependency on the input image noise, a random noise pattern has been added to the input images (additive noise simulation) as well as input images have been multiplied by 1 plus fixed random noise pattern (simulation of multiplicative fixed pattern noise). All relevant sources of noise in the real imaging process like readout noise, dark current noise, photonic noise or pixel response non-uniformity (PRNU) can be interpreted as combination of these two simulated types of noise. The OF field has been determined with correlated fragments size 24x24 pixels and sampling distance 12 pixels and compared to a reference (ideal) one, derived directly from the reference trajectory data and the known 3D model of the landing site.

The results of the optical flow sensitivity to image noise are shown in Figure 9 for additive noise and in Figure 10 for multiplicative fixed pattern noise added to the input images.

The noise value varied from $\sigma = 0.5\%$ to $\sigma = 32\%$ of average image brightness.

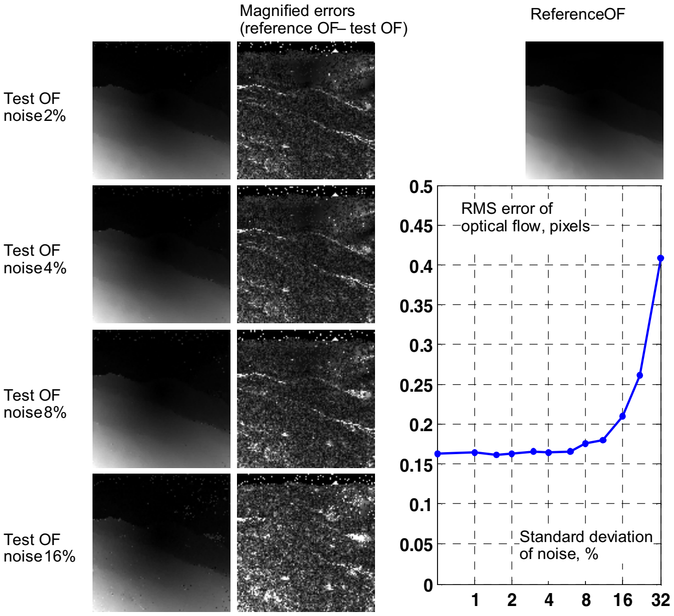

Fig. 9. Results of the optical flow sensitivity w.r.t. additive image noise (correlation window size 24x24 pixels)

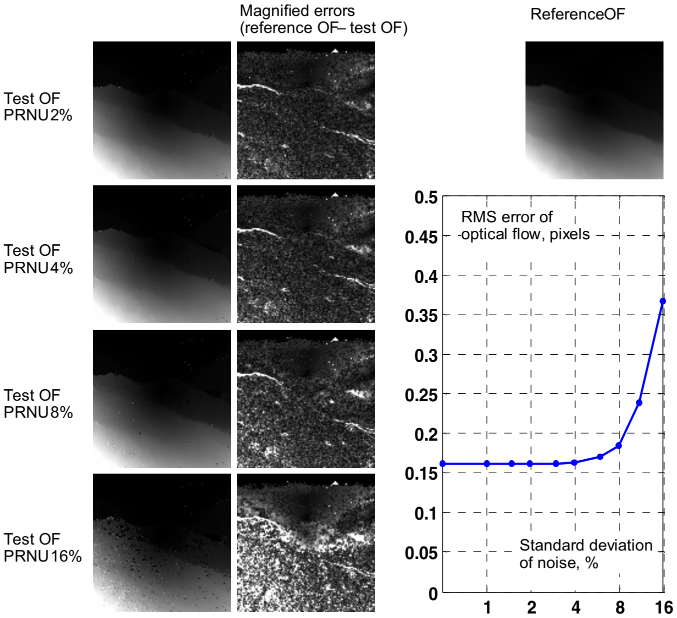

Fig. 10. Results of the optical flow sensitivity w.r.t. multiplicative image noise (correlation window size 24x24 pixels)

Images in the left column represent the 2D patterns of the OF vectors magnitudes, the middle column contains the errors patterns, determined as a difference between the reference (ideal) and test OF fields. RMS error values are shown in the diagram at the bottom right corner.

Figure 9 shows, that additive noise with standard deviation within 12% of average image brightness has little influence on the OF field accuracy. Starting from $\sigma = 12\%$, 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 24x24 can be set to $\sigma = 12\%$ of average image brightness.

The effect of multiplicative noise is very similar to that of additive noise. According to Figure 10, the limit of acceptable multiplicative image noise (PRNU) for optical flow determination with fragments size 24x24 can be set to $\sigma = 6\%$ of average image brightness.

VI. EXPECTED PERFORMANCES

Expected performances of the optical flow processor (Table 1) have been estimated on the base of the conceptual design of the processor and results of simulation experiments, taking into account also the test results of the existing hardware models of the optical correlator made within previous studies [14,15].

TABLE 1. EXPECTED PERFORMANCES OF OPTICAL FLOW PROCESSOR

Input	3D scene
Output	optical-flow fields
Optical-flow resolution (max)	64x64=4096 vectors/field
Optical-flow resolution (min)	8x8=64 vectors/field
OF fields rate @ 4096 vectors/field	10 fields/s
OF fields rate @ 64 vectors/field	500 fields/s
Processing delay	One frame (0.002 … 0.1 s)
Inner correlations rate	50000 correlations/s
OF vectors determination errors	$\sigma = 0.1 \ldots 0.25$ pixels
OF processor dimensions	40x25x10 mm (w/o camera)
OF processor mass	within 25g
Power consumption	within 1 W

For mobile robotic and space applications it is however important to evaluate a performance measure related to mobility, which takes into account also the processor power consumption and volume related to the computing performance in terms of flow vectors per second and accuracy.

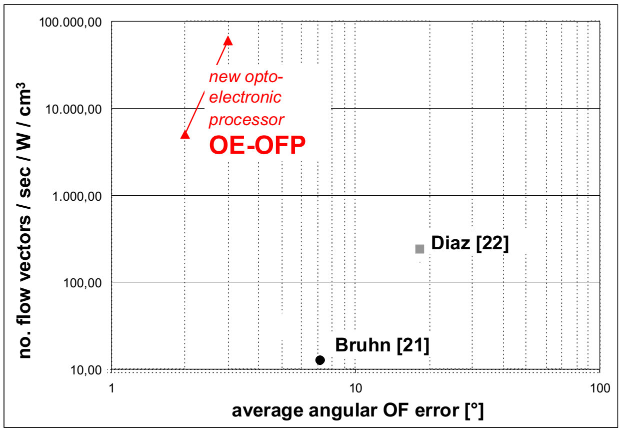

Fig. 11. Performance-to-mobility comparison of optical flow processors

Figure 11 shows these performance-to-mobility measures taking into account also the power consumption and the volume of the optical-flow processor module. It follows that the proposed opto-electronic optical flow processor design (OE-OFP) shows unique performances in comparison with the fastest digital optical-flow computation solution currently available (Bruhn [21]; Diaz [22])

VII. APPLICATION AREAS

The proposed optical flow processor is intended to be used mainly in the field of visual navigation of mobile robots (ground, aerial, marine) and space flight (satellites, landing vehicles). The small size, mass and power consumption makes the proposed OE-OFP particularly suitable for application onboard micro air vehicles (MAVs).

From the obtained optical flow, 3D information can be extracted and a 3D model of the visible environment can be produced. The relatively high resolution (up to 64x64 OF vectors) and very high accuracy (errors $\sigma < 0.25$ pixels) of the determined optical flow makes such 3D environment models detailed and accurate. This 3D environment models can be used for 3D navigation in complex environment [18] and also for 3D mapping, making the proposed OF processor ideally suited for 3D SLAM. The applicability of the optical flow data derived with the proposed principles (joint transform correlation) and technology (optical correlator) to real world navigation solutions even under unfavorable constraints (inclined trajectories with considerable large perspective distortions) has been proved by the authors in recent work [19,20].

The anticipated real time performance of the processor (10 frames/s) provides a wide range of opportunities for using the obtained optical flow for many additional tasks beyond localization and mapping, e.g. vehicle stabilization, collision avoidance, visual odometry, landing and take-off control of MAVs.

VII. SUMMARY AND CONCLUSIONS

The conceptual design of an advanced embedded optical flow processor has been presented. Preliminary performance evaluation based on a detailed simulation model of the complete optical processing chain shows unique performances in particular applicable for visual navigation tasks of mobile robots. The detailed opto-electronic design work is currently started.

REFERENCES

[1] B.K.P. Horn, B.G. Schunck: "Determining Optical Flow", *Artificial Intelligence* 17 (1981), pp. 185-203.

[2] S.S. Beauchemin, J.L. Barron: "The computation of optical flow", *ACM Computing Surveys (CSUR)*,vol. 27, no. 3, pp. 433 – 466, September 1995.

[3] A. Bruhn, J. Weickert, C. Feddern, T. Kohlberger, C. Schnörr: Real-Time Optic Flow Computation with Variational Methods, *CAIP* 2003, *LNCS* vol. 2756, pp. 222-229, 2003.

[4] B. Galvin, B. McCane, K. Novins, D. Mason, S. Mills: "Recovering Motion Fields: An Evaluation of Eight Optical Flow Algorithms", *Proceedings of 9th British Machine Vision Conference*, pp. 195-204, Southampton, Great Britain, 1998.

[5] B. McCane, B. Galvin, K. Novins: "On the Evaluation of Optical Flow Algorithms", *Proceedings of 5th International Conference on Control, Automation, Robotics and Vision*, Singapur, 1998, pp. 1563-1567.

[6] H. Liu, T.H. Hong, M. Herman, T. Camus, R. Chellappa. "Accuracy vs Efficiency Trade-offs in Optical Flow Algorithms", *Computer Vision and Image Understanding*, vol. 72, no. 3, pp. 271-286, 1998.

[7] D.G. Lowe: "Object recognition from local scale invariant features". *Proceedings of the Seventh International Conference on Computer Vision (ICCV'gg)*, Kerkyra, Greece, September 1999, pp. 1150-1157.

[8] S. Se, D.G. Lowe, J. Little: "Vision-based mobile robot localization and mapping using scale-invariant features", *Proceedings 2001 ICRA - IEEE International Conference on Robotics and Automation*, vol. 2, pp. 2051 – 2058, 2001.

[9] G. Barrows, C. Neely: "Mixed-mode VLSI optic flow sensors for in-flight control of a micro air vehicle", *Proc. SPIE Vol. 4109, Critical Technologies for the Future of Computing*; pp. 52-63, 2000.

[10] J.C. Zufferey: "Bio-inspired Vision-based Flying Robots". Thèse n° 3194, Faculté Sciences et Techniques de l'Ingénieur, EPFL, 2005.

[11] W.K. Pratt: "Correlation techniques of image registration", *IEEE Transactions on Aerospace Electronic Systems*, vol. 10, pp. 353-358, May 1974.

[12] S. Jutamulia: "Joint transform correlators and their applications", *Proceedings SPIE*, 1812 (1992), pp. 233-243.

[13] J.W. Goodman: *Introduction to Fourier optics*. McGraw-Hill, New York 1968.

[14] Tchernykh, V., Dyblenko, S., Janschek, K., Seifart, K., Harnisch, B.: "Airborne test results for a smart pushbroom imaging system with opto-electronic image correction", *Sensors, Systems and Next-Generation Satellites VII, Proceedings of SPIE*, vol. 5234 (2004), pp.550-559.

[15] K. Janschek, V. Tchernykh, S. Dyblenko: "Opto-Mechatronic Image Stabilization for a Compact Space Camera", *Preprints of the 3rd IFAC Conference on Mechatronic Systems - Mechatronics 2004*, 6-8 September 2004, Sydney, Australia, pp.547-552.
Congress Best Paper Award, invited/submitted/accepted paper for Control Engineering Practice.

[16] V. Tchernykh, K. Janschek, S. Dyblenko: "Space application of a self-calibrating optical processor or harsh mechanical environment", *Proceedings of 1st IFAC Conference on Mechatronic Systems - Mechatronics 2000*, September 18-20, 2000, Darmstadt, Germany. Pergamon-Elsevier Science. vol. 3, (2000), pp.309-314.

[17] K. Janschek, V. Tchernykh, S. Dyblenko: „Verfahren zur automatischen Korrektur von durch Verformungen hervorgerufenen Fehlern Optischer Korrelatoren und Selbstkorrigierender Optischer Korrelator vom Typ JTC", Deutsches Patent Nr. 100 47 504 B4, Erteilt: 03.03.2005.

[18] K. Janschek, V. Tchernykh, M. Beck: "Optical Flow based Navigation for Mobile Robots using an Embedded Optical Correlator", *Preprints of the 3rd IFAC Conference on Mechatronic Systems - Mechatronics 2004*, 6-8 September 2004, Sydney, Australia, pp.793-798.

[19] K. Janschek, V. Tchernykh, M. Beck: "An Optical Flow Approach for Precise Visual Navigation of a Planetary Lander", *Proceedings of the 6th International ESA Conference on Guidance, Navigation and Control Systems*, 17 – 20 October 2005, Loutraki, Greece.

[20] V. Tchernykh, M. Beck, K. Janschek: "Optical flow navigation for an outdoor UAV using a wide angle mono camera and DEM matching", submitted to 4th IFAC Symposium on Mechatronic Systems – Mechatronics 2006, Heidelberg, Germany.

[21] A. Bruhn, J. Weickert, C. Feddern, T. Kohlberger, C. Schnörr: "Variational Optical Flow Computation in Real Time", *IEEE Transactions on Image Processing*, vol. 14, no. 5, May 2005

[22] J. Díaz, E. Ros, F. Pelayo, E.M. Ortigosa, S. Mota: "FPGA-Based Real-Time Optical-Flow System", *IEEE Transactions on Circuits and Systems for Video Technology*, vol. 16, no. 2, February 2006