Pre-processing for Multidimensional Spatial Filtering Technique

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Abstract Spatial filtering technique is widespread used point-like one component velocity measurements. Although the calculation steps to get the spatial filtering signal are quiet simple (multiplying and adding). The paper describes the application for multidimensional measurements. For this, different setups for spatial filtering measurements are presented, to show possibilities how pre-processing can be done. In spatial filtering technique, by means of array detectors (CCD or CMOS), the bottleneck is the read out of the Sensor. Pre-processing can be done by summing up pixel grey values on-chip for data compression. The paper presents, after an introduction to the spatial filtering technique, a smart pixel Sensor witch sums up pixels rows and columns on-chip. Frame rate up to 3200 Frames per second are reachable. For two dimensional measurements this Sensor is arranged in an array of sensors where every sensor it selves forms an interrogation area like in Particle Image Velocimetry (PIV). The control of the array is made by a field programmable gate array (FPGA). Sensor data can be read out and the spatial filtering signals can be calculated parallel. Another concept for pre-processing is the use of a digital light processing (DLP®) mirror array. The electrically controllable mirrors can form a grid. Reflected light can be collimated on a photodiode. The mirror array already performs the pre-processing in the receiver path.

1. Introduction

In a wide range of applications the determination of the velocities is of high interest. Beside the measurement of flow velocities also surface velocities are measured optically in a number of industrial processes. In some cases point wise measurement techniques like Laser Doppler (Albrecht, Borys, et al. 2003) are sufficient. Whereas the laser Doppler technique is used for point like flow velocity estimation the spatial filtering technique is used for point-like estimation of solid surface velocities and length, as paper web and rolling stock. Because of high data rates and limited number of detectors these techniques have the potential of real time measurements.
Camera systems are used for one- or multi-dimensional measurements, like in Particle Image Velocimetry (PIV) (Raffel, Willert, et al. 2007). An observed scene is illuminated by a laser light sheet or for 3D/3C measurements by a volumetric illumination. The exposure time is given by the pulse duration of the laser or LED. The pictures of the scene are captured by special PIV double frame cameras or by high speed cameras.
For low frame rate of about 50 double-frames per second or less (depending on the resolution) the images can be transferred to the computer and processed directly by e.g. cross correlation analysis or particle tracking in real time. In some cases the processors of the graphic card can be used for speed up the calculation for large images (Tarashima, Tange, et al. 2010). There are two concepts for time resolved measurements. In one case a double frames with higher repetition rate (above 50Hz) can be processed by two frame cross correlation. The higher repetition rate of the double frames must be adapted to the dominant process frequencies. In the second concept the repletion rate of the camera is high enough (e.g. >1kHz) for continuously observation of the process and

analysis can be done for two or more consecutive frames. The last-mentioned technique allows the reconstruction of particle trajectories.
There are two bottlenecks for real time processing of high resolution time resolved image data. First of all the image date must be read out from the sensor chip and transferred to memory for further processing. Because of internal capacities the pixel clock for standard CCD arrays is limited to about 50MHz. Therefore the frame rate for a 1 megapixel CCD camera is limited to 50Hz. In case of high speed CMOS sensors e.g. (Cremers, Agarwal, et al. 2009) the read out is quasi parallel and the grey values of the pixels are stored in an internal memory of a camera. For 1kHz frame rate and 1 megapixel one GByte data must be saved in one second. Afterwards the read out time is limited by the transfer channel, e.g. a Gigabit Ethernet connection, and take generally much longer than the image acquisition.
The second bottleneck is referred to the image processing and velocity estimation. In case of multi-dimensional time resolved velocity measurements several gigabytes of image data must be analyzed per second. Image processing by standard routines as cross correlation and feature tracking easily exceed the capacity of standard computer and graphic cards.
The present contribution decreases both bottlenecks by using smart pixel sensors and digital micromirror devices (DMD®) for image acquisition and spatial filtering technique for optimized real time velocity estimation.
Spatial filtering velocimetry was first described by (Ator 1963) and compared to optical correlation (Ator 1966). First measurement systems for determination of flow velocities use transmission gratings in the receiver path (Aizu, Ushizaka, et al. 1986). Other sensor realizations use lenticular gratings (lens arrays) (Hanson, Jakobsen, et al. 2005) or fiber optics (Petrak and Rauh 2009). A further way is the use of structured array detectors (CMOS or CCD) where the characteristic of the grating can be adapted to the process (Fiedler, Kumpart, et al. 1996, Schaeper, Menn, et al. 2008). After a short description of the spatial filtering technique by using two-dimensional structured detectors two sensor concepts and first measurements will be presented.

2. Spatial filtering velocimetry by structured detectors

2.1 Principle

The one dimensional spatial filtering technique uses a structured spatial filter in the image plane of an optical system. Generally the one dimensional image $i(x)$ is weighted by the spatial filter $g(x)$ and the signal is generated by integration or sum over the whole image.

$$s = \int i(x) g(x) \tag{1}$$

For moving structures the image moves by the velocity v, which is equal to a displacement of vt

$$s(t) = \int i(x - vt) g(x) \tag{2}$$

A simple 0D-1C configuration with an optical hardware grating can be seen in Figure 2.1a. Generally instead of hardware gratings structured array detectors are used in commercial instruments. For point-like (0D) and one component (1C) systems with a CCD-line the integration over the grating is directly accumulated by special timing of the CCD during the read out (Schulz and Fiedler 1985). For two-component sensors usually two dimensional array sensors are used, as CCD or CMOS image sensors. The desired spatial filter is realized by multiplying the grating function with the pixels grey values (Bergeler and Krambeer 2004). The signal generation by the structured grating can be written as

$$s(t) = \sum_n i_n(t) g_n \tag{3}$$

Here $i_n(t)$ is the time dependent value of pixel n and g_n is the weighting factor of the grating function for pixel n. A 0D-1C spatial filter based on a structured detector can be seen in Fig. 2.1b. Because the pixel can be weighted also by negative values a mean free signal can be generated by such a differential spatial filter.

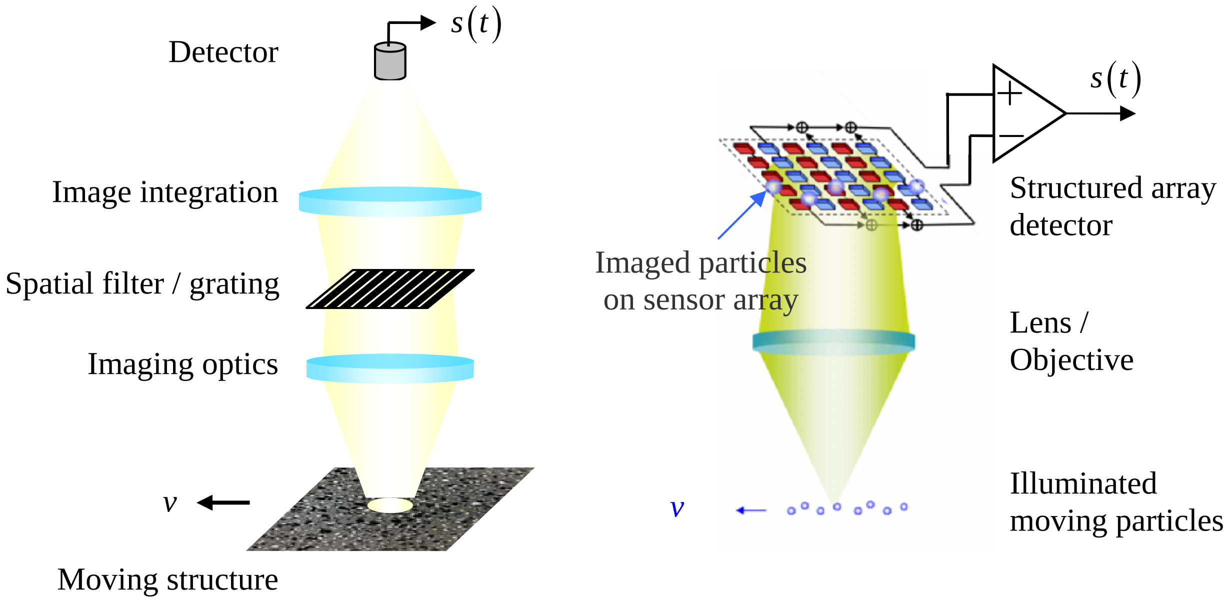

Figure 2.1: a) left: Spatial filtering system with hardware grating, b) right: implementation of a differential grating using structured array detectors.

Typical signals are given in Figure 2.2. The solid curve corresponds to a cosine grating, whereas the dotted curve is generated by a sine grating, which is orthogonal to the cosine one.

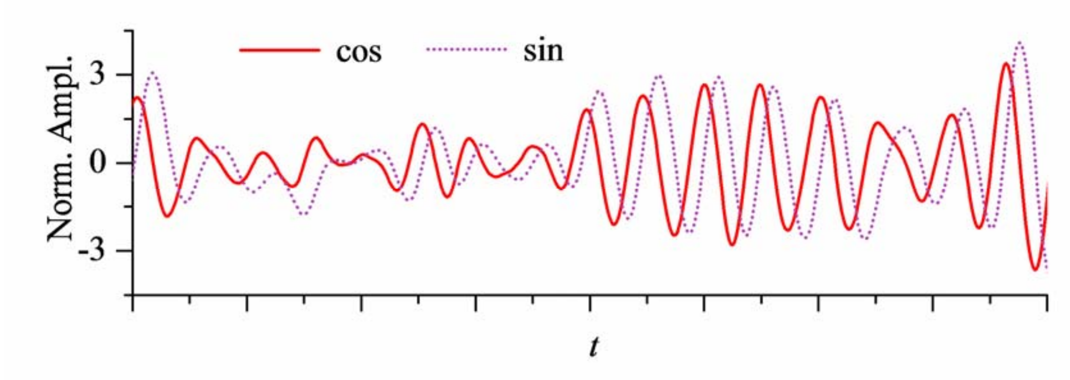

Figure 2.2: Typical signal from two orthogonal harmonic spatial filters.

The frequency f_0 of the signal $s(t)$ is proportional to velocity of the observed structure and can be calculated from the magnification of the optical system M and the spatial Period G of the grating

$$v = \frac{f_0 G}{M} \tag{4}$$

By applying a second 90 degree rotated grating a second velocity component can be measured and the 2C velocity vector is given by

$$|v| = \sqrt{v_x^2 + v_y^2} \quad ; \qquad \varphi_v = \arg(v_y + \mathrm{j}v_x) \tag{5}$$

Similar to PIV technique the spatial filter can be applied to several interrogation areas in a captured image sequence. Therefore 2D-2C velocity fields can be measured.
The advantage of spatial filtering technique is the simple signal generation. As seen in Eq. (3) each pixel has to be multiplied by a weighting factor and all pixels have to be summed after. In case of horizontal and vertical gratings on a two dimensional array detectors the weights are identically in each column (c) and row (r). Therefore the multiplication can be done after the pixel sum

$$s(t) = \sum_r \left(g_r \sum_c i_{c,r}(t) \right) \tag{6}$$

The complexity for M images with N^2 pixels reduces to $O(MN^2)$ instead of $O(MN^2 \log(N))$ for standard PIV correlation processing by FFT or $O(MN^4)$ for DFT processing.

2.2. System description

As given in Eq. (2) the temporal depending image information is weighted by the grating. The integral can be interpreted as a correlation of the image and the grating. By using simple harmonic gratings, e.g. a cosine function, Eq (2) can be written as

$$s(t) = \int i(x - vt)\cos(kx)\,\mathrm{d}x = a_k(t) \quad ; \qquad k = \frac{2\pi}{G} \tag{7}$$

where the signal is the time dependent Fourier coefficient of the even cosine function with spatial frequency k. In a similar way sine gratings can applied and the complex signal for a grating with spatial frequency k is the time dependent complex Fourier coefficient of the moving structure

$$\begin{aligned} \underline{s}(k,t) &= \int i(x - vt)\exp(-\mathrm{j}kx)\,\mathrm{d}x \\ &= \Im\{i(x - vt)\}_k = \Im\{i(x)\}_k \exp(-\mathrm{j}kvt) \end{aligned} \tag{8}$$

The index k specify that only one Fourier coefficient is used for complex signal generation. A shift of the image in the time domain by vt is expressed by a phase shift, which corresponds to a rotation of the complex pointer in the exponential function by $-kvt$. Therefore the spatial filtering technique with harmonic gratings directly generates one complex Fourier coefficient. The image movement is transformed to the rotation speed of the complex pointer and the phase evolution of the coefficient is directly proportional to the velocity.

The same analysis can be done for two dimensional images or separate interrogation areas. In this case one spatial harmonic filter is given by

$$\begin{aligned} \underline{s}(\mathbf{k},t) &= \int i(x-v_x t, y-v_y t)\exp\left(-\mathrm{j}\mathbf{k}\cdot\mathbf{p}\right)\mathrm{d}x\,\mathrm{d}y \\ &= \Im\left\{i(x,y)\right\}_{k_x,k_y}\exp(-\mathrm{j}\mathbf{k}\cdot\mathbf{v}t) \end{aligned} \qquad (9)$$

Where $\mathbf{k}$ is the two dimensional vector describing the spatial frequency and $\mathbf{p}$ is the variable point vector

$$\mathbf{k} = \begin{pmatrix} k_x \\ k_y \end{pmatrix} = k\begin{pmatrix} l \\ m \end{pmatrix} \; ; \qquad \mathbf{p} = \begin{pmatrix} x \\ y \end{pmatrix} \; ; \qquad \mathbf{v} = \begin{pmatrix} v_x \\ v_y \end{pmatrix} \qquad (10)$$

A special harmonic grating is sensitive for velocities parallel to the directional cosines l and m of the spatial frequency vector.
In case of two-dimensional images a harmonic spatial grating generates one temporal dependent Fourier coefficient in the Fourier domain. The velocity can be estimated by the phase evolution of the complex pointer. The described analogy between spatial filters and Fourier transform explains the advantage of the spatial filtering technique in comparison to standard PIV cross correlation processing. Where the PIV technique uses the complete Fourier transform of every interrogation area to calculate to correlation, the spatial filtering technique estimates only one Fourier coefficient, which becomes much more efficient. Nevertheless the choice of a representative coefficient depends strongly on the spectral characteristic of the images and the spatial filter. Because perfect harmonic gratings cannot be realized, each grating includes further harmonics, which must be suppressed or considered.

2.3 Signal processing

As shown in paragraph 2.1 the signal frequency is proportional to the velocity of the image. The frequency estimation can be implemented by a number of methods. In commercial 0D-1C instruments zero crossing algorithms with different trigger levels are implemented. The advantage is a simple hardware realization, which can handle signals up to several MHz in real time. The temporal resolution depends on the signal frequency and is generally in the order of several periods for reliable frequency estimation.
Also a Fourier transform of the signal given in Fig. 2.2 is possible. The window must be adapted to the length of stationary harmonic signals and is therefore connected to the autocorrelation function of the image itself. One disadvantage of the Fourier transform is a jagged spectral peak function in the power spectral density (PSD) as can be seen in Fig 3.3. It results from the phase jumps in the signals and the temporal changing superposition of different harmonic function with same frequency but different phases.
A third possibility is given in Eqs. (8) and (9). The rotating speed of the complex pointer, which is equal to phase changes for equidistant sample times, is a measure for the velocity. The orthogonal signal pairs can be generated by orthogonal gratings, e.g. sine and cosine function, or by Hilbert transform from one signal. The advantage of the orthogonal signal generation is the high temporal resolution, which is equal to the sample rate. Nevertheless the noise increases for high temporal resolution and limits the application to processes with high SNR.
In the following setups mainly the Fourier transform is used for frequency estimation.

3 Hardware implementation for 2D-2C measurements

3.1 Time resolved setup

To compare the spatial filtering velocimetry with standard time resolved 2D-2C cross-correlation PIV-system the setup in Fig 3.1 was used.

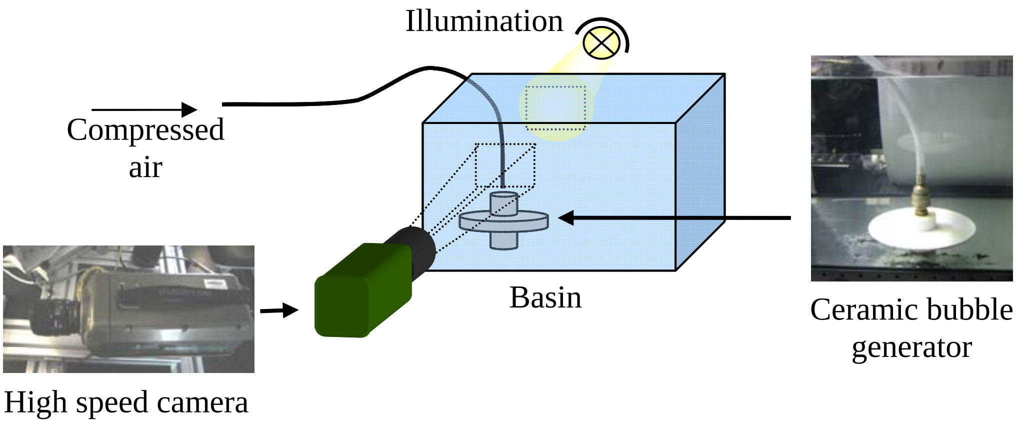

Figure 3.1: Measurement setup for observing bubbles in a water basin

In a water filled basin air bubbles were generated by a ceramic bubble generator. The flow was illuminated by a 12V halogen lamp with diffusor from the backside. Pictures of the scene were taken with a Phantom V12.1 camera from Vision Research. The camera has a resolution of 1280×800 Pixels and was running with a frame rate of $100\ \mathrm{Hz}$. The images were processed with standard PIV software from DantecDynamics and with spatial filtering technique. In a second experiment small tracer particles was used and the frame rate of the camera were increased to $1\mathrm{kHz}$.
In Figure 3.2 mean velocity values of one bubbly flow sequence are shown. The vertical black bar is the air tube for the ceramic bubble generator. Interrogation areas of 64x64 pixels size were used. A first analysis was made with commercial cross-correlation algorithm. The blue arrows in figure 3.2 show the mean values of 1024 single results. For the same sequence of 1024 frames spatial filtering velocimetry was applied. The size of spatial grating period G (in x and y direction respectively) was 16 Pixels. All velocities in each interrogation area were determined by using the power spectral density (PSD) distribution of each spatial filtering signal. The final velocity and direction was calculated by Eq. (5). The comparison between particle image velocity and spatial filtering velocimetry shows comparable results. Differences of the vector length are caused by the different processing tools. Only some minor differences are in the velocity directions.
The PSD distribution of the spatial filtering signal, shown in Fig. 3.3 for one interrogation area of the whole sequence, gives information about the mean frequency (peak of PSD) and about distribution of frequencies. The latter one represents velocity fluctuations and is connected with turbulence.

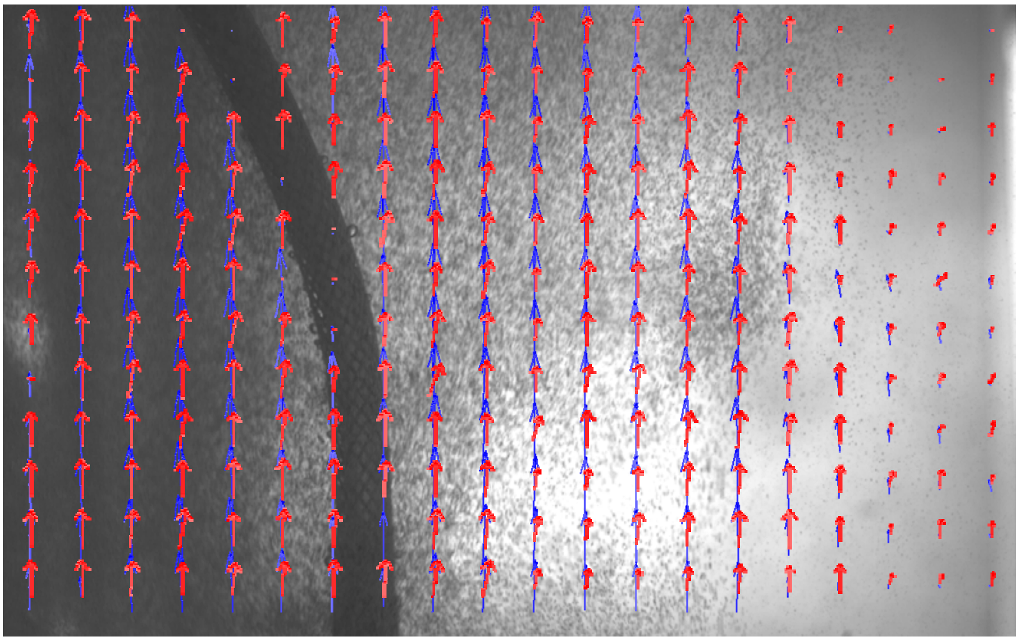

Figure 3.2: Observed bubbles in the water basin (blue arrows: mean of 1024 cross-correlation results, red arrows: results of same sequence using the PSD peak of spatial filtering signals)

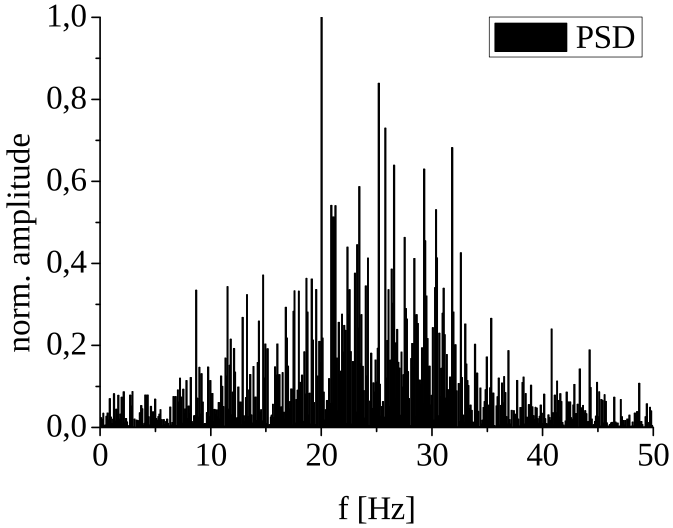

Figure 3.3: PSD of spatial filtering signal in vertical direction

The example shows, that the spatial filtering velocimetry can be used for 2D-2C determination of velocity fields. The main advantage is the reduced number of operations. As described in paragraph 2 for each interrogation area all pixel rows and columns are summed. This reduces the number of information from $N_{ROI}XY$ pixel grey values down to $N_{ROI}\left(X+Y\right)$ values by using only two operations per pixel. Here N_{ROI} represents the number of interrogation areas. In the presented example the $64\times 64=4096$ pixels of each interrogation were compressed in the first step down to 128 values. The remaining 30720 value for all 20×12 interrogation areas were weighted by a harmonic function and summed for the spatial filtering signal. Therefore overall 2,078,720 addition operation and 30720 multiplications were used for each image. This corresponds to only 2.06 operations per pixel, which is much less than standard PIV algorithms.

3.2 Array of smart pixel sensors

Already in (Schaeper, Frank, et al. 2007) a sensor was proposed to be suitable for spatial filtering velocimetry. The smart pixel sensor was original made for position detection of light points with 256×256 pixels and a fast continuously read out of 3200 frames per second. The frame rates can be reached by on-chip pre-processing. The pixels rows in x-direction and columns in y-direction are summed up and digital converted internally to 2×256 single rows and columns values. So this sensor holds a feature for real time measurements using spatial filtering velocimetry, because the first most complex signal generation step is already integrated in the hardware. The values of rows and columns have to be weighted by a given grating function. These values have to be summed up for each direction to a single point of the time dependent spatial filtering signal $s(t)$.

In (Schaeper, Kühn, et al. 2011) first time an array of such sensors was presented. A number of this sensor can be arranged in a matrix for real 2D-2C velocity estimation with $3.2\,\mathrm{kHz}$. Figure 3.4 shows the realized prototype for 16 velocity vectors.

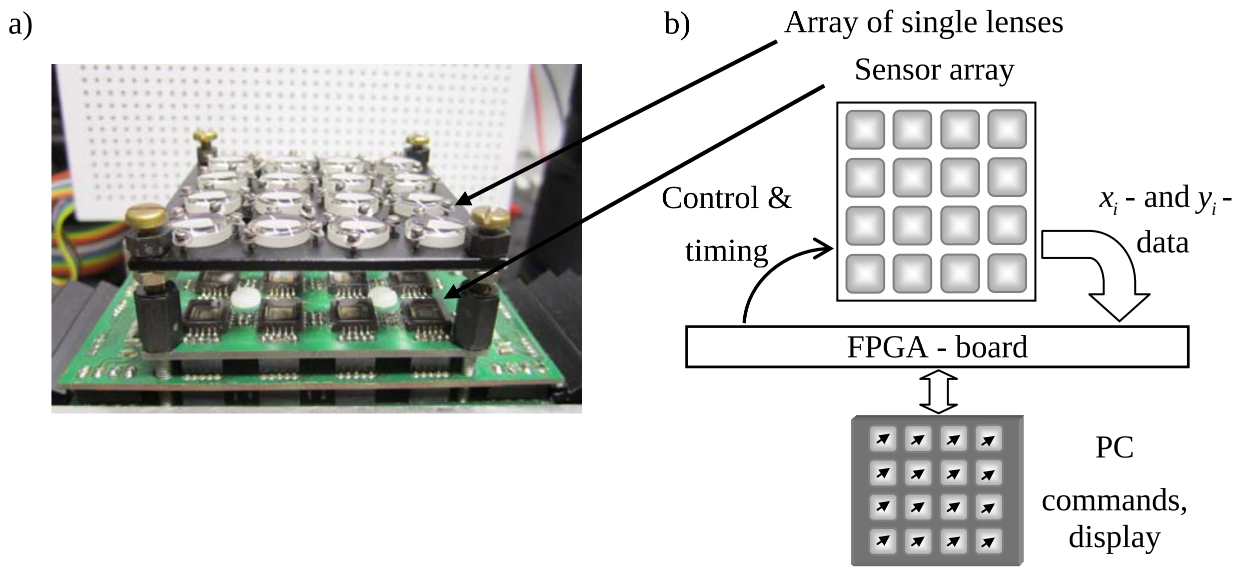

Figure 3.4: Sensor array of smart pixel sensors (a: picture of the sensor array, b: schematic configuration of array sensor)

On the left side in figure 3.4 the hardware realization of the developed sensor array is shown. On the top single lenses arranged to image different interrogation areas. A field programmable gate array (FPGA) board was used to take the timing and control of the sensor array. Furthermore the FPGA realized a parallel read out of the $4\times4\times2\times256$ line values, the weighting by a grating function and the transfer of data via USB. Uncertainties of the sensors position and twist within the array can be reduced by adjusting each lens position and calibration measurements on a surface. Fig. 3.5 shows the developed GUI (Graphical User Interface) for control and real time acquisition.

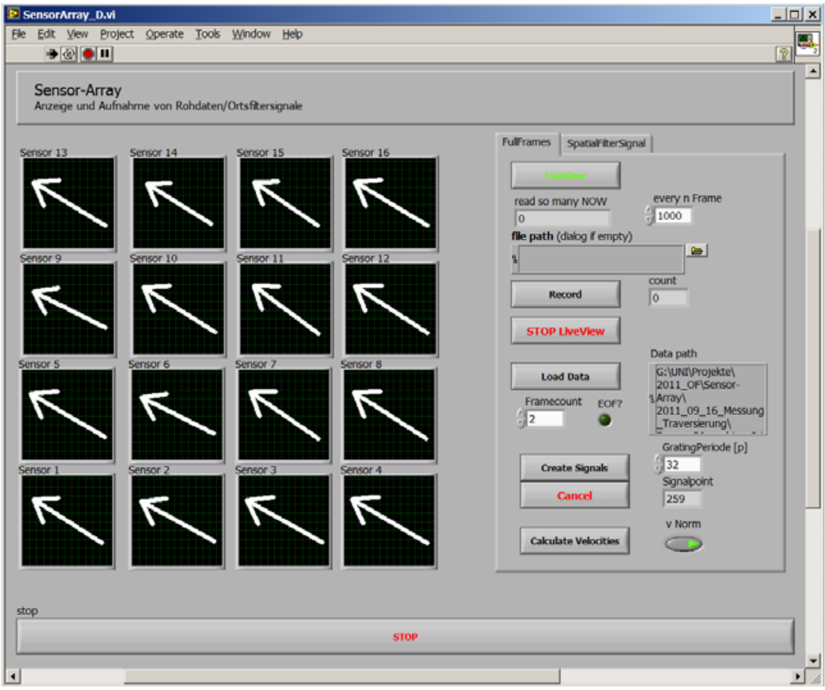

Figure 3.5: GUI of the kHz real time 2D-2C sensor concept.

3.3 Micro mirror array

A second concept study uses micro-opto-electromechanical (MOEM) devices called DLP®. A DLP® device consists of an array of switchable micro mirrors (TexasInstruments 2012). The standard application is the light processing for video projectors. The mirror array has a pixel pitch of $7{,}6\ \mu m$ and a mirror tilt about $\pm 12°$ (TexasInstruments 2009). The number of mirrors can reach several Millions, which corresponds to the pixel number of CCD und CMOS cameras. The mirrors can be switched in several microseconds, which correspond to repetition rates of up to $20\,\text{kHz}$.

In the present case we use the mirror array with a reversed optical path. Figure 3.6 shows the principle, which bases on (Degner, Damaschke, et al. 2011). The imaged scene is directly weighted by the mirror array. Because only two stable mirror positions can be used, the resulting grating is rectangular. The reflected light is collimated on two photodiodes, which realize two spatial filters. A differential signal $s(t)$ of the spatial filter is generated by subtracting the two signals of the photodiodes.

There are several advantages of this concept. First of all the whole signal generation of the spatial filter is optically. Therefore no operations are necessary and the sample rate of the spatial filter is only limited by the photo detectors and the AD converter. A second advantage is the high repetition rate of the mirror state. So different grating functions (e.g. for changing the $90°$ direction of the grating or for shifting of the grating) can be alternating generated with high update rates.

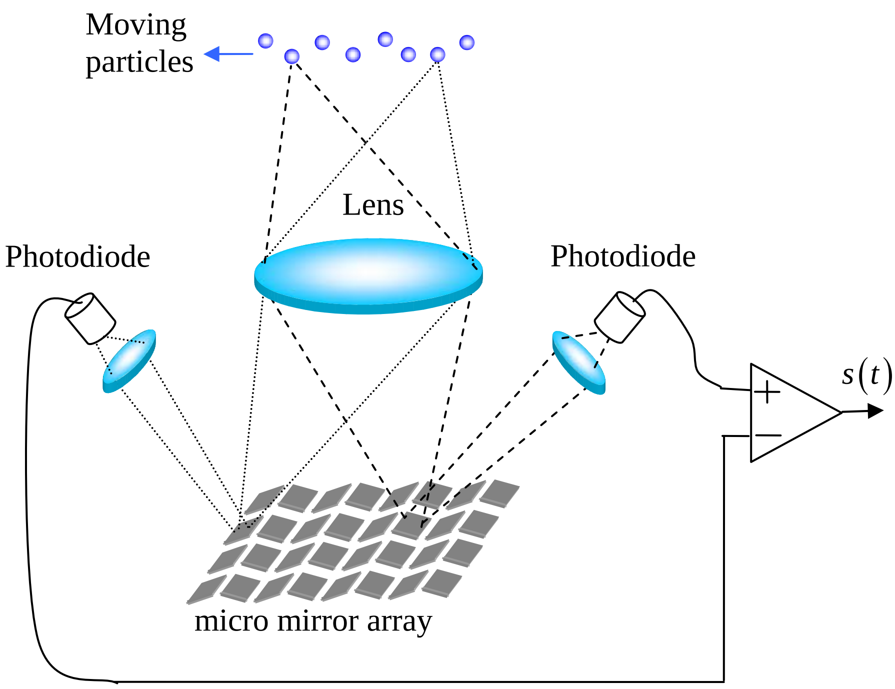

Figure 3.6: Principle of micro mirror array for spatial filtering velocimetry (shown: differential grating)

6. Conclusion

The main problems in time resolved PIV technique is the read out time of the sensor array and the image processing. In the paper two concepts are presented to compress the pixel information by spatial filtering, Smart-pixel sensors and optical integration. We proposed the comparability of standard PIV and multidimensional spatial filtering velocimetry using structured array detectors. Spatial filtering can be used instead of cross-correlation for much faster analysis of moving intensity distributions. So real time analysis pictures can be implemented. When using two 90° shifted grids for each direction a phase based algorithm can be used to estimate the displacement frame to frame. Furthermore we proposed the use of a micro mirror device for inherent data compression in the optical path.

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