Low-Latency Shack–Hartmann Wavefront Sensor Based on an Industrial Smart Camera

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Abstract—Wavefront sensing is important in various optical measurement systems, particularly in the field of adaptive optics (AO). For AO systems, the sampling rate, as well as the latency time, of the wavefront sensors (WFSs) imposes a restriction on the overall achievable temporal resolution. In this paper, we propose a versatile Shack–Hartmann WFS based on an industrial smart camera for high-performance measurements of wavefront deformations, using a low-cost field-programmable gate array as the parallel processing platform. The proposed wavefront reconstruction adds a processing latency of only 740 ns for calculating wavefront characteristics from the pixel stream of the image sensor, providing great potential for demanding AO system designs.

Index Terms—Algorithms, cameras, field-programmable gate arrays (FPGAs), image sensors, optical distortion.

I. INTRODUCTION

IN MANY OPTICAL imaging systems, the image quality is diminished by undesired aberrations. Wavefront aberrations occur when light passes through optical heterogeneous paths, such as turbulent atmosphere [1] or heating haze [2]. A measured wavefront contains information of the optical path differences (OPDs) with respect to, e.g., an ideally plane wavefront, spatially distributed over the sensing area. Such wavefront deviations are classified as wavefront aberrations throughout the following discussion. The measurement of the wavefront can be used to characterize the translucent media or increase the imaging resolution. To improve the image quality, one can either use subsequent image processing [3] or actively manipulate the optical path in real time with, e.g., a deformable mirror (DM) [4] as widely applied in adaptive optics (AO) systems. Wavefront sensing is used in various application domains such as aero-optics measurements [5], fluid measurements [6], characterization of optical components [7], laser optics [8], astronomy [1], [9], [10], and medical imaging [11]. Recent works deal with the development of high-speed wavefront sensors (WFSs) [12], [13], such as for extremely large telescopes [14].

Wavefront aberrations can be measured in several ways, leading to various designs of WFSs. A common technique is based on the Shack–Hartmann WFS [15] that utilizes a microlens array to segment the incoming wavefront onto an active sensing area, as shown in Fig. 1. Due to aberrations, the focused spots are displaced within the focal plane of the corresponding microlens from the ideal focal point, defined by a reference wavefront, such as an ideally plane wavefront. The displacement of these easily detectable and spatially locatable spots is proportional to the mean inclination of the wavefront fragment, serving as input for a mathematical estimation of the total wavefront shape. The time-consuming wavefront reconstruction can be parallelized for high performance, such as by the use of field-programmable gate arrays (FPGAs).

With their highly parallelized and programmable architecture, FPGAs offer several advantages over standard digital signal processors and CPUs, such as real-time capability through a parallel working scheme, flexibility and efficiency in data word length, highly efficient I/O interfaces, and less power consumption at comparable performance [16]. Recent contributions report the usage of FPGAs in Shack–Hartmann WFS for displacement calculation [17], [18], wavefront reconstruction, or least squares reconstruction for DM control [19], [20] and as part of a closed-loop AO system [21].

In a previous work, we showed the usage of a versatile industrial camera as Shack–Hartmann WFS and its internal FPGA as preprocessing stage for wavefront reconstruction [22]. In the following, we describe a further development of our WFS to achieve a higher processing performance as needed for real-time control AO applications. In particular, we focus on a low overall latency, an important factor for closed-loop systems [18], and versatility through reconfiguration to allow a broad field of applications. In this context, the term “smart camera” is used for an encapsulated and versatile camera design with an FPGA, close to the image sensor, and an embedded processor.
Section II summarizes the synthesized FPGA algorithm based on a vector–matrix multiply (VMM) algorithm. The second part discusses an efficient wavefront reconstruction method based on a vector–matrix multiply (VMM) algorithm. Section III is divided into two parts. The first part explains the computation of the centroid displacements of the spots. The second part discusses an efficient wavefront reconstruction method presented in Section II, the theoretical background for the relation between the displacements of the centroids and the wavefront reconstruction method is given. The FPGA algorithm presented in Section III is divided into two parts. The first part explains the computation of the centroid displacements of the spots. The second part discusses an efficient wavefront reconstruction method based on a vector–matrix multiply (VMM) algorithm. Section IV summarizes the synthesized FPGA algorithm and describes the measurement results of a laboratory prototype.

II. THEORETICAL BACKGROUND

A wavefront of a given monochromatic wave phenomenon of wavelength \( \lambda \) is defined as a surface composed of points of equal phase of the describing field strength, originating from the same source. Following the ideas of scalar optical theory, the wavefront of an incident coherent optical wave can be analytically described by the phase distribution \( \phi(x, y) \) of the complex amplitude at a given plane that is perpendicular to the direction of wave propagation

\[
U(x, y) = A(x, y) \cdot \exp(j\phi(x, y))
\]

with \( A(x, y) \) being a potential scalar amplitude distribution. This notation is based on a simplified description of optical phenomena commonly used in Fourier optics [23].

A Shack-Hartmann WFS analyzes the phase distribution \( \phi(x, y) \) of the incident optical wave at the plane of a microlens array in terms of spatial distribution of the local slopes of the incident wave. The microlens array spatially divides the incident wave into multiple small segments (SEGs), defined by its multiple microlens elements on a periodic grid, typically rectangular or hexagonal. When this spatial sampling process fulfills the Shannon sampling theorem and the curvature of the incident wavefront is small compared to the spatial sampling width, an approximately plane wave SEG is obtained for each wavefront subset. By placing the image sensor in the focal plane of the microlens array at its focal distance, each wavefront subset is analyzed by the corresponding lens element in terms of local spatial frequency, corresponding to the slopes of the wave subsets with respect to normal incidence. Following [24], the incident slope sets \( s_{x,ij}, s_{y,ij} \) for each grid element \((i, j)\) are directly related to the partial spatial derivative of the phase distribution of the optical field

\[
s_{x,ij} = \frac{\lambda}{2\pi} \frac{\partial}{\partial x} \phi(x_{ij}, y_{ij}) \quad s_{y,ij} = \frac{\lambda}{2\pi} \frac{\partial}{\partial y} \phi(x_{ij}, y_{ij}).
\]

These obtained slopes are related to the spatial frequencies \( f_x \) and \( f_y \) of the incident plane wave at position \((x, y)\) according to Fourier optics theory [23].

A. Slope Calculation

The image of a plane wave at normal incidence on an optically ideal thin lens (along its optical axis) leads to a single intensity point for geometrical optics interpretation. When diffraction at existing apertures is taken into account, a diffraction pattern is being observed. A distortion of the inclining wavefront leads to spatially distributed tilts, given by the slope sets \( s_{x,ij}, s_{y,ij} \) of the wave subsets. These tilts with respect to a plane normal to the optical axis lead to a displacement \( (\Delta x_{ij}, \Delta y_{ij}) \) of the intensity pattern away from the optical axis position on the image plane. The pixel array spatially samples and digitizes the projected intensity distribution at the sensor plane. A common technique for estimating wavefront slopes from displaced intensity patterns is the calculation of the position of the intensity center of gravity (centroid) for each subelement

\[
s_{x,ij} = \frac{\Delta x_{ij}}{f} = \frac{1}{f} \left( \frac{\sum_u \sum_v u \cdot I_{ij}(u,v)}{\sum_u \sum_v I_{ij}(u,v)} - x_{off,ij} \right)
\]

\[
s_{y,ij} = \frac{\Delta y_{ij}}{f} = \frac{1}{f} \left( \frac{\sum_u \sum_v v \cdot I_{ij}(u,v)}{\sum_u \sum_v I_{ij}(u,v)} - y_{off,ij} \right).
\]

Here, \( I_{ij}(u,v) \) denotes the intensity value at the pixel position \((u, v)\) within the corresponding digitized subelement. The displacement of the centroid is decomposed into its Cartesian components \( \Delta x_{ij} \) and \( \Delta y_{ij} \) and set into relation to the reference position by means of the individual offset reference values \( x_{off,ij} \) and \( y_{off,ij} \). Dividing by the focal length \( f \) of the lens array leads to the slope of the corresponding wavefront SEG.

B. Wavefront Reconstruction

The slope values \( s_{x,ij} \) and \( s_{y,ij} \) as given by (3) are used to obtain the phase distribution \( \phi(x, y) \) [see (1)]. Three major wavefront reconstruction methods are reported in the literature, namely, the zonal [25] and modal [26] approaches and an approach based on a Fourier transformation (FT) [27].

In the zonal approach, not the whole wavefront is derived, but only discrete values are calculated, which represent OPDs at discrete sampling points that are given by a grid that reflects the geometry of the microlens array. Commonly used grids for Shack-Hartmann sensors are the Fried [28] and the Southwell [29] grids. The first approximates the phase distribution by means of a bilinear fit, and the latter approximates the phase distribution by a biquadratic spline fit.
The **modal approach** uses superimposed orthogonal modes weighted by independent expansion coefficients for the wavefront approximation, such as Zernike polynomials [26]. If only a few specific modes are of interest, such as astigmatism, coma, defocus, and spherical aberration, the computational effort can be reduced by limiting the reconstruction to these specific modes. The FT-based approach comprises a forward FT of the slope calculations, an inverse filter applied in the spatial domain, and an inverse FT.

Zonal and modal methods are based on a similar mathematical structure and, therefore, are chosen for a first implementation on the industrial smart camera. Both approaches result in a set of linear equations, also referred to as VMM, which can be represented by

\[
\mathbf{s} = \mathbf{Ax}
\]

where \( \mathbf{s} \) is the slope measurement vector of dimension \( m \) and \( \mathbf{A} \) is an \( m \times n \) coefficient matrix, where \( m \) and \( n \) depend on the selected sampling grid configuration or on the number of used modal basis modes. The vector \( \mathbf{x} \) is of size \( n \) and represents the OPDs at given sampling points or gain factors of the orthogonal modal functions, respectively. In general, \( m > n \), which leads to an overdetermined system. If \( \text{rank}(\mathbf{A}) < n \), the inverse can be calculated using singular-value decomposition, leading to the Moore–Penrose pseudoinverse \( \mathbf{A}^+ = \mathbf{V} \Sigma^+ \mathbf{U}^T \), where \( \mathbf{U} \) and \( \mathbf{V} \) are orthogonal matrices of dimensions \( m \times m \) and \( n \times n \), respectively, and \( \Sigma^+ \) contains the reciprocal singular values of \( \mathbf{A} \) on its main diagonal. The inverse problem eventually is solved by

\[
\mathbf{x} = \mathbf{V} \Sigma^+ \mathbf{U}^T \mathbf{s} = \mathbf{A}^+ \mathbf{s}.
\]

### III. Implementation

In the following, a parallelized centroid detection and wavefront reconstruction algorithm is presented. Fig. 3 shows an overview of the complete algorithm, comprising a threshold filter \( \mathbf{T}_r \) to reduce readout noise of the image sensor, a slope calculation unit (SCU) module for slope calculation, a VMM module for wavefront reconstruction, and a configuration module.

The module can be parameterized through the control interface with the configuration memory (SDRAM) stores the matrix elements. The application performing a vector–matrix multiplication. An external synchronous dynamic random access memory (SDRAM) stores the matrix elements. The application can be described in detail.

The analyzed measurement data are relayed via direct memory access (DMA) to the embedded processor, where a C++ program sends the data via Ethernet to an external PC for further processing.

#### A. Slope Calculation Unit (SCU)

The 2-D pixel array of the image sensor is divided into a fixed grid of squared SEGs, matching the size of a microlens. The individual slope components \( s_{x,ij} \) and \( s_{y,ij} \), as given by (3), are calculated in parallel to the image transfer from the image sensor to the FPGA. In Fig. 4(a), the relation between the spatial pixel position and the individual SEGs can be seen. Fig. 4(b) shows the corresponding timing diagram for a single image frame with exposure time \( t_{\text{exp}} \) and transfer time \( t_{\text{transfer}} \) (upper panel) and the time for the proposed wavefront calculation (middle panel). The memory transfer timing (lower panel) will be described in Section III-B. The image acquisition starts with the initial trigger \( t_{\text{EOF}} \), followed by the exposure time of the sensor. The pixels of an image frame are transferred row by row from the image sensor to the FPGA as a serial pixel stream. When the last pixel of a SEG is reached [the gray-highlighted pixels in Fig. 4(a)], a corresponding trigger (\( T_{i1} \) to \( T_{ij} \)) is set in order to start the division of the sums in a parallel operating stage (middle panel). The processing time \( t_{ei} \) for a single slope consists of the processing time for the last partial sums and the division of their final results. This time mainly depends on the chosen fixed point precision determining the complexity of the division. Fig. 5 shows the inner structure of the row, column, and overall intensity summing unit and the first...
moment stage, which corresponds to (3) for a single SEG in a pipelined architecture. First-in/first-out (FIFO) buffers are used as intermediate storage elements for the partial sums of SEGs within an image row. After the final division, the displacements of the spots are calculated by subtracting the corresponding reference values \( x_{\text{off},ij} \) and \( y_{\text{off},ij} \), which are stored in an internal memory of the FPGA. The algorithm assumes only one spot in the corresponding SEG, which limits the maximum acceptable spot displacement and determines the dynamic range of the sensor. In order to detect crosstalk between SEGs caused by too large wavefront tilts, a parameterizable counter can be set to invalidate the result if a SEG shows too many illuminated pixels.

**B. Vector Matrix Multiply (VMM)**

Due to the fixed sampling geometry, the reconstruction matrix \( A^\dagger \) [see (5)] can be calculated in advance. In order to reduce the internal memory consumption, \( A^\dagger \) is stored in an external SDRAM, and only parts of it are transferred into the memory of the FPGA right before calculation. The matrix \( A^\dagger \) is divided into \( k \times i \) submatrices \( B_k \) of dimension \( m \times 2j \), as shown in Fig. 6, where \( j \) is the row index of a SEG and \( m \) is a factor, depending on the internal timing. This factor is \( m \leq \frac{u}{c_p} \), where \( u \) is the size of a SEG in pixels and \( c_p \) is the number of pixels computed at each clock cycle. Note that \( \frac{u}{c_p} \) is the number of clock cycles between two adjacent slope values. In general, the dimension \( n \) of the result vector \( x \) is greater than \( j \), yielding to \( k \) submatrices \( B_k \), which are processed in parallel. The data transfer from the SDRAM into the internal memory of the FPGA is shown in Fig. 4(b) (lower panel) and triggered by \( L_i \). The data transfer must be completed before the slope calculation \( s_{i1} \) of the first SEG in each image row ends. Assuming a quadratic size \( u \) of each SEG, \( k \) can be calculated by

\[
k = \frac{u(u - 1)}{2c_e c_p m} + \frac{u + c}{m^2 2j c_e}.
\]

The number of clock cycles required for the transfer of a single matrix element, referred to as \( bx_{mj} \) and \( by_{mj} \), is given by \( c_e \). Fig. 6(b) shows the FPGA logic of a subblock, calculating \( m \) elements of the result vector \( x \) by means of time multiplexing of two parallel multipliers for the \( x \) and \( y \) slopes, respectively. A FIFO buffer stores the sum of the elements of the result vector. The complete result vector \( x \) can be computed by several subblocks running in parallel. The time \( t_v \) (Fig. 4) required to finish the vector-matrix multiplication for each subblock is determined by the number of elements \( m \) which are processed sequentially and the time needed for the multiplication itself. Finally, the result vector is transferred sequentially to the output, given by the transfer time \( t_t \).

**IV. RESULTS**

A Festo R1B industrial smart camera (Festo AG & Company, Esslingen am Neckar, Germany) serves as the platform for the proposed WFS algorithm. A detailed description by the manufacturer of this camera can be found in [30].
The smart camera consists of a CMOS image sensor (Micron MT9V403, Micron Technology Inc., Boise, ID), a Spartan-3 XC3S1000 FPGA (Xilinx Inc., San Jose, CA), and an embedded processor (PXA255 XScale, Marvell Corporation, Santa Clara, CA). A stripped-down Linux operating system runs on the smart camera and offers easy access to industrial interfaces such as Ethernet and controller area network bus. The image sensor with a maximum resolution of 640 × 480 pixels is clocked at 60 MHz, acquiring 186 frames per second at full resolution. Higher frame rates can be achieved by reducing the height of the image, given by the number of image rows. The standard objective lens is replaced by a rectangular lens array with a pitch size of 150 μm, a focal length of 10 mm, and a circular aperture of about 4.5 mm (Flexible Optical B.V., Rijswijk, The Netherlands). The aperture trims the incoming wavefront and confines the lens array to approximately 600 lenses, and thus image SEGs, that are projected onto the CMOS sensor. The system parameters of the sensor prototype are listed in Table I.

<table>
<thead>
<tr>
<th>Lens pitch</th>
<th>150 μm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixel pitch</td>
<td>9.9 μm</td>
</tr>
<tr>
<td>Segment size</td>
<td>15 × 15 pixel</td>
</tr>
<tr>
<td>max. Region of interest</td>
<td>450 × 450 pixel</td>
</tr>
<tr>
<td>Aperture diameter</td>
<td>4.5 mm</td>
</tr>
<tr>
<td>Usable microlenses</td>
<td>~ 600</td>
</tr>
</tbody>
</table>

A. FPGA Design

Since circular apertures are commonly used, the wavefront must be analyzed within a circle. The sensor restricts the computation to rectangular regions of interest, so a square region has been chosen, which covers the whole circular aperture, as shown in Fig. 7. The SCU module computes the slopes of all SEGs within the region of interest, while the VMM module considers only SEGs within the circle. The size of a SEG directly depends on the selected lens array and the pixel pitch of the image sensor. The codomain of the slope calculation is limited by half the width of a SEG to a maximum of [−8, 8]; the codomain of the reconstruction matrix \( A^\dagger \) is normalized to [−1, 1]. The point spread function of the subaperture, given by the individual microlens, covers several pixels of the image sensor and allows the calculation of the slopes with subpixel resolution. The minimum resolvable spot displacement is 1/64 of a pixel when six fractional bits are used for the slope calculation. For the matrix elements, 22 bits are used. Following (6), with \( m = 7 \) defined by half the width of a SEG, \( c_p = 2 \) as the number of pixels concurrently processed, and \( c_c = 2 \) due to the 16 bit data interface of the SDRAM, the reconstruction matrix is processed by three parallel working VMM subblocks. The algorithm is designed to handle a matrix with 37 800 elements, which equal to 21 coefficients for a maximum number of 30 × 30 SEGs. Table II shows the resource usage of the synthesized FPGA design, divided into three main modules, namely, peripheral, SCU, and VMM. The peripheral module contains logic to interface peripheral components such as the image sensor, the SDRAM, and the embedded processor. The SCU module uses hardware multipliers for fast calculations. The FIFO buffers are based on block RAMs. The memory blocks of the VMM module use two block RAMs. The bit width of the VMM data requires two hardware multipliers for each operation, resulting in four needed multipliers for each VMM subblock. The algorithm is designed to run at a clock speed of 100 MHz, leading to a processing time for the slope calculation of \( t_s = 400 \text{ ns} \), a processing time of \( t_v = 130 \text{ ns} \) to finish the VMM operation, and a transfer time of \( t_t = 210 \text{ ns} \) of the result vector. The overall latency time is therefore 740 ns (cf. Fig. 4), given by the required 74 clock cycles. The program allows for runtime parameterization of the region of interest, the size and focal length of the lens array, the individual threshold values,
Fig. 9. Recorded images of $16 \times 16$ subapertures on the CMOS sensor for three differently aberrated wavefronts of the laser beam. (a) Plane, non-aberrated wavefront. (b) Plane wavefront that is aberrated by a cylindrical lens aligned to the $x$-axis of the sensor. (c) Plane wavefront that is aberrated by a cylindrical lens aligned to the $y$-axis of the sensor. The highlighted SEGs clearly show the spreading of the spots along the alignment axis toward the rim of the image.

Fig. 10. Reconstructed OPDs based on the slope results of the FPGA for a wavefront due to a cylindrical lens deforming the plane reference wavefront with rotations of (a) $0^\circ$ and (b) $90^\circ$ inside an area of $28 \times 28$ SEGs.

and the calibration values. This makes the WFS versatile and easily reconfigurable for different measurement applications.

B. Experimental Results

An optical setup was built to test and verify the Shack-Hartmann WFS prototype. The optical setup (Fig. 8) consists of a 0.5-mW HeNe laser ($\lambda = 632.8$ nm) pointed at the WFS, a polarizer for intensity regulation, and a spatial filter to flatten the wavefront. A cylindrical lens with a focal length of 30 mm is used to expand the beam in one dimension and introduce a controlled aberration at an adjustable distance to the sensor. Rotation of the lens by $90^\circ$ around the optical axis of the system enables a separate observation of the $x$ and $y$ displacements of the spots, which are generated by the controlled wavefront aberration caused by the cylindrical lens. Fig. 9 shows the subimage of the sensor for $16 \times 16$ SEGs. The image without the inserted lens [Fig. 9(a)] is used as reference for the slope calculation and shows a regular spot grid with all focal points at the center of the corresponding SEG. When placing a cylindrical lens with its tangent plane aligned to the $x$-axis of the image sensor into the optical path, only spots along the $x$ coordinate are affected by the astigmatic aberration [Fig. 9(b)]. Fig. 9(c) shows the sensor image after rotation of the cylindrical lens by $90^\circ$, resulting in a spreading of the spots along the $y$-axis, while the $x$-axis is unaffected [compare to Fig. 9(a)].
For the measurements, the wavefront created by the cylindrical lens is evaluated for a circular boundary, fitted into $28 \times 28$ SEGs. The slope calculation is executed on the FPGA, and the results are internally transferred to the embedded processor and sent to an external PC via Ethernet. A measurement program written in LabView (National Instruments Corporation, Austin, TX) performs a wavefront reconstruction.

The wavefront reconstruction based on the zonal approach in Southwell configuration [29] and processed in the host PC is shown in Fig. 10. The phase distribution $\phi(x, y)$ (1) was reconstructed, resulting in the OPD $\text{OPD}(x, y)$ shown in Fig. 10. The relation of the OPD and the phase distribution is given by $\phi(x, y) = \frac{2\pi}{\lambda} \cdot \text{OPD}(x, y)$, with $\lambda$ being the observed wavelength. The $x$- and $y$-axes in the figures have been normalized by the lens pitch such that the scale matches the indices of the corresponding SEG$_{ij}$.

As a second wavefront reconstruction method, a modal-based approach processing weighting factors for Zernike polynomials $Z_{m,n}(r, \theta)$ is presented [26], where $r$ and $\theta$ denote cylindrical coordinates

$$Z_{m,n}(r, \theta) = \sqrt{n+1} R_{n,m}^{(m)}(r) \Theta_{m}^{(n)}(\theta)$$

$$R_{n,m}^{(m)}(r) = \sum_{s=0}^{\lfloor \frac{n-|m|}{2} \rfloor} \frac{(-1)^s(n-s)!^2}{s!(n+m)/2-s!((n-m)/2-s)!} r^{n-2s}$$

$$\Theta_{m}^{(n)}(\theta) = \begin{cases} \sqrt{2} \cos(|m|\theta), & m \geq 0 \\ \frac{1}{\sqrt{2}} \sin(|m|\theta), & m = 0 \\ \sqrt{2} \sin(|m|\theta), & m < 0. \end{cases}$$

For a given radial degree $n \geq 0$, the azimuthal frequency $m$ goes from $-n$ up to $+n$ with a step of $+2$.

As described in Section IV-A, with the proposed FPGA algorithm, a maximum of 21 weighting factors can be processed. Fig. 11 shows 14 individual weighting factors and the corresponding Zernike modes of total 21 calculated modes for the same cylindrical wavefront, excluding the unobservable piston mode. The (black mesh) Southwell approach and the (color coded) Zernike approach lead to the same result, as can clearly be seen.
the astigmatic mode while the defocus stays the same, confirming the unchanged distance between the sensor and the lens. The superposition of all Zernike polynomials is shown in Fig. 12. A comparison between the wavefront based on the Southwell approach (black mesh) and the wavefront based on the Zernike polynomials (colored surface) shows that the amount of weighting factors is sufficient for representing the cylindrical wavefront created with this setup. In addition, the modal coefficients are also advantageous when combining individual wavefront correction elements, with each correcting a specific aberration mode. Examples are correction collars to compensate for spherical aberrations used in high-numerical-aperture microscopy [31], [32] or a steering mirror to compensate for tip and tilt used in AO systems to reduce the stroke of DM actuators [25].

The results of our prototype Shack–Hartmann WFS show the versatility of industrial smart cameras and their potential as robust and easy (re-)configurable WFS, which can be used for a wide field of measurement applications. The proposed algorithm processes 21 elements of a result vector, such as weighting factors for Zernike polynomials, and only adds a latency time of 740 ns to the image readout which is independent of the size of the region of interest, suitable for real-time AO systems.

V. CONCLUSION

In this paper, we have presented a low-latency wavefront reconstruction algorithm targeting a low-cost FPGA and the experimental results of a fast Shack–Hartmann WFS based on an industrial smart camera. The FPGA implementation calculates the slopes based on a center-of-gravity spot detection as the basis for a VMM algorithm in order to reconstruct the wavefront. The wavefront reconstruction algorithm based on a VMM algorithm adds only 740 ns to the image sensor readout while calculating a total number of 21 Zernike coefficients or 21 elements of a result vector in general at a field of view up to 30 × 30 SEGs, independent of the adjustable sensing area. The algorithm features runtime parameterization of the region of interest, lens-geometry factors, calibration data, and individual thresholds. The prototype WFS has been tested successfully in a laboratory prototype, using a defined wavefront as input for testing the zonal and modal reconstruction approaches. Next work will be focused on increasing the number of computable coefficients by systematic investigation of the necessary bit width of the fixed point numbers while maintaining a precise wavefront result.

Future work will be directed toward the implementation of a full AO system on the smart camera, including the WFS as well as the control system to control a DM. An approach based on the vector–matrix multiplication of an influence matrix could directly process signals for the actuator space of a DM. It is expected that this will considerably reduce the delay between wavefront sensing and aberration correction, which will improve the bandwidth of AO systems based on a smart camera.

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