3D-Surface Metrology

Hybrid microoptic sensors using the chromatic-confocal focus detection principle (HymoSens)
Supported by: BMBF (FZK: 02P D2551)

Micro optical components: Fast parallel characterization of micro optic arrays
Supported by: German Ministry of Education and Research (BMBF); FKZ: 13N7479 / 1

Integration of optical measurement techniques for laser welding process control (INESS)
Supported by: BMBF: INESS (Integration of optical measurement techniques for laser welding process control), FKZ: 02PD2523

Full Field, Fast Confocal Laser Microscopy for Measuring the Mechanical Properties of Cortical Bone
Supported by: Alfried Krupp von Bohlen und Halbach-Stiftung

Aberration correction in a confocal microscope (METAMO)
Supported by: Landesstiftung Baden-Württemberg, Project: "Metamo"

Microscopic three-dimensional topometry with LCOS displays
Supported by: Deutsche Forschungsgemeinschaft (DFG) under contract Ti 119/ 37-1 "Adaptive Sensork zur Bestimmung der Mikrogeometrie"

Evaluation and Characterization of Liquid Crystal SLMs for Digital Comparative Holography (DISCO)
Supported by: The German Ministry for Education and Research (BMBF) under the contract 13N8095 as subcontract of BLAS, Bremen

Collaboration with industry: A new white light interferometer
In collaboration with: Mahr GmbH

Depth-Scanning Fringe Projection (3D-MicroScan)
Supported by: BMBF 3D-MicroScan 16SV'942

Direct Calibration Scheme for the Depth-Scanning Fringe Projection (3D-MicroScan)
Supported by: BMBF 3D-MicroScan 16SV'942
Hybrid microoptic sensors using the chromatic-confocal 
focus detection principle (HymoSens)

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Miniaturized point sensor

Increasing demands for checking tolerances in small mechanical and optical precision components require improved measurement techniques. In particular, components with a complex geometry, such as small holes or channels, are difficult to access using state of the art tactile measurement systems. Optical measurement systems have the advantage that no mechanical forces occur during the measurement, which could distort or displace a miniaturized sensor head and therefore influence the result.

The main focus of this project is to develop a miniaturized optical sensor for this application. The sensor makes use of the chromatic-confocal measurement principle, which has no need for a mechanical depth scan. Therefore, a chromatic-confocal point sensor can be designed without any moving parts. This knowledge was used to design a miniaturized sensor head with an outer diameter smaller than two millimeters (see Fig. 1 and Fig. 2). A special feature of the sensor head is its capability to measure with a 90 degree redirection. This enables us to measure surfaces within small holes with high accuracy.

A diffractive element is applied to achieve the necessary chromatic dispersion of the light. The diffractive microoptic is produced by the ITO using photolithographic processes and reactive ion etching of the structure of thin substrates of fused silica.

The alignment structures and mounts between the different optical elements are produced by the Institut für Mikrostrukturtechnik (Forschungszentrum Karlsruhe) from PMMA using deep X-ray lithography, this is the first step of the LIGA process (Direct LIGA). The LIGA technique (German acronym for lithography, electroplating and molding) utilizes x-ray synchrotron radiation and provides a high performance for manufacturing microcomponents and systems with close tolerances and high aspect ratios (large structural height (> 1000 µm)).

Chromatic confocal area sensor

Confocal microscopy is a widespread method to measure volume structures or surface topographies. It has a growing impact on the measurement of technical micro-structures. In comparison to confocal laser scanners, a chromatic-confocal setup achieves a complete parallelization of the depth scan by using white-light and chromatic effects of the focusing lenses.

The maximum parallelization is achieved by measuring a complete area instead of a point or a line. We realized such a setup by using a colour camera as an area-spectrometer. This sensor is capable of one-shot measurements and fast high precision measurements in a large measurement volume. Therefore, one can choose between high speed measurements and fast measurements with increased axial resolution without any change in the setup. In the high resolution mode, it is also possible to get information about the colour distribution on the object surface.

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References:


Micro optical components:
Fast parallel characterization of micro optic arrays

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The importance of micro-optical arrays, e.g. for the collimation of diode-lasers for Optical Networks or for Hartmann-Shack sensors, is increasing. The most important fabrication errors are void elements, these are deviations of the focal length and aberrations. A good knowledge of the optical properties of the micro lenses is essential for the quality control of the micro lens fabrication.

For this industrial application, a very robust system which evaluates arrays of some thousands lenses in a few seconds is needed. All existing measurement systems (Mechanical stylus profilometry, Twyman-Green interferometry, Shack-Hartmann-sensors, atomic force microscopy) have in common that the micro lenses are tested serially. Therefore a 100%-quality control is not feasible. Interferometric techniques moreover demand a high mechanical stability of the setup. Our approach is based on the confocal principle: The array to test plays the role of the front objective in a confocal microscope (Fig. 1).

We illuminate the total microlens array (MLA) with collimated light ($\lambda=633$ nm) from a single mode fiber (F) working as a point light source. A flat mirror (M) is placed in the focal plane of the microlens-array. We image the pupils of the micro lenses with the tubelens ($L_T$), through the confocal pinhole (P), onto the camera (CCD). During the measurement the mirror is shifted along the optical axis through the focal plane of the array.

![Fig. 1: Optical Setup](image1)

A CCD image is stored for each position of the mirror. It is well known that the axial response of a confocal setup also possesses inherent information about the aberrations: The maximum value of the intensity is shifted axially, the FWHM-value increases and characteristic side lobes occur if the lenses are not perfect (Fig. 2). We use this fact to determine the aberration of microlens arrays. Void elements or deviations of the focal length are also detected. In contrast to other measuring techniques, the two-dimensional information of the wavefront is not available in our case, we have the one-dimensional axial response instead. We obtain a fast, alignment insensitive and parallel measuring system.

![Fig. 2: Axial confocal signals](image2)

For evaluation of the system we produced a diffractive microlens-array with well defined deviations. The deviations are void elements, lenses with spherical aberration and lenses with defocus. Fig. 2 shows the axial responses for an aberrated microlens (focal length $f=400$ µm, numerical aperture NA=0.15, spherical aberration $W_40=-\lambda$). For comparison the axial responses of the surrounding microlenses featuring no defined aberrations and a simulation of the axial response of an aberrated lens are displayed. For evaluation of the axial response a Neural Network was used [3]. The Neural Network can determine spherical aberration coefficients in the range from $-0.7\lambda$ to $0.3\lambda$, with less than 1 % RMS error. This system demands only a few tens of seconds of operation time, including for measurement and computation, to determine the aberrations of a 100 x 100 microlens array.

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Integration of optical measurement techniques for laser welding process control (INESS)

T. Wiesendanger, A. Ruprecht, K. Körner, H.J. Tiziani, W. Osten

A Keyhole-Sensor for in-process-control of laser welding

Laser beam welding has gained an increasing acceptance in industry, due to its high penetration depth over weld width ratio, small heat effects and high welding speed (about 15 m/min). In laser welding process control one of the most important parameters is the depth of the weld. There are already techniques which determine the welding depth, but these systems are based on secondary process radiation where the welding depth is measured indirectly. Therefore, a system for the direct measurement of the welding depth is needed. The highly dynamic processes in the welding zone, especially inside the keyhole, require a very fast measurement system of at least 1 kHz measuring frequency. The desired measurement range is 1 mm.

To our knowledge, there is no system that performs a direct measurement of the welding depth in a cw welding process. Confocal microscopy is a very robust method widely used in biology and with increasing importance for topographical measurements of technical surfaces. It is robust with respect to vibrations. To obtain the confocal axial response curve, we have to scan the sample axially. The desired measurement speed and the axial scanning range make it impossible to move the sample or the objective axially. Therefore, a fast scanning of the focus is required. We use a small pentaprism mounted on a vibrating tuning fork, to modulate the optical path length in the setup (cf. Fig. 1).

![Fig. 1: Optical Setup of the Keyhole-Sensor](image)

Thus, we achieve an axial scan of the focus spot. As the moving mass is comparatively small, we can run the system at high measurement frequencies and over large measurement ranges. As a light source, we use a high power disk laser (wavelength: 532 nm, optical power: 3 W), which is coupled into a multimode fiber (diameter: 50 µm). After collimation to a beam diameter of 15 mm and passing through a beam splitter, the light is focused into a pentaprism (cf. Fig. 2), which is mounted on the vibrating tuning fork.

![Fig. 2: Pentaprism mounted on a tuning fork](image)

The tuning fork oscillates at its natural frequency of 768 Hz. By the oscillation of the prism, the optical path length is modulated. We successfully tested mechanical amplitudes of the prism up to ±110 µm. After passing the pentaprism, the light is collimated by a lens again and enters the commercial laser welding head. The laser welding head contains a beam splitter and a front lens. As the welding laser is also delivers collimated light to the welding head, the welding laser focus is within the measurement range. Due to the change in the optical path length caused by the oscillating prism, the axial position of the sensor focus is modulated correspondingly.

![Fig. 3: Integration into the Laser welding cell](image)
A Chromatic-confocal line sensor for weld seam testing

The topography of the weld seam can give additional information about the quality of the welding process. To accomplish a high throughput, short measurement times are demanded. The chromatic-confocal approach enables the parallelization of the complete depth-scan of confocal topography measurements. Therefore, mechanical movement can be reduced, or completely avoided, and the measurement times are shortened. Chromatic-confocal point sensors are already commercially available but they need lateral scanning in the x- and y-directions to measure the surface topography. We achieved a further parallelization in the x-direction by realizing a chromatic-confocal line sensor using a line focus and a spectrometer. This configuration has the advantage that cylindrical work pieces can be measured by rotating the work piece. The rotation is already performed during the welding process.

The setup is shown in Fig. 4. Polychromatic light from a Xenon arc lamp is coupled into a multimode fiber. The light from this fiber is collimated and then focused by a cylinder lens to form a line focus, which is imaged onto the object. The reflected light is imaged via the beam splitter onto a slit aperture. This slit aperture is the confocal aperture, which blocks the defocused light and stray light. At the same time it is the entrance slit of a spectrometer. In contrast to the point sensor, the light along the line is not integrated but the lateral information about the object is used. Therefore, we used a line spectrometer, which is able to maintain the lateral resolution. We used a spectral range from 450 nm to 700 nm, and a spectrometer with a relatively low spectral resolution to limit the amount of measurement data. The topography along the focal line can be measured with a single spectroscopic image.

Fig. 5: Depth discriminated spectral image of a trench

Fig. 6: Corresponding line profile of the trench (cf. Fig. 5)

Fig. 4: Optical setup of the line sensor

Fig. 5: Depth discriminated spectral image of a trench

Fig. 6: Corresponding line profile of the trench (cf. Fig. 5)

References:


Full Field, Fast Confocal Laser Microscopy for Measuring the Mechanical Properties of Cortical Bone


Facing the fact of growing life expectancies of humans, bone diseases are an ever growing menace. To overcome this problem, accurate knowledge about the internal structure of the bone tissue is essential.

Confocal microscopy is a well established technique in biology, medicine and materials science due to its depth discriminating property. At the ‘Institut für Technische Optik’ this method is used to determine three-dimensional high-resolved surface topographies of technical objects. In order to study the internal materials properties of bone, the confocal evaluation technique was adapted in order to visualize structures underneath the bone surface.

Bone tissue is translucent and light can penetrate several tens of micrometers inside the sample. This property allows us to detect sub-surface microfractures and other structures. The confocal measurements on bone tissue were performed using a confocal microscope with a rotating microlens disk. This system was developed at our institute. The principle of the system is shown in Figure 1.

Unlike other confocal microscopes with a rotating Nipkov disk with a low light efficiency of about 1%, this setup uses 60% of the light. Consequently, the system can operate with a LED at low costs and without problems of speckling.

The measurement and evaluation routines had to be adapted to the new task for acquisition of volume data. A deconvolution routine was added. Images can be successfully obtained from depths down to 80 microns with an axial resolution in the submicron range. The system can be used to perform measurements of stressed bone samples, as the microscope can acquire images of a whole plane in a single measurement, and automatically scan through the desired volume.

Fig. 1: Principle of the confocal microscope with rotating microlens disk

Fig. 2: Intensity on a single line in depth

Fig. 3: Confocal axial response signal in bone tissue

Fig. 4: Osteocyte lacunae, 55 µm under the bone surface

Supported by: Alfried Krupp von Bohlen und Halbach-Stiftung
Confocal microscopy is a measurement technique widely used in biological and technical applications. In case of the deployment of a monochromatic light source a time consuming axial scan is inevitable. Moreover when performing measurements underneath a refractive index mismatching layer we have to cope with aberrations, especially spherical aberration which degrades the signal quality and thus also the measurement accuracy. To overcome these problems we integrate an adaptive mirror into a confocal microscope. The adaptive mirror is used to perform the fast axial scan as well as the aberration correction. To optimize the shape of the adaptive mirror we introduce an optimization criterion which we call Wavefront-Information-Entropy-Method (WIEM). In contrast to most other criteria in this context, WIEM represents a single numerical value which is ideal for the optimization algorithm. As an optimization algorithm we use a genetic algorithm. Fig. 1 shows the optical setup. The adaptive mirror is shown in Fig. 2. Measurement results using the adaptive mirror for the axial scan are displayed in Fig. 3. Fig. 4 depicts the confocal signal before and after optimization.

**Fig. 1:** Optical setup

**Fig. 2:** Adaptive Mirror

**Fig. 3:** Axial scan using the adaptive mirror

**Fig. 4:** Aberration Correction

**References:**


Microscopic three-dimensional topometry with LCOS displays


The optical measurement of three-dimensional microtopography is an important field for the control of industrial processes. Different measurement principles have been developed for various requirements, such as measurement field size, lateral and depth resolution, and measurement time. Common methods are confocal microscopy [1], white-light interferometry [2], [3], and microscopic fringe projection based on the principle of triangulation [4]-[8]. While confocal microscopy and white-light interferometry offer resolutions down to the nanometer-range, the microscopic fringe projection offers a fast and robust method for measurement field sizes from ca. 1 mm² up to several square centimeters with a depth resolution in the micrometer-range. For the generation of the fringes, mechanical Ronchi gratings [4]-[7], the digital micromirror device (DMD, developed by Texas Instruments) or transmissive twisted nematic liquid crystal displays (LCD) [9] have been used. Pixelated devices like the DMD or LCDs offer more flexibility compared to mechanical gratings. With these elements, the fringe period can be adapted to the object under test. They also permit the adaptation of the fringe brightness to a locally varying brightness of the measurement scene [8].

The measurement setup

In order to apply the LCOS display as a fringe projection device, we used an experimental setup that has proven to be very suitable for microscopic fringe projection [4]-[8]. The measurement principle is illustrated in Fig. 1. The setup is based on a Leica MZ 12.5 stereo microscope with a zoom range from 0.8 to 10.0 and interchangeable objectives with magnifications of 0.63 x, 1.0 x, and 1.6 x, respectively. This gives us the possibility of varying the measurement field size from 21.2 x 15.7 mm² down to 0.83 x 0.62 mm².

As a detector, we used a digital CMOS camera Photonfocus model MV-D1024k with 1024 x 1024 pixels, a pixel pitch of 10.6 µm, and a gray scale resolution of 8 bits. The pixel clock of the camera was 80 MHz. Both exposure time and frame time could be changed by software in steps of 50 ns. This enabled us to adjust the exposure time to exact multiples of the projection time of the LCOS display (16.67 ms for 60 Hz) resulting in virtually flicker free images. For the acquisition of images, the CMOS sensor could be programmed to read out only the desired regions of interest (ROI). Hence, the measurement of parts of the measurement field was possible.

Measurements

In order to demonstrate the performance of the LCOS measurement system, we conducted measurements on several technical surfaces. For all the measurements we present here, we used a 4 bucket algorithm with a preceding 8 bit Gray code sequence to unwrap the phase. The period of the sinusoidal fringes was 12 LCOS pixels.

The full triangulation angle $\beta_T = \beta_1 + \beta_2$ varies slightly over the measurement field, leading to a lowly varying z resolution (± 5 %). In order to compensate this variation, we conducted a sensitivity calibration according to Ref. [7]. The calibration was done by moving the stereo microscope to different z positions above a reference mirror with a translation stage. At each position, the absolute phase was measured. From these measurements, a sensitivity field could be calculated which represents the relationship between the change in height and the change in the phase. As a reference, we used the measured phase for the position in the middle of the depth of sharpness, i.e. $z = 0$.

Fig. 1: Scheme of the stereomicroscope used for the measurements
Fig. 3 shows the topography of a roughness standard fabricated by HALLE Feinwerktechnik with a mean roughness of $Ra = 3.40 \, \mu m$ (manufacturer's data). The measurement was conducted with the 1.0 x objective and a zoom factor of 4.0 resulting in a measurement field size of $3.18 \times 2.35 \, \text{mm}^2$ and a z resolution of 0.43 $\mu m$.

Fig. 3 shows the topographies of two different chrome-plated steel sheets exhibiting different surface textures. These measurements were made with the 1.6 x lens and a zoom factor of 8.0. The measurement field size and the height resolution were $1.04 \times 0.77 \, \text{mm}^2$ and 0.085 $\mu m$, respectively.

**Conclusions**

We have shown that the application of an LCOS display as the fringe generating element in a stereo microscope makes measurements with high accuracy possible. In combination with a CMOS camera, the achievable z resolution is in the micrometer range. Since the switching time of the ferroelectric liquid crystal layer is below 100 $\mu s$, the theoretical limitation of the measurement time is the frame rate of the projected images. Thus, LCOS displays have a very high potential for future high speed measurement applications.

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**References:**


Evaluation and Characterization of Liquid Crystal SLMs for Digital Comparative Holography (DISCO)

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For industrial applications, fast technologies for shape comparison between a master and a test object are needed. This task can be fulfilled with the help of comparative digital holography, which is the concern of the BMBF project DISCO (Distant Shape Control by Comparative Digital Holography). For the reconstruction of the recorded master hologram, a SLM is used. As the development of SLMs for this purpose is too expensive, commercially available elements are used. These elements are especially made for devices like projectors and are deployed as amplitude modulators. To be able to use the more efficient phase holograms, a phase modulator is needed. Therefore, the available SLMs can be applied, but they have to be characterized in detail. Their phase shifting properties and the according amplitude modulation have to be known to use them as phase modulators. In addition the knowledge of their Jones-Matrix [1] is a great advantage if further simulations or polarisation calculations should be made. ITO had the task of characterizing the SLMs. A modularized test bench, which can easily be adjusted for the different measurements, was set up. At the moment it's possible to measure the following properties:
- Phase shift
- Amplitude modulation
- Diffraction efficiency
- Contrast
- Display homogeneity
- Jones-Matrix

All the measurements can be made by varying the direction of the incident light, as the illumination setup can be rotated around the axis of the display (See Fig. 1).

For the phase shift measurement, different methods were implemented and evaluated. The most preferable method to be found was the double slit experiment. In figure 2, the image and the result of a phase shift measurement are presented. The result shows the comparison of two different displays for two different polarizer / analyzer combinations.

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References:


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**Fig. 1:** Test bench in the configuration for phase shift measurements

**Fig. 2:** Left: Image of a phase shift measurement, each line represents the interference pattern of one gray level

Right: Results of the phase shift measurement of two different displays
In collaboration with the company Mahr GmbH in Göttingen, a new white light interferometer “MarSurf WS 1” for contactless 3-D measurements was developed, by which a vertically resolution of 0.1 nm can be achieved. The ITO provided a software library for initial testing of the interferometer.

By the use of a short coherent light source it is possible to measure objects with steps. The optical setup follows the design of a classical Mirau interferometer, apart from that only a light source with low-coherence is employed. The reference field of the interferometer is integrated in the Mirau objective, reducing significantly the size of the sensor. During the measurement, the Mirau objective is moved along the vertical axis, and a sequence of images is acquired, used to calculate the 3-D topography of the object.

The sensor can be applied in micro inspections rooms as well in the production. By use of an innovative algorithm to analyse the measured signals specular like lenses and mirrors as well as rough objects can be measured. The material of the object is thereby irrelevant for the measurement, objects made of glass, paper, lacquer, metals or fluids can be addressed.

References:


**Fig. 1:** Principle of a Mirau type white light interferometer

**Fig. 2:** Interferograms in several depths of focussing

**Fig. 3:** Photo of the white light interferometer MarSurf WS 1
Today, the fringe projection technique is a commonly used method for various 3-D profiling, 3-D shape, or 3-D scene measurement techniques, based on the projection of a grating onto the surface of an object. The deformation of the fringe pattern observed from a different direction contains the information for determining the height map [1][2][3].

We are currently introducing a new depth-scanning triangulation method for absolute 3-D profiling of a macroscopic scene based on fringe projection technique. A scanning focal plane allows the phase to be determined for any desired depth range of the measurement volume. Furthermore, the limitations in the depth of focus that occur when using projected light techniques will be overcome, allowing a larger aperture and therefore better use of light. Additionally, we use a small angle of triangulation to reduce shadowing in the scene.

The projection and detection channels of the DSFP setup are laid out as two nearly identical, and parallel, optical paths as shown in Fig. 1 [4]-[8]. For projection, we use a Ronchi grating illuminated by a collimated white light source. An image-sided telecentric lens (L) with relatively high aperture is used to image the Ronchi grating into the object space. The optical path of the detection channel only differs in that a CCD-array takes the place of the Ronchi grating into the object space. The optical path of the detection channel only differs in that a CCD-array takes the place of the Ronchi grating. It makes use of an identical lens, labelled D. Both Ronchi grating and CCD-array are mounted on a single high precision translation stage, whose axis is parallel to the optical axis of the measurement system. Furthermore, those devices are aligned, so that their planes of focus coincide. Thus, by simultaneously shifting the Ronchi grating and the CCD-camera along the zA-axis in the array space, we shift this plane out of focus throughout the whole depth of the measurement volume. An additional lateral shift of the Ronchi grating along the xA-axis produces the time-dependent intensity variation onto the CCD-array, which is needed to detect the phase variation.

By using image-sided telecentric lenses, we can practically overcome the lateral shifting of imaged points when the magnification is slightly modified, e.g. due to (de)focusing. For the detection lens D, this means that an object point is imaged at the same position of the CCD-array (i.e. onto the same pixel), when the image is slightly defocused.

Therefore, the modulated periodic intensity signal $I$ that is detected by each individual pixel of the CCD-array can be interpreted as a signal type, commonly known from the short coherence interferometry [9]:

$$I = I_0 \left[1 + m \left(z_\lambda - z_{\lambda,0}\right) \cos \left(2\pi \frac{z_\lambda - z_{\lambda,0}}{\lambda_{LA}} + \phi_0 + \Delta \phi\right)\right]$$ (1)

where $m$ is the modulation function, $z_\lambda$ is the component of the translation of the grating and of the CCD camera chip in the $z_\lambda$-direction, $z_{\lambda,0}$ is the $z_\lambda$-coordinate of the image position of an object at point P that is illuminated by a light emission point LE of the grating plane. The distance $d$ is the basis of triangulation of the measurement arrangement and $p$ is the grating period. The lines of the grating are parallel to the $y_\lambda$-coordinate. The unknown start position of the grating is described by $q_{\phi,0}$. $\Delta \phi$ is a slowly varying phase term dependent on distortions due to the objectives.

In our experimental setup, the Ronchi grating is shifted exactly parallel to the oblique straight line $g_\lambda$ in the array space. The wavelength of triangulation in the array space depends only on the geometry of the optical arrangement and can be expressed as:

$$\lambda_{TA} = \frac{pf}{d}$$ (2)
where $f'$ is the focal length for the identical objectives for illumination (L) and detection (D). With the knowledge of the other geometric-optical parameters of the setup, the pixel pitch of the CCD camera, and the scale ratio $\beta_p$ for the sharp imaging of the grating into the point $P$ in object space, the lateral coordinates $(x_{OP}, y_{OP})$ of the point $P$ can be also calculated. The position $z_{AP}$ of the image point of $P$ is given by Newton’s formula with:

$$z_{AP} = \frac{-f'^2}{z_{OP}}$$

(3)

where $z_{OP}$ is the $z_{OP}$-position of the object point $P$ in object space.

The best focus position is calculated from the maximum of the envelope that is stored in the envelope field, $Z_E$, giving information about the fringe order. Finally, the calculation procedure provides the exact phase at the maximum of the envelope. The algorithms used are explained in detail in Refs. [8] and [9].

Fig. 2: Measurement result of a human face from one point of view

In Fig. 2 we show a result of a measurement with the depth-scanning fringe projection of a human face from one point of view.

References:


Supported by: BMBF 3D-MicroScan 165V942
Direct Calibration Scheme for the Depth-Scanning Fringe Projection (3D-MicroScan)


We adapted the direct calibration approach to perform both lateral and depth calibration of a depth scanning fringe projection setup. This approach enables us to introduce the dependency of the lateral calibration functions to magnification in the form of the \( Z \)-coordinate, and thus to tackle the problem of the lateral calibration of a focusing system for the first time \[1\].

The direct calibration of this setup is performed in array space. It is based on the determination of three transformations \( T_x, T_y \) and \( T_z \) between the measured coordinates \( P = (x', y', z') \) and the corresponding distortion free coordinates \( P' = (x', y', z') \), according to eq. (1):

\[
\begin{align*}
  x' &= T_x (x', y', z') \\
  y' &= T_y (x', y', z') \\
  z' &= T_z (x', y', z')
\end{align*}
\]

Polynomial transformations as shown in eq. (2) and (2a) proved to be suitable for this task.

\[
\begin{align*}
  T_x: \quad x' &= \sum_{i=1}^{M} \sum_{j=1}^{N} \sum_{k=1}^{P} a_{ijk} \cdot x^i \cdot y^j \cdot z^k \\
  T_y: \quad y' &= \sum_{i=1}^{M} \sum_{j=1}^{N} \sum_{k=1}^{P} b_{ijk} \cdot x^i \cdot y^j \cdot z^k \\
  T_z: \quad z' &= \sum_{i=1}^{M} \sum_{j=1}^{N} \sum_{k=1}^{P} c_{ijk} \cdot x^i \cdot y^j \cdot z^k
\end{align*}
\]

whereby

\[
\frac{i}{M} + \frac{j}{N} + \frac{k}{P} \leq 1
\]

(2a)

The transformations, \( T_x \) and \( T_y \) of the lateral calibration use all three measured \( \hat{z}_i \) coordinates \( (\hat{x}_i, \hat{y}_i, \hat{z}_i) \). In contrast, for the depth calibration transformation, \( T_z \), the calibrated lateral coordinates, \( x_i \) and \( y_i \), in combination with the measured \( \hat{z} \) coordinate are used. Following this approach, the lateral and the depth calibration can be decoupled. This is a commonly used procedure for calibration of 3-D measurement systems because it leads to more stable and easier to interpret results. The additional condition introduced by eq. (2a) was also used to reduce the number of polynomial coefficients to be determined, leading thus to a shorter computation time. Introducing eq. (2a) does not affect the accuracy, which was achieved by using only eq. (2).

In order to determine the coefficients, \( a_{ijk}, b_{ijk}, \) and \( c_{ijk} \) of the polynomial transformations, the coordinates of control points can be identified for the coordinates measured with the depth scanning fringe setup. We will shortly show this identification for the case of the transformation \( T_z \). In the case of \( T_x \) and \( T_y \), the identification can be processed in a similar way. Utilizing eq. (2) and (2a), with a number of \( n \) different control points, leads to a linear system of \( n \) equations, which can be expressed following the formalism of linear algebra:

\[
X' = \hat{X}' A
\]

where \( X' = (x'_1, x'_2, \ldots, x'_n)^T \) is the vector of the coordinates of the control points used as reference values, \( A = (a_{ijk}, \ldots, a_{ijk}, \ldots, a_{ijk}) \) is the vector of the polynomial coefficients, and \( \hat{X}' \) is the design matrix, built according to eq. (2).

\[
\hat{X}' = \begin{bmatrix}
  x'_1 & y'_1 & z'_1 \\
  \vdots & \vdots & \vdots \\
  x'_n & y'_n & z'_n
\end{bmatrix}
\]

This system of equations can be solved provided the number of known set of coordinates \( (x'_1, y'_1, z'_1) \) and measured sets of coordinates \( (\hat{x}'_i, \hat{y}'_i, \hat{z}'_i) \) is equal to or exceeds the number of unknown coefficients \( a_{ijk} \). A large set of known and measured coordinates leads to better results since the influence of the measurement uncertainty is partly compensated by redundancy. According to eq. (3) the vector \( A \) can be expressed by:

\[
A = (\hat{X}'^T \hat{X}')^{-1} \hat{X}'^T \hat{X}'
\]

A well known and numerically stable method to solve eq. (2) consists of computing a QR decomposition of \( \hat{X}' \), where \( \hat{X}' = QR \). \( Q \) is an orthogonal matrix and \( R \) is an upper triangular matrix. This leads to:

\[
R \cdot A = Q^T \cdot X'
\]

Since \( R \) is an upper triangular matrix, eq. (6) can be solved for \( A \) by back-substitution.

We conducted several series of measurements to prove the quality of the calibration. For each series, the depth of the calibrated volume was about 300 mm. This is limited by the range of our translation stage. We covered working distances ranging from 600 mm up to 1300 mm.
After intensive investigation, the best combination for the grade of the polynomial transformations proved to be equal to 4 for the lateral calibration as well as for the depth calibration (i.e. $M = N = P = 4$ referring to eq. (2)). Using these values, we achieved a depth accuracy of $z_{\text{RMS}} < 0.1\text{mm}$ at a distance of $z \approx 800\text{ mm}$ which corresponds to an accuracy of $z_{\text{RMS}}/z \leq 1:8000$ or $z_{\text{RMS}}/\text{diag} \leq 1:5000$. Those relative accuracy values were also verified over the whole calibrated depth range. Further investigations proved the lateral mean relative accuracy to be about 0.5 pixels over the whole calibrated range, compared to about 1.5 pixels for non-calibrated data. This corresponds to an average lateral accuracy of 0.3 mm at a distance $z = 800\text{ mm}$ for calibrated data. We also investigated the long term stability of our setup and found that a set of calibration coefficients may be employed without significant loss of accuracy even after the system has been powered down for several days, provided thermal stability is reached.

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References: