Projection of structured light in object planes of varying depths for absolute 3D profiling in a triangulation setup

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ABSTRACT

We are currently introducing a new 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 of the depth of focus occurring by projected light techniques will be overcome, allowing a large aperture and therefore better use of light. Two different systems based on this technique will be shown: System I uses both vertical and lateral translation of a Ronchi grating. System II uses an LCD element for generation of different fringes which has to be translated vertically, only. The basic principle of the new method is explained. First measurement results of both systems demonstrate the efficiency of the newly developed algorithms and the innovative measurement arrangements.

Keywords: fringe projection, structured light, focusing, phase-shifting, contrast evaluation, absolute 3-D profiling

1. INTRODUCTION

Today the fringe projection technique is a commonly used method for various 3-D profiling, 3-D shape or 3-D scene measurement techniques 1-7, 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.

Especially the application of phase shifting techniques in interferometry 8-10 enabled the implementation of the phase shift method in the fringe projection technique 11-13. To achieve an absolute 3-D map, the coded light approach techniques 14-16 were also often used. Past history shows that the interferometry with two or more light wavelengths 17,18 or with two effective wavelengths by two different angles of incidence 19 also influenced the fringe projection techniques. This was demonstrated by the implementation of fringe projection techniques with two or more effective wavelengths 1,20-22. Another example of the very close connection between interferometry and fringe projection technique is demonstrated by the generation of a variable effective wavelength in the fringe projection arrangement by an interferometer 23,24.

The evaluation of the contrast of a fringe pattern on a fixed object illuminated with structured light in different vertical positions of a grating 25,26 or in different height positions of a vertically moved object in case of a fixed grating 27, has already been used for depth discrimination of an object. However, in a triangulation measurement arrangement with a vertically moved grating or object, the phase information in the detected signals has not been evaluated so far.

After 1990, there was a rapid development of short coherence or white light techniques for the absolute measurement of the 3-D topography 28-33. However, it is difficult to apply these techniques if the surface height values exceed the range of 10 mm because the number of images can easily be over 10,000. Therefore, this technique is more convenient for the microscopic range. Influenced by the successful development of short coherence techniques 28-33, the question arose if there could be an equivalent in the fringe projection technique for microscopic or macroscopic applications. The answer is yes. Therefore, the evaluation of both phase and contrast information was applied to a vertically scanning stereo microscope 34 for the first time, and we called it scanning fringe projection technique (SFP).
At first, we present in this paper a modified short coherence phase evaluation techniques for the macroscopic projection fringe techniques using both phase and contrast information for the detection of the absolute 3-D topography of macroscopic objects and scenes. In the second section we present a modified setup that uses discrete steps for depth scanning. Here, the phase measurement is realized by phase shifting and the phase demodulation by using synthetic wavelengths. Therefore, the grating itself does not need to be moved perpendicular to the optical axis. The only movement is the simultaneous positioning of LCD and CCD to select the desired focal plane.

2. SYSTEM I - EXPERIMENTAL SETUP
The experimental setup of system I, the 3D-MicroScan75, is schematically shown in Fig. 1. It is based on the arrangement of two identically designed objectives L and D, positioned in parallel with a telecentric ray path. However, telecentricity only exists in the array space where a grating and a CCD camera chip are placed. In this layout, we use the pupil of the objective L for the illumination of the object and the separate pupil of the objective D for the detection with the pupil centres PC_{OL} and PC_{OD} respectively. There is the possibility of both lateral and axial movement for the illuminated Ronchi grating by a controlled x_{A}-stage and a controlled z_{A}-stage. This results in an oblique shift of the projected grating, leading to an oblique scan of the projected fringe pattern in the measurement volume. The camera is also placed on the common z_{A}-stage, and by means of an accurate adjustment of the axial position of the grating and the camera chip, the image planes of the grating and the camera chip, always remain coplanar in the object area. The coplanar image planes are shifted step by step through the whole depth of the measurement volume. Additionally, by means of the control of the x_{A}-stage, the grating is shifted exactly parallel to the straight line g_{A} that is defined by the focal point F_{AL} of the illumination lens and the principal point H_{D} of the detection lens. Therefore, the image of any element of the grating and the image of every corresponding pixel of the camera always remain in coincidence in the whole measurement volume due to the compliance
with the Scheimpflug condition. The triangulation angle of the 3-D sensor $\alpha_D + \alpha_L$ is limited to about 10°. This considerably reduces the disturbing shadowing of the current commercial triangulation measurement devices. Due to the scanning of both stages, every pixel of the CCD camera detects a modulated periodic signal from a detected point of the scene which is illuminated by the structured light. The information about the surface topography is included in the phase of that signal. In addition, the modulation information can be used for determining the absolute order.

The experimental setup of the 3D-MicroScan75, is presented in Fig. 2. In the foreground, both parallel positioned objectives, from Flektogon-type 1:1,4/12 made by Jenoptik, can be seen. The triangulation basis, the pupil distance $d=75$ mm corresponds to the pupil distance of a human. The relatively large pupil diameter of 8 mm of these objectives is a useful advantage of this 3-D measurement system for a better utilization of the light source that is a 175 W Xenon lamp.

### Fig. 2: Photo of the 3D-MicroScan75 sensor

(1 illumination objective, 2 camera objective, 3 Ronchi grating, 4 CCD camera, 5 light guide at a Xenon lamp, 6 $x_A$-linear translation stage, 7 $x_A$-motor, 8 length measurement system, 9 $z_A$-motor, 10 length measurement system, 11 $z_A$-linear translation stage).

#### 3. SYSTEM I - THEORY OF SIGNAL GENERATION

From our previous work \[^3\] we know that the modulated periodic intensity signal $I$ in a triangulation setup with focussing, can also be interpreted as a signal commonly known in the short coherence interferometry and we can write for the detector plane in the co-ordinates of the array space $(x_A, y_A, z_A)$:

$$I(x_A, y_A, z_A) = I_0 \left[ 1 + m[x_A, y_A, z_A - z_{AP}(x_A, y_A)] \cos \frac{2\pi}{\lambda_{SCA}} \left( \frac{z_A - z_{AP}(x_A, y_A) + x_A - d - x_{AA}}{p} \right) + \varphi[y_A, z_A, z_{AP}(x_A, y_A)] \right]$$

where $m[x_A, y_A, z_A, z_{AP}]$ is the modulation function, $z_A$ is the component of the translation of the grating in the $z$-direction, $z_{AP}(x_A, y_A)$ is the co-ordinate of the image position of an object point $P$ and $p$ is the grating period and $d$ is the basis of triangulation of the measurement arrangement. The term $(x_{AA} - d)/p$ describes the additional phase value due to the carrier frequency of the grating and $x_{AA}$ the unknown start position of the grating.

In our experimental setup during the scan, the line grating is shifted exactly parallel to the oblique straight line $g_A$ in the array space. Here, $\kappa$ describes the slope factor of a general straight line $g_{Ac}$. For $\kappa=1$, the $\Delta x_A'$-shift of the grating as a function of $\Delta z_A$ follows as
The wavelength of triangulation \( \lambda_{TA} \) in the array space only depends on the geometry of the arrangement and can be expressed for our case (see fig. 1) as

\[
\Delta x_A = \Delta z_A \cdot \frac{d}{f'}.
\]

The wavelength of triangulation \( \lambda_{TA} \) is a constant for the described case. The absolute object phase \( \varphi_{obj} \) of an object point P with the co-ordinates \((x_{op}, y_{op}, z_{op})\) (see fig. 3) and also eq. (1), can be expressed according to

\[
\varphi_{obj} = -\frac{2\pi \cdot z_{AP}}{\lambda_{TA}}.
\]

The minus signs result from the co-ordinate system used here. The absolute phase \( \varphi_{obj} \) of an object point P, can be expressed by the \( z_{AP} \)-position of the optically conjugated image point \( P_{AP} \). With the knowledge of the absolute object phase \( \varphi_{obj} \) of every point P and the geometric-optical parameters of the arrangement, it is possible to determine its \( z_{OP} \)-co-ordinate. With the information of the geometric-optical parameters of the setup and the pixel pitch of the detector array used here and the scale ratio \( \beta_p \) for the sharp imaging of the grating into the object space, the lateral co-ordinates \((x_{op}, y_{op})\) of the point P can be calculated absolutely, too. The position \( z_{op} \) of the image point P is defined by the Newton’s formula with

\[
z_{AP} = -\frac{f^2}{z_{OP}}
\]

and with \( z_{op} \) as the \( z_{OP} \)-position of the object point P in the object space. With eq. (4) we can write

\[
\varphi_{obj} = -\frac{2\pi \cdot f^2}{\lambda_{TA} \cdot z_{OP}} = \frac{2\pi \cdot f' \cdot d}{p \cdot z_{OP}}.
\]

The phase term \( \varphi_f(x_a, y_a, z_{AP}) \) in eq. (1) includes the influence of errors of both objectives also depending on the following term \( z_{AP}(x_a, y_a) \) and the not completely compensated deviations from telecentricity. However, this phase term \( \varphi \) has only small changes over \( z_A \) and the position \( z_{AP} \) of an image point.

To get a simpler model, we use the case \( \kappa = 1 \) and we get for the scan wavelength \( \lambda_{ScA} \)

\[
\lambda_{ScA} = \lambda_{TA}.
\]

The scan wavelength \( \lambda_{ScA} \) determines the signal frequency in eq. (1). Due to the telecentric array space and the geometry of the arrangement used here, \( \lambda_{ScA} \) is constant. This is a considerable advantage.

The modulation function \( m(x_a, y_a, z_f \cdot z_{AP}) \) of equation (1) can be expressed as the product of the modulation function of illumination \( m_I \) and detection \( m_D \). For the non-diffraction limited case and for scattering surfaces which is normally assumed here, it can be written in the array space as:

\[
m(z_A - z_{AP}) = m_L(z_A - z_{AP}) \cdot m_D(z_A - z_{AP})
\]

For the modulation function \( m_L \) we get with the condition that \( |z_{AP}| < f'/20 \) with the fringe number \( \rho_{fA} \)}
with \( u_A \) as the aperture angle in the array space and \( p \) as the period of the used grating.

\[
\rho_{LA} \approx \frac{2 \tan u_A \cdot (z_A - z_{AP})}{p}
\]

where \( J_1 \) is the Bessel function of first order and first kind. Assuming that the objective for illumination (L) and that for detection (D) are both identically constructed and accurately adjusted, and finally both objectives are used with the same aperture stop, then we can write for our special case: \( m_L \approx m_D \). Note that the aperture angle \( u_A \) determines the bandwidth of the detected signals in the frequency domain, too.

5. SYSTEM I - SIGNAL EVALUATION

A signal as described in eq. (1) was detected by means of our 3D-MicroScan75 sensor presented in Fig. 3. A slope factor \( \kappa = 1 \) is used that was achieved by the synchronous control of both stages. At first, the detected signal of every pixel is high-pass filtered, in order to remove the contribution of the mean intensity and slowly varying intensity modulations. This is done by subtracting two consecutive frames. Afterwards, the signal is multiplied by the sine and the cosine of the well-known carrier signal and low-pass filtered (a quadrature demodulation). This leads to the real and the imaginary part of the complex signal history. The absolute value corresponds to the contrast function which is represented by the envelope and the phase value provides us with the phase of our signal and we get the phase field \( Z_e \). The best focus position is calculated from the maximum of the envelope that is stored in the envelope field \( Z_E \). This gives us the fringe order. Finally, the calculation procedure supplies the exact phase at the maximum of the envelope. The algorithms are explained more detailed in Refs. 35 and 36.

Fig. 3: Modulated periodic signal taken from a single pixel with the 3-D MicroScan sensor (period \( p \) of the Ronchi grating: 100 \( \mu m \), \( z_A \)-step: 1.5 \( \mu m \)).

To decrease the influence of imaging errors of the measurement setup and to achieve absolute coordinates, at least one reference measurement and an object measurement have to be combined. First, the reference envelope field \( Z_{ER} \) and the reference phase field \( Z_{ER} \) are calculated for a plane reference plate containing the well-known spatial carrier frequency \( 1/p \) of the line grating, the start position \( x_{LA} \) and the sum of the systematic errors of the whole sensor. In all measurements that we have carried out so far, the slope factor \( \kappa = 1 \) was consequently applied because of the resulting simplification of the evaluation procedure as well as the used algorithms. Due to the continuity of the reference plate, the calculated reference phase field \( Z_{ER} \) can be unwrapped for eliminating \( 2\pi \)-discontinuities and we get the reference phase field \( Z_{ERU} \). Provided that the imaging errors show a very low spatial frequency, a separation of phase components which describe the values at the maximum of the envelope and the phase errors due to imaging errors, can be performed by subtraction of the best fit polynomial, the polynomial \( (x_A, y_A) \). We get the reference phase field \( Z_{ERU,P} \) that is subtracted from the reference envelope field \( Z_{ER} \). The resulting reference field \( Z_R \) is stored.

The object measurement is carried out, and we get both the object envelope field \( Z_{EO} \) and the object phase field \( Z_{EO} \). Because we carry out a scan line of the grating parallel to the straight line \( g_A \), the phase at the point of maximum contrast is independent of the object position \( z_{OP} \). Therefore, at that point, the phase in a single pixel of the field \( Z_{EO} \) is only the sum of the errors of the elements of the object envelope field \( Z_{EO} \), the imaging errors of the objectives, the spatial carrier frequency and the start position of the grating. Because these imaging errors slowly vary over \( z_A \) and \( z_{AP} \), the stored reference
polynom \((x_A, y_A)\) can be subtracted from the field \(Z_{BO}\). Subsequently, the spatial carrier frequency is eliminated and we calculate the values modulo \(\lambda_{TA}\). The further calculation of the envelope field \(Z_{EO}\) with the reference field \(Z_R\) provides the result object field \(Z_{AO}\) with the elements \(z_{APO}(x_A, y_A)\) for the co-ordinates in the array space:

\[
Z_{AO}(x_A, y_A) = Z_{EO}(x_A, y_A) - \left[ Z_{EO}(x_A, y_A) - \text{polynom}(x_A, y_A) - \frac{f'}{d}(x_A - d - x_{AA}) \right] \mod \lambda_{TA} - Z_R(x_A, y_A). \tag{11}
\]

Nevertheless, these co-ordinates are still relative to the initially measured reference plate. The absolute \(z_{APR}\)-co-ordinates of the array space for an object can be achieved by the addition of the absolute \(z_{APR}\)-co-ordinates of the reference plate calculated from eq. (5) to the elements of the result field \(Z_{AO}\). Note that the values of the field \(Z_{AO}\) are negative due to the coordinate system used here. The presented algorithm enables the measurement of unknown objects without using neighbor ship relations, and it is possible to measure single object points without ambiguity problems. In the process of the phase evaluation, a digital band pass filter was used to reduce the signal noise.

We know that we have used a simplified model. E.g. the triangulation basis \(d\) is not a constant for non-paraxial rays because the pupil center definition is only valid for paraxial rays. Furthermore, there are small deviations from the telecentricity of both objectives. In our model, we have transferred all imperfections into the phase term \(\phi(x_A, y_A, z_A, z_{AP})\) and therefore, we will have to make a calibration in the whole measurement volume. Because we use very complex calculation algorithms, e.g. digital narrow band pass filtering, the influence on the imperfections of the setup have not been clearly estimated yet. Extensive measurements and calibration procedures have to be tested.

### 6. SYSTEM I - EXPERIMENTAL RESULTS

For testing the measurement capabilities of the new 3-D measurement setup MicroScan75 and the new signal processing, we performed a series of different measurements. Fig. 4 shows the non-scaled measurement of a wavelike object sprayed in white with different wave amplitudes: 1 mm, 0.25 mm and 0.09 mm and the wavelengths: 10 mm, 5 mm and 2 mm. The written co-ordinates are valid for the array space but we changed the sign of the values for a better understanding of all the results presented here. The calculation of the object space co-ordinates can be performed after the calibration of the measurement system that we have still to carry out. Fig. 5 demonstrates the measurement of a Volkswagen gear block with a depth of about 600 mm. About 220 images were taken from a single point of view. For a better observation, the result is presented in two separate parts. The calculation of the object space co-ordinates can be performed after the calibration of the measurement system.
7. SYSTEM II – EXPERIMENTAL SETUP

In System II, a very similar setup to System I is used (Fig. 6). Again, two camera lenses are positioned parallel to the measurement direction in front of the system. Compared to System I the lenses do not need to be telecentric or even of the same type. The distance \( d \) of the optical axes is 100 mm, which still results into a small, handy measurement system. Also, similar to System I, there is a CCD camera and a grating in the image space of the lenses. Both are mounted on a translation stage for movement along the optical axes to change the focus plane in object space. Different to System I, instead of a Ronchi grating a LCD is used for fringe generation. The LCD allows to apply phase shifting with different synthetic wavelengths for phase measurement and therefore no additional movement of the grating is necessary.

Currently, in System II two different camera lenses are used (\( f_1 = 50 \) mm and \( f_2 = 12 \) mm) to get the same apex angle for the CCD and LCD that have different sizes. Therefore they need different focusing positions performed by two parallel

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Fig. 5: Measurement of a Volkswagen gear block with a depth of about 600 mm from a single point of view.

Co-ordinates in the array space
- depth of object: 600 mm
- min. distance of object: 400 mm
translation stages. The next version of System II will have LCD and CCD elements of the same size, same lenses and only one translation stage.

Fig 6: Scheme of the scanning setup (top view) and photo (side view). Size of active parts (LWH): 22x16x7 cm.

For measurement, the operator defines the measurement volume by minimum and maximum desired distance. Automatically a series of focused distances is calculated which covers the volume. Then LCD and CCD are driven using the series of positions (normally not more than 3 to 6). In each position the phase is measured which takes between one and twenty seconds. The time depends on the user selectable wanted accuracy. Noise is decreased during measurement by averaging. Therefore, by using the lower accuracy, the device can be used like a camera without special stabilization.

The resulting series of images is transferred to a computer for evaluation. Without system calibration it is possible to obtain pseudo 3-D data. When the system is calibrated, real XYZ co-ordinates are obtained for the complete measured area. The system resolution depends on object distance and varies due to the small triangulation basis of 10 cm from about 0.2 mm (0.5 m distance) to 5 mm (5 m distance).

8. SYSTEM II – THEORY AND SIGNAL EVALUATION

To explain the used basis of System II we refer to the mathematical model of System I, again. For signal evaluation System I gets a signal \( I_n \), which is drawn in Fig. 7:

\[
I_n \sim \text{modulation}(z, \text{phaseshifts}) \cdot \cos[\phi(z) + \text{phaseshifts}]
\]  

(12)

Fig. 7: Signal evaluation in System I (left) and System II (right).
The movement of the grating perpendicular to the optical axis produces phaseshifts. Using algorithms described above it is possible to extract the phase $\phi$ modulo $2\pi$. Synchronized with the perpendicular movement of the grating is the focusing movement of grating and CCD parallel to the optical axis, which results in a changing modulation of the signal. This produces an envelope for the signal that depends on object distance $z$. The phase $\phi$ contains accurate information about object position and is demodulated using the rough object distance $z$ extracted from the signal envelope.

System II gets a very similar signal $I_{II}$:

$$I_{II} \sim \text{modulation}(z) \cdot \cos[\phi(z) / \lambda + \text{phaseshifts}]$$

By projecting sinusoidal fringes of different synthetic wavelength $\lambda$ it is possible to achieve the demodulation of $\phi$. For each wavelength $\lambda$ the fringes are phase shifted and evaluated using known phase shifting algorithms. Using four phase shifts such a measurement only needs about 12 to 24 images for an absolute phase measurement. To achieve real sinusoidal fringes it was necessary to linearize the LCD response. The absolute phase is determined for different overlapping focused regions in object space, so the whole measurement volume is sampled. Using a geometric model the phase is converted to XYZ co-ordinates. The modulation is also delivered by the used algorithms and can be used to identify the optimum data set in overlapping regions.

To calculate the necessary focal planes to be focused we use ray optic algorithms to describe the depth of focus depending on the f-stop $k$ ($f$-aperture), focal length $f$ of the used lens and the circle of confusion $u$ which has to be smaller than the fringe spacing. For a given focal plane $b$ we get a front focal plane $b_f$ and a back focal plane $b_b$ by the basic focal depth formulas:

$$b_f = \frac{b}{1 + u \cdot k \cdot \frac{b - f}{f^2}}$$
$$b_b = \frac{b}{1 - u \cdot k \cdot \frac{b - f}{f^2}}$$

Fig. 8: Constructing a series of focal plane positions to cover a given depth area.

Both planes $b_f$ and $b_b$ enclose the volume for valid (focused) measurements as shown in Fig. 8. To determine a series of focused planes to cover the complete space from $b_{min}$ to $b_{max}$ we start an iterative calculation using the focal depth formulas:

- We start with the first series $b_{max} = b_{f1}$ to calculate $b_1$.
- The back focal plane of $b_1$ is now the front focal plane $b_{f2}$ of $b_2$.
- This method is repeated until $b_{fN} \leq b_{min}$.
This leads to a series $b_N$ of focal plane distances which can be calculated by:

$$
\begin{align*}
  b_N &= \frac{f}{1 - \frac{b_{max}}{1 + \frac{u \cdot k}{f}}} \\
  &= \frac{f}{1 + \frac{u \cdot k}{f}} \\
\end{align*}
$$

(15)

9. SYSTEM II – EXPERIMENTAL RESULTS

The principle of 3-D profiling using a small triangulation angle and the ability to scan deeply into the measurement volume allows to inspect a class of objects which is normally difficult to measure by triangulation: objects with high gradients that extend deeply over a long distance like tubes and similar objects. Exemplary, we profiled the same Volkswagen gear block with System I and II. The results of System II are presented in Fig. 9.

For this measurement we worked with increased accuracy using a measurement time of 20 s. By this averaging the phase error caused by electronic noise has been reduced down to the level of occurring phase shifting errors. Because of the small triangulation basis, we have a small triangulation angle of about $5^\circ$. For typical triangulation sensors an area related resolution of $10^{-3}$ is expected under these conditions. We had a measurement field extension of 500 mm and the data set reveals a resolution better than 0.5 mm which means our area related resolution is better than $10^{-3}$. The resolution can be increased by using more phase shifting steps to decrease the phase shifting errors with the disadvantage of needing more images and therefore taking more time.

![Fig. 9: Measured VW gear block: Virtual Reality Model of and cut through pseudo 3D-data set.](image)

In Fig. 9, only unfiltered data are presented. Only few points were impossible to measure and the data show high resolution despite the small triangulation basis. It was possible to measure the ground co-ordinates of inlets. To create the virtual reality model and the line cut from Fig. 9, scaled pseudo 3D data are used where X- and Y-co-ordinates are taken as non-corrected equally spaced distances. After calibration of the system all the data points can be calculated into real XYZ co-ordinates.

10. CONCLUSION AND OUTLOOK

In this paper we have presented the new scanning fringe projection techniques (SFP), used for the macroscopic range, employing both phase and contrast information. With a combined evaluation of the modulation and the phase of the signal, it was possible to acquire the topography without ambiguity problems. The modulation information was used for determining the fringe order, and the possibilities of the phase evaluation methods were used to achieve a high accuracy.
First results of complex objects demonstrate the function of the innovative arrangement of the sensor system and the newly developed algorithms. The calibration of the 3-D measurement system, which is necessary in order to get the absolute coordinates of the object space, is a task that will be performed in the near future. Furthermore, a better understanding of the innovative but rather complex measurement technique in connection with the implemented components could be the basis for employing a measurement equipment with increased accuracy, especially for small triangulation angles. This is a precondition for small and low-cost, mobile 3-D sensors.

For System II different LCD and CCD of same size will be used to take two same camera lenses for illumination and imaging. The calibration procedure will be simplified by this and we will calibrate the system to get real XYZ co-ordinates after a measurement. Also during redesign the setup will be further miniaturized to get a small camera like measurement instrument.

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