Confocal Line Scanning Sensor

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Abstract. We have developed a novel confocal-based imaging sensor for surface characterization. In this case, a tilted-plane technique is incorporated in a confocal imaging system to create a new parallel scanning scheme, enabling the sensor to be designed and developed as a robust and simple configuration. With a tilted disk consisting of in-line pinholes, a motionless parallel $z$ scanning scheme is manifested when the specimen is transversely scanned through the stationary diffraction-foci projecting at different depths. This sensor uses a line scanning approach, so that it is entitled as a Confocal Line Scanning Sensor (CLSS). In this paper, the CLSS principle, the concept of data processing, and major calibration are described. The sensor was first developed as a two-dimensional profiler to cover the measurement ranges of up to 50 $\mu$m in depth and up to 15 mm in lateral length. Experimental results were carried out using calibrated specimens for roughness measurement. In this system, the optical lateral resolution is 0.5 $\mu$m, and the depth resolution, defined by noise-limited approach, is 15 nm.

1. Introduction
Increasing the speed of measurement and reducing the complexity of the setup pose significant challenges in the development of a confocal imaging system for price reduction and new market penetration. The confocal imaging technique, first described by Minsky in 1961 [1], has become a powerful tool for surface characterization. Using a pinhole to function as a spatial filter, a confocal imaging system can perform the optical sectioning also known as the depth-discrimination property, and enhance the lateral resolution as compared to a conventional light microscope [2]. However, these enhancements in resolution and in optical sectioning are substituted by the need to scan an observed focal-point in three dimensions to render a 3D surface topography. A real-time Nipkow disk, first incorporated in a confocal microscope by Petrain and Hadravsky [3], can facilitate only the raster scan in the lateral plane ($x - y$), in which case the depth scanning is still required.

In such a circumstance, combining the techniques of motionless parallel depth ($z$) scanning and lateral scanning become a single solution to increasing the speed of a large area measurement. In this paper, a novel technique of motionless parallel depth scanning is demonstrated using a tilted-plane technique [4]. Pursuant to that, a feasible simple and robust setup was designed and developed to preserve the high resolution of a confocal imaging system and the high light-budget efficiency per wavelength of quasi-monochromatic illumination.
1.1. Principle of the Confocal Line Scanning Sensor (CLSS)

The CLSS inspects the specimens using a back-reflection scheme; the emitted light is reflected backward from the specimen to the CCD. In this new approach, a tilted pinhole mask is used to generate multiple optical probes or diffraction-foci projecting at different depths with uniform spacing (Δx, Δz) in the tilted focal plane, as shown in Figure 1(a). Following the Scheimpflug’s rule [5], the measurement range in depth can be extended by increasing the tilt angle of the pinhole mask and so the focal plane. When the specimen is transversely scanned through these foci, a parallel depth scanning is manifested in the z-axis, achieving 160 sampled points per shot. In consequence, the transverse scan of the specimen enables a measurement of a two-dimensional profile of infinite length. Moreover, the stationary diffraction-foci are formed using an optical setup comprising no moving parts, making the setup robust and simple.

1.2. Experimental setup

Key components of the CLSS are presented in Figure 1(b). A light emitting diode (LED), emitting green light at λ = 532 nm wavelength, is exploited as a stable, inexpensive, and incoherent light source. To capture the reflected light signal, a charge-coupled-device (CCD) camera (AVT Dolphin, F145B) is employed. In this design, the Köhler illumination is incorporated to maintain the most uniform illumination, realizing with condenser and collector lenses. An infinity-corrected objective applied in the system helps to facilitate a straightforward calculation in the pinhole mask design. Therefore, an infinity-corrected 20× objective and a matching tube lens (f = 180 mm) from Olympus is selected to carry out the experiment. To eliminate the back reflection from the pinhole mask, the beam from the beam splitter to the CCD is tilted with respect to the normal axis. This method helps minimize the number of optical surfaces used in the setup, as compared to applying polarizers and a quarter-wave plate. The measurement is then conducted using a stepper motor (Haydon 35000 Series, E35H4N-05) to scan the specimen in the lateral direction at 5.8 frames per second (fps).

2. Data Processing and Calibration

2.1. Concept of data processing

A significant role of the data processing is extracting the surface height information from the intensity output. The maximum reflected light intensity carries the surface height information in the form of a confocal curve, as shown in Figure 2(c). In consequence, new algorithms for data processing were developed particularly for use in the CLSS. In the CLSS, the data is acquired in the order that is delineated in Figure 2(a). The data set is then sorted to meet the same x-coordinate as demonstrated in Figure 2(b). When the intensity along the z axis is plotted

Figure 1. CLSS setup. (a) Tilted focal plane. (b) Schematic of the experimental setup.
2.2. System Qualification and Calibration

The qualification of the system parameters is needed to run the data reconstruction. The central parameter is the ratio \( r \) of the lateral scanning acquisition step size \( \Delta F \) to the lateral focal interval \( \Delta x \):

\[ r = \frac{\Delta F}{\Delta x}. \]

This parameter is used to sort the data as shown in Figure 2(b). To reveal \( r \), a lateral displacement standard with periodic chrome stripes, approximately 100 nm high, on glass is used. It is placed so that the stripes are perpendicular to the scanning direction, and an image stack as shown in Figure 3(a) is acquired. The parallel stripes in this image stack have an inclination defined by \( r \). The inclination \( r \) is measured using edge detection modules contained in computer-aided vision systems.

With the knowledge of \( r \), the scanning axis step size can then be calibrated. From the measurement in Figure 3(a), the confocal curve is reconstructed as shown in Figure 2(c). For each \( x \) position of the scanner, the maximum reflected intensity is measured and the periodic pattern is plotted over the uncalibrated \( x \) position, as shown in Figure 3(b). The autocorrelation of the periodic pattern is calculated and its maxima and minima locations are plotted as shown in Figure 3(b). By calculating the mean period length \( \Delta P \) of the maxima and minima along the \( x \)-axis, the calibrated \( x \)-coordinate can be computed from the uncalibrated coordinate \( (x') \) using the absolute period length \( \tau \):

\[ x = x' \cdot \tau / \Delta P. \]

Finally the axial focal interval \( \Delta z \) is calibrated by a standard procedure measuring a groove normal as described in the ISO 25178-701 standard [9].

3. Experimental Results and Discussion

The experiments were carried out on several calibrated specimens, using 20 × objectives. The results in Figure 4 demonstrate that roughness measurement is feasible with the CLSS. In consequence, we compared the CLSS measurements in Figure 4(a) to a commercial confocal microscope, \( \mu \)surf custom from NanoFocus, in Figure 4(b) using the very same objective. For the CLSS, a good agreement of the surface roughness value \( R_a = 1.66 \mu m \) to the calibrated value of the standard \( (R_a = 1.63 \pm 0.03 \mu m) \) could be found. In Figure 4(b), the \( \mu \)surf reveals
Figure 3. Calibration of the lateral focal interval ($\Delta x$). (a) Measured data of a square periodic pattern. (b) Autocorrelation of the measured data of a square periodic pattern.

more details of the profile in accordance with a higher sampling density using a finer lateral-sampling interval of 0.8 $\mu$m, as compared to a relatively large lateral-sampling interval of 2.5 $\mu$m used in the CLSS. In addition, the interpolation of the raw data, applied in the data sorting in Figure 2(b), may further smooth the confocal curve in Figure 2(c), which will filter the high frequency components of the reconstructed profile as the end effect.

On the other hand, the new parallel $z$ scanning scheme of the CLSS has a distinct advantage in adjusting the data density, to improve the resolution in the lateral direction. However, the higher data-sampling density, the more measurement time are needed and the lower the measurement speed. Basically, the lateral resolution of the CLSS is a function of the sampling interval in the lateral direction, which follows the Nyquist sampling theorem, and limited by the optical lateral resolution. The optical lateral resolution of the CLSS is 0.5 $\mu$m, based on 20× 0.45NA objectives and $\lambda =$ 532 nm, where the optical lateral resolution is the FWHM of the lateral intensity response. In contrary, the axial resolution is defined using noise limited approach. The noise limited precision can be verified straight forward by referring to the root-mean-square $R_q$ of the profile measurement on a flatness standard [10]. Accordingly, the noise-limited axial resolution of 15 nm was obtained with the CLSS, using a mirror of $\lambda/4$ flatness.

Figure 5 depicts the axial intensity response obtained with a flat mirror, known as a confocal curve. The graph shows that the FWHM is 3.5 $\mu$m, which is 1.52 times larger than the theoretical value of 2.3 $\mu$m. This is partially caused by using pinholes larger than the theoretical optimum.

Figure 4. Measurement results of a roughness standard calibrated by Physikalisch Technische Bundesanstalt (PTB) of $R_q =$ 1.63 $\mu$m. (a) A profile obtained with the CLSS, $R_a =$ 1.66 $\mu$m. (b) Details of the same place compared to a commercial confocal system, $\mu$surf custom from NanoFocus.
By evaluating the maximum peak of the confocal curve, the surface height ($h$) at a given $x$ coordinate is calculated using the centre-of-mass algorithm [7,8] of the form

$$h = \frac{\sum_{z_p \in FWHM} I_{z_p} \cdot z_p}{\sum_{z_p \in FWHM} I_{z_p}},$$

where $I$ denotes the intensity output obtained in the axial coordinate ($z_p$), and $p = 1, 2, ..., n$ are the indices of data sampled in the axial/vertical direction.

4. Conclusion

In conclusion, a novel parallel depth scanning scheme of the CLSS offering a new solution for two-dimensional (2D) optical profiling with a simplified and robust configuration is verified in this paper. Based on this new measuring scheme, a tilted-plane technique is originally incorporated in a confocal imaging system. Accordingly, the algorithms for data processing and calibrations were particularly developed to support the new measuring approach. The experimental results demonstrate the feasibility of measuring surface roughness by using the CLSS, attaining the optical lateral-resolution of 0.5 µm and the noise-limited axial resolution of 15 nm. Nonetheless, the CLSS can be further developed as a three-dimensional surface topographer, when the variation of the magnification introduced by the tilt is corrected. In the current setup, the CLSS can cover the measurement ranges of 50 µm in depth and of 15 mm in lateral length, with the measurement speed of 5.8 fps. However, the measurement ranges can be enhanced using a high NA objective at low magnification, whereas the speed of measurement can be further increased using a faster data acquisition technique and a faster camera.

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