Endoscopic geometry inspection by modular fiber-optic sensors with increased depth of focus

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ABSTRACT

Within the scope of the Collaborative Research Centre (CRC) Transregio 73 (SFB/TR73) research project, a new kind of micro fringe projection system is being developed. By using flexible imaging fibre bundles, it becomes possible to collect complete data sets of filigree and hardly accessible assembly geometries.
The talk presents the principle of the new kind of endoscopic micro fringe projection system and points out its certain advantages. It combines a laser light source with a Digital Mirror Device (DMD), image fiber and advanced micro optics. Thereby a 7.5 times increased depth of focus of 3 mm compared to 0.4 mm with common light sources could be achieved. Preliminary considerations of the optical design, simulation results and the consequential setup are as well shown as measurement results of the current system.

Keywords: Fringe projection, Endoscopy, Measuring Endoscopy, Laser, Micro, Depth of Focus, GRIN-Optics

1. INTRODUCTION

A quality inspection of assembly parts and tool surfaces becomes more and more important in times of advanced quality management. The trend leads for many parts to 100% testing methods within the running fabrication process. Suited measurement techniques therefore should be, above all, flexible and fast in order to keep up with the production process. Large area analysis of topographies nowadays can be realised with commercially available fringe projection systems with very high accuracy. However, these systems reach their limits for assemblies of high complexities, because of shading effects in the area of measurement.
Within the scope of the Collaborative Research Centre (CRC) Transregio 73 (SFB/TR73) research project, funded by the German Research Foundation (DFG), a new kind of micro fringe projection system is being developed, aiming on the collection of data sets of filigree and hardly accessible assembly geometries.
These sets can be used to generate an own geometric model or to complete measurement data sets of large-scale systems. These models can immediately give feedback about the running manufacturing process and can be used for in situ optimization in the fabrication line to avoid high reject rates. Additionally, measured data of functional surfaces can be combined with spot measurements of conventional coordinate measurement systems. Flexible endoscopes are well known from medical engineering as well as from technical inspection in engines and turbines. Up to now the measuring ability of these endoscopes, especially in the third dimension, is only very limited due to missing information on distance to the object and an integrated scale. Fringe projection systems overcome both problems in one technical approach. However, in contrast to common fringe projection systems micro-optics and fibre couplers have to be used for the adaptation in endoscopy. That also increases the requirements on the light sources to guarantee a high incoupling efficiency and therewith a high contrast micro fringe pattern on the specimen.

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2. EXPERIMENTAL SETUP

2.1 First approach experimental setup

For initial research a first approach setup was designed (Figure 1). Because of its high light output and homogeneous light profile a Köhler illumination was chosen by using a 150 W halogen bulb and parabolic reflector to illuminate the image creating part of the fringe projector. A high resolution DMD was taken that combines a high repetition rate with small pixels, high resolution (1024 x 768) and a good filling factor. The high filling factor as well as the highly reflective surfaces of the mirror avoid heat problems occurred by the high power halogen illumination.

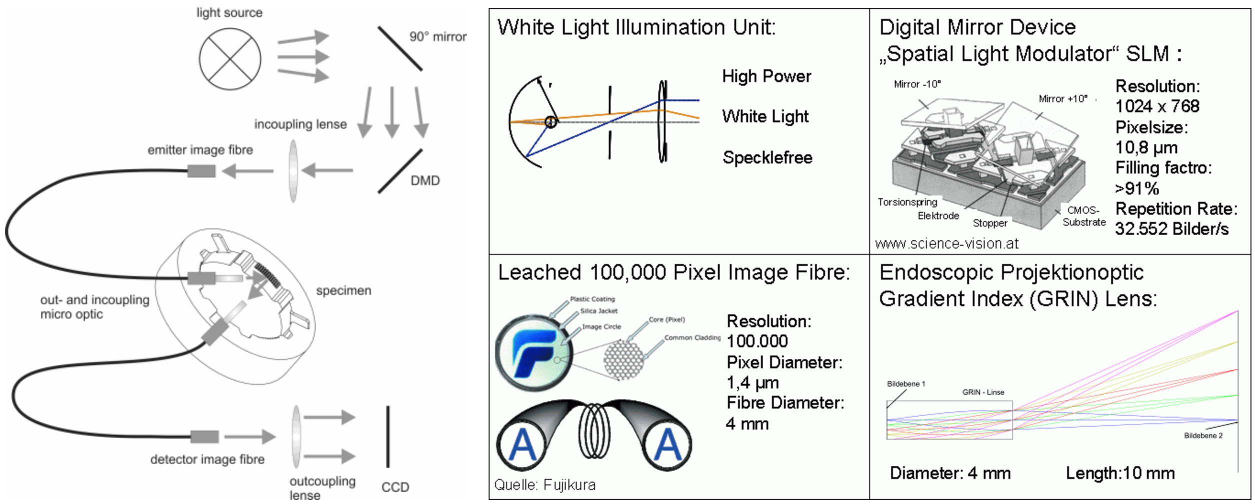

Figure 1: First approach setup (schematic) left; used components (right)

Using a microscope objective with a high numerical aperture (NA) as an incoupling lense the created fringe or sine pattern is then focused to the 4 mm diameter of an image fibre consisting of 100’000 single step index fibres of 1,4 µm effective diameter. At the end a Gradient Index (GRIN) microlens is used generate the picture on the specimen. (Figure 1). A GRIN lens and image fibre of the same kind adjusted in a triangulation angle of 45° transfers the image to a high resolution CCD element.

By taking pictures in certain distances between a planestandard-specimen and the triangulation optics, the maximum depth of focus was 0.4 mm, where the contrast was still processable. For most purposes that is insufficient. To increase the depth of focus an aperture was installed right after the light source. With increasing f-number N (1) the focal depth increases, but at the time also the light intensity at the detector decreases significantly, which again does not lead to a sufficient contrast on the aimed image size of 4 mm diameter.

$$\mathrm{N} = \frac{f}{D} \tag{1}$$

N is the f-number, where f is the focal length and D the diameter of the entrance aperture.

Targeting a short measuring time for an in process control, the illumination time should be short, also the amount of heat created by the light source should stay under an extreme level. An alternative light source should therefore have a high intensity on a small spot comparable to a high f-number. Lasers normally fulfill these conditions by their nature. However, they have disadvantages as well, such as its Gaussian beam profile and coherence effects that cause speckle accumulation.

2.2 Final Setup

In the final setup the Köhler light source was replaced by a powerful but less heat creating diode pumped solid state (DPSS) illumination laser with 100mW that is connected to a beam shaper with a rotating diffuser (Figure 3). The Beam shaper, consisting of two common microlens arrays, creates a flat top with an equalized intensity square profile (Figure 2) that was calculated to fit exactly to the size of the DMD [1].

Figure 3 illustrates the beam path to the first fibre incoupler. The beam shaper consists of two 60 mm lenses set up as a telescope with a rotating diffuser disc in its focus. The diffuser creates a changing speckle pattern that is later integrated on the CCD-Camera. Thereby the speckle contrast is lowered to a negligible level. Fringe contrasts of a common non coherent light source can easily be achieved without significant drawbacks for the purpose.

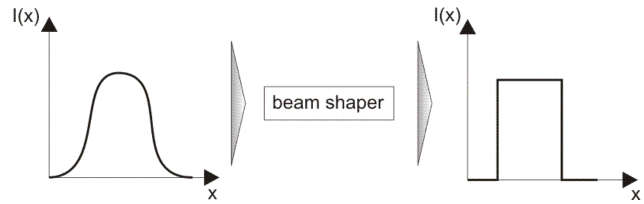

Figure 2 : Beam shaper intensity profile

Further, on two fly eye lense arrays with a single lense pitch of 500 µm, a 4.5 mm focus and anti reflex coating are used to change the Gaussian to a square beam shape. The flat top is then projected to the Far Field and the DMD positioned in the exact image plane of a Fourier lense with high focal length. Another focusing optic with high NA transmits the DMD-picture into the fibre. Successful approaches with analog setups were already made by other groups [2].

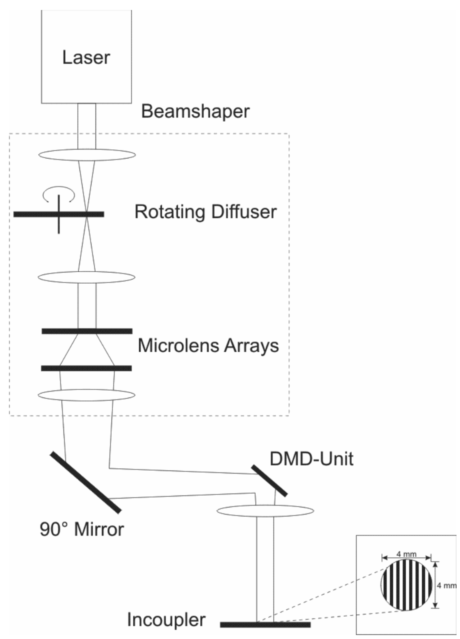

Figure 3 : Beamshaper setup (schematic)

Within the beam shaping process the divergence angle stays in an acceptable range. It was measured to be less then 3°. That still hits the requirements of a high f-number, high intensity light source. In Figure 4 the whole setup is presented schematically. The high resolution pattern by that is reduced to a 100.000 pixel picture, due to the limited number of fibres in the imaging fibre.

Using ray tracing simulations with FRED® optical engineering software of “photon engineering”, ideal micro optical designs and optimized picture planes were determined and adapted by the development of an iterative adjustment procedure for the setup. Afterwards the incoupling lense in front of the first fibre was replaced by a Beam-Profiler (LBP-2-USB of Spectra Physics GmbH) to determine the qualities of the setup.

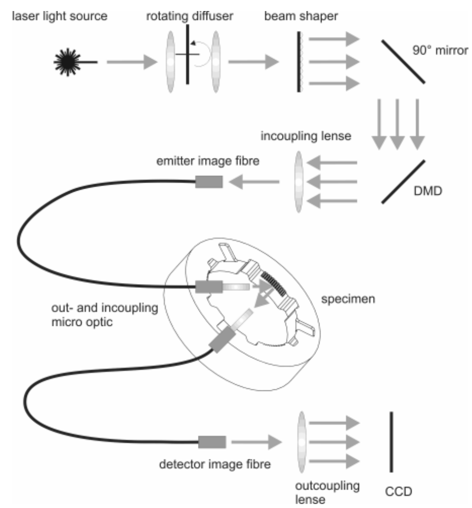

Figure 4 : Final setup (schematic)

3. EXPERIMENTS AND RESULTS

The Beam-Profiler was adjusted perpendicular to the beam on a micrometer stage and a narrowband wavelength filter with a transmission of more than 90 % in the wavelengths around 532 nm ± 10 nm and a high reflection of more then 99% of the other wavelengths. The filter reduces influences of ambient light to a negligible level. In addition all measurements were taken in dark environment. The Beam-Profiler is moved perpendicular to the beam and pictures are taken in distances of 25 mm to each other. Afterwards a graphics program was used to create an overview of the whole profile in one picture. Figure 5 shows the first approach with only the Beam Shaper assembly without the despeckling setup. The left side shows a cut through the middle of one of the pictures, the right side is the same cut after a median filtration. The flat top predicts a square shape, but is far too noise to be used in electronic image processing also the cut shows high inhomogeneities compared to its neighbour cuts within the same picture.

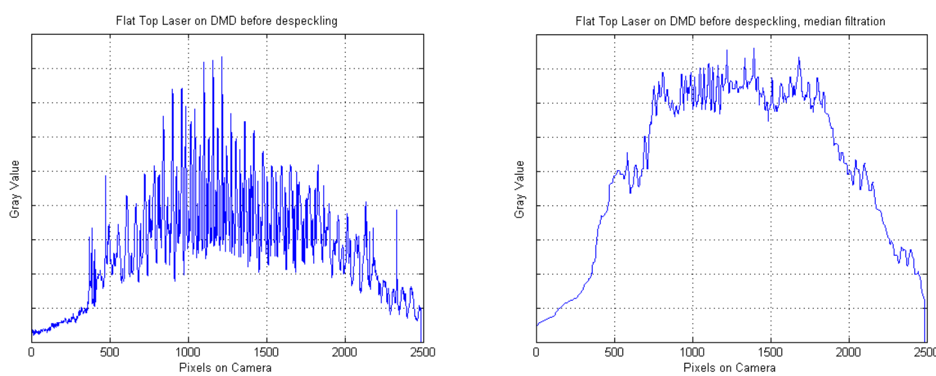

Figure 5 : Flat Top without rotating diffuser before (left) and after (right) median filtration

After activating the diffuser (Figure 6) the image quality and homogeneity increases significantly, with the median filter the flat top distribution is clearly visible. Also the homogeneity of the whole picture becomes comparable to a non coherent light source. Figure 7 presents the difference in the whole picture, already with a projected fringe pattern. The falling intensity distribution from the bottom to the top of the picture originates from a tilting angle of the projection surface. Both pictures were taken by the CCD-Camera behind the detector fibre bundle (Figure 4). For the analysis of the depth of focus a plane surface is moved in discrete steps of 250 µm in direction of the beam path in the focal area of the lense. Once the initial 150 W Halogen-Bulb was used as light source. The f-number was adjusted with an aperture in front of the light to maximum contrast as a compromise with intensity. The projected pattern is a b/w stripe pattern. Figure 8 (top) shows the intensity distribution of a representative line of pixels in different distances of the target to the sensorhead. The contrast for a grey-code based image processing is only sufficient for in a distance of 400 µm, which can be seen in the middle area of the picture.

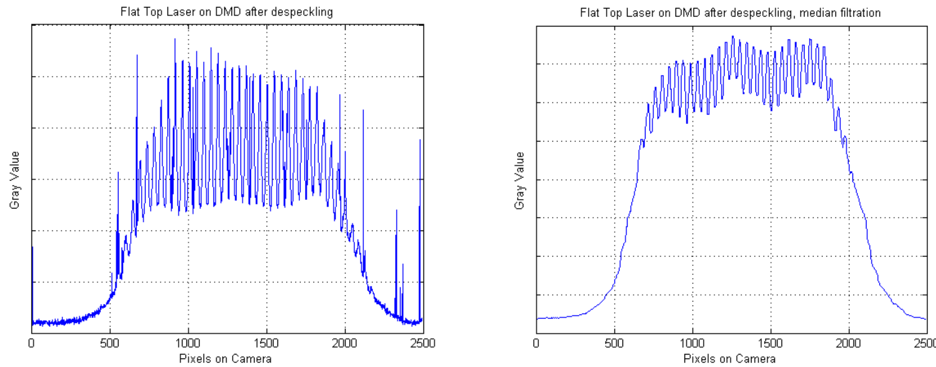

Figure 6 : Flat Top with rotating diffuser before (left) and after (right) median filtration

The same experiment is then repeated with the laser assembly as described in Figure 4. No aperture is used this time, only the laser power was adjusted for a good contrast at the same frame rate of the camera as it was chosen before. Results are shown in Figure 8 (bottom). The contrast is increased in the whole are, even in the edges of measured focal area, image processing is still possible by the means of contrast. That means a significant increase of the depth of focus to 4 mm.

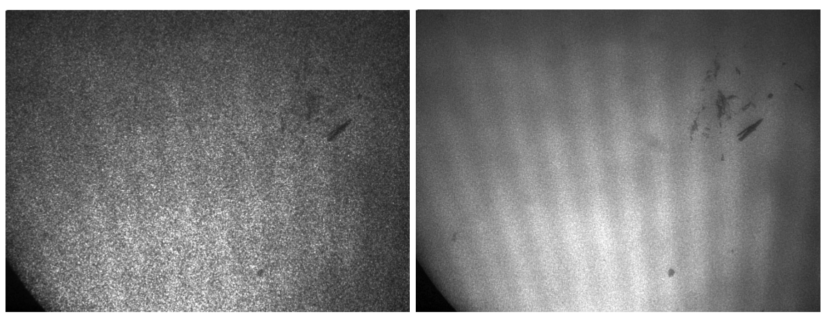

Figure 7 : Laser projected fringe pattern without (left) and with (right) rotating diffuser

The f-number was calculated to be about 9 (Figure 9). Tests were performed to see whether the gray code and sine pattern processing is working as predicted in the new measurement volume with a tilted plane specimen. The results show, that data processing is successful in the whole Volume (Figure 10).

For the transformation in a 3D model of a specimen it is necessary to transform the reflected picture into coordinates. By the projection of a stack of black and white stripe patterns in order of a Gray-code projector and camera are aligned on the specimen and corresponding pixels of both devices identified. With the information of the triangulation and the beforehand made camera coordinate calibration the exact geometry of the sample can be calculated to compare its shape to the CAD model with the accurate measures. To increase the resolution of the system four phase shift cosine patterns are projected to the specimen's surface. Added to the before taken Gray Code pattern it creates a highly accurate and well defined scatter plot for 3D measurements.

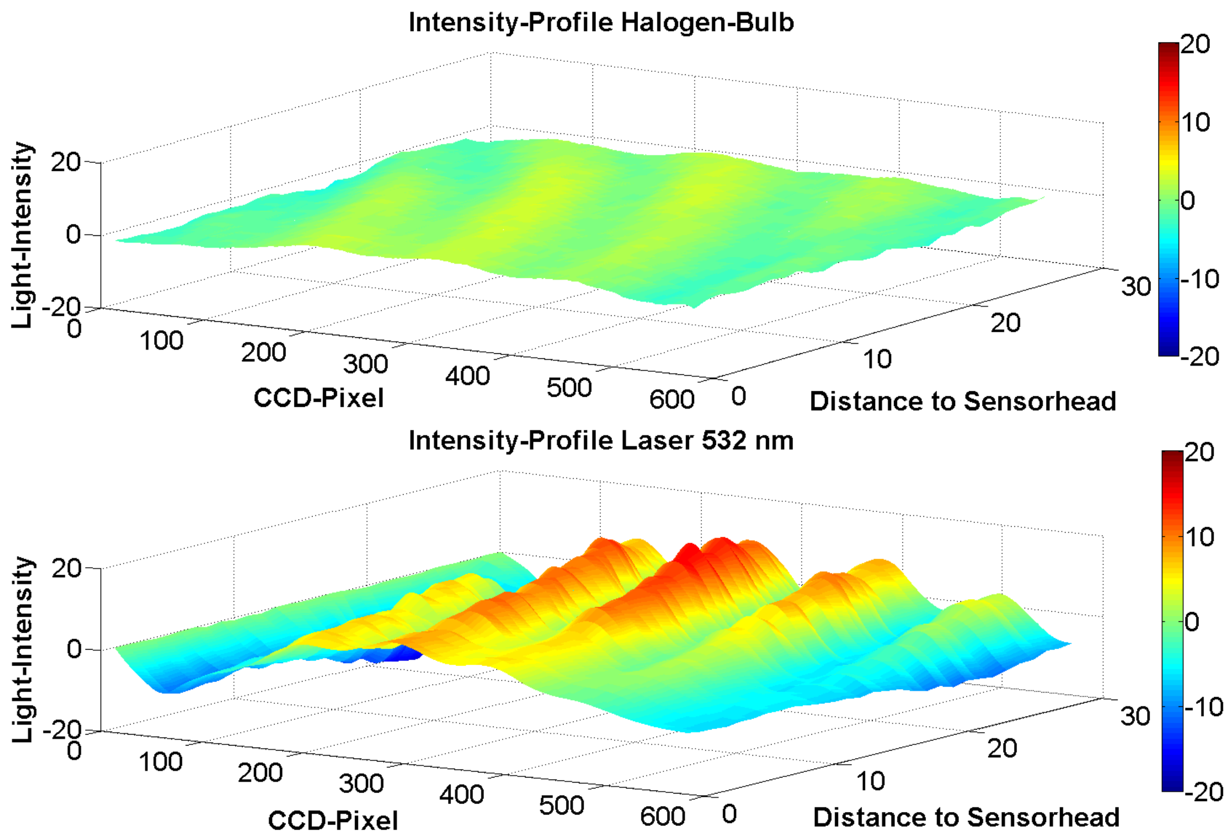

Figure 8 : Intensity distribution of a projected fringe pattern on the CCD-Camera with 150 W Halogen-Bulb (top) and Laser Illumination (bottom)

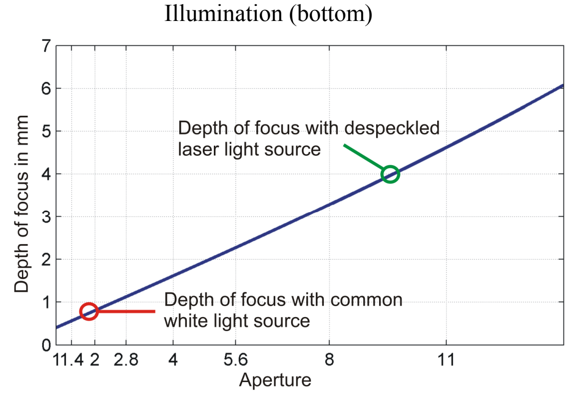

Figure 9 : Depth of focus in dependence of the Aperture respectively f-number

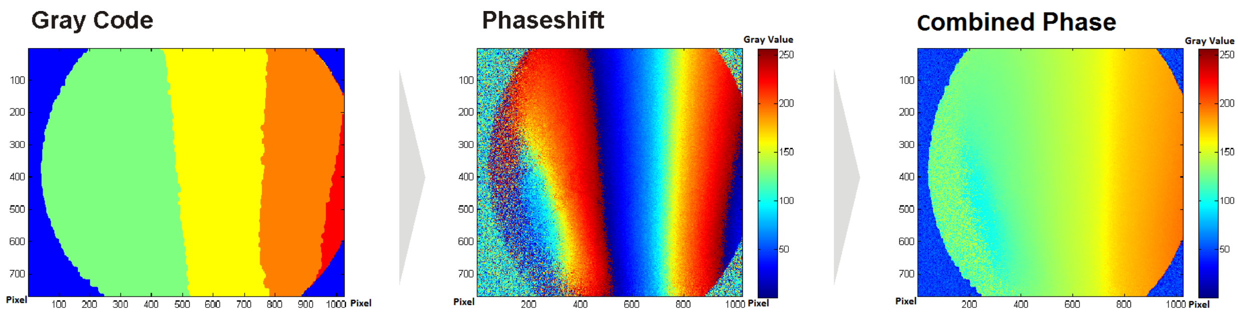

Figure 10 : Phase Algorithm on a flap surface (Grey Code – top, Phase shift – middle, combined phase - bottom)

4. DISCUSSION AND OUTLOOK

The results show that laser illumination of micro fringe projection systems is a very good alternative to common LED or bulb based light sources. At a low power consumption and low heat output, a laser can create a very high depth of focus. The Depth of focus of the shown experimental setup was increased about 7.5 times from 0,4 mm to 3 mm. Problems with speckle contrasts that normally occur at coherent light sources were solved for the purpose.

As a next step the micro optics at the fibres will be optimized on the base of optical simulations with FRED® and disruption of scattered and ambient light will be excluded by a laser save housing (Figure 11).

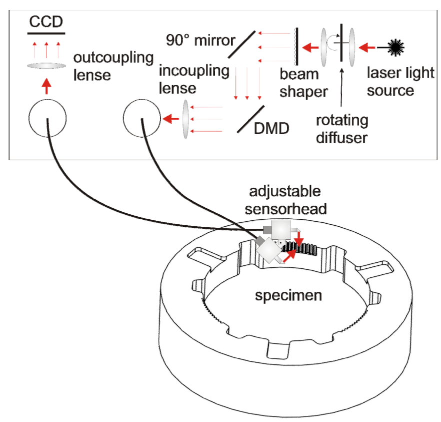

Figure 11 : Laser based endoscopic fringe projection system schematic

5. ACKNOWLEDMENT

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