Coherent Pattern Projection for Highspeed 3D Shape Measurements

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1 Introduction

Since many years laser triangulation is a key technology for metrological measurements. Manifold sensors exist that measure single spot distances or distance profiles via triangulation between the illumination source (e.g. laser diode) and an imaging system incorporating typically a digital detector. The physical limits have been investigated and derived by several researchers [1]. It has been stated that the main limitation for laser triangulation is subjective laser speckle noise that occurs when the laser spot or line is imaged onto the detector.

This leads to an error in point localisation and therefore conceals the real 3D point location. Thus, for industrial shape inspection tasks requiring highest accuracy in comparable volumes applicants are advised to use incoherent 3D shape measurement technologies to overcome the subjective speckle noise limitation. The well-established fringe projection sensors use a halogen light bulb or a light emitting diode (LED) source. They are widely applied in combination with temporal coding, showing several patterns (typically phase-shifted fringes) for one 3D reconstruction. Those sensors deliver very high accuracy in a comparable measurement volume but are typically slow (measurement time in the range of several seconds) compared to laser triangulation sensors due to their need for sequential image projection.

We propose two new 3D sensor concepts using coherent laser light and temporal coding. They are affected by subjective speckle noise but are much faster in projection than most of the incoherent fringe projection methods. Hence, they represent a technique in between the aforementioned. This paper will explain both setups and shows that a projection rate of nearly 200 kHz is possible.

2 Laser Speckle Projection for 3D Shape Measurements

The 3D sensor concept based on coherent laser speckle projection is shown in Figure 1. A laser source emits a laser beam that is diffracted at an acousto-optical deflector (AOD). The AOD is controlled by a frequency-driven piezo transducer

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that emits an acoustic wave into the crystal of the AOD. By changing the frequency of the wave, the induced diffraction grating period is changed and the angle of diffraction is altered. This allows an angle scanning of the input beam in the first diffraction order behind the AOD. The first order beam is then focussed onto a diffuser that acts as a statistical diffraction grating and gives random bright-dark regions in the far field well-known as objective laser speckles. The optional lens behind the diffuser can be used to refract light into the desired measurement volume.

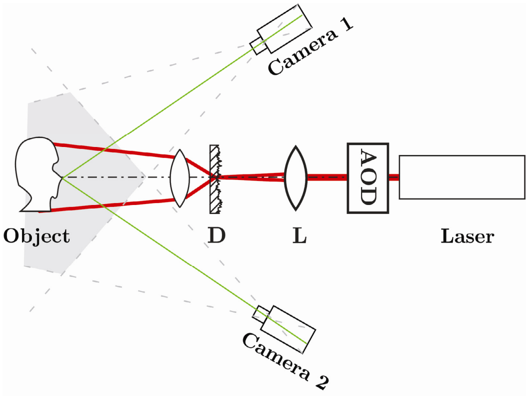

Fig. 1 Setup for sequential laser speckle pattern projection for 3D shape measurements using stereophotogrammetry with structured illumination

During the measurement both cameras take images of the object. Every image itself shows the illuminated object with a different statistical objective laser speckle pattern that is created by changing the focal spot position on the diffuser. Since the speed of sound within the crystal is high, one can change the diffraction angle at unprecedented 200 kHz which represents the maximum pattern projection rate for this setup. A quantitative measurement proofs this in Section 3.

We performed measurements to characterize the accuracy of the system in comparison to an incoherent approach that has been validated to be as accurate as state-of-the-art fringe projection systems [2]. Hence, the comparison is valid also to compare relatively the laser speckle projection technique to common fringe projection sensors.

For the measurements we used two highspeed cameras (PCO Dimax, 720x480 Pixel, 4630 Hz) with a focal length of 17 mm and a base distance of 0.28 m. The measurement volume was approx. 20x15x10 cm³. In between the two cameras we placed the laser speckle projection unit to synchronously project patterns and capture images. The captured images were taken for temporal correlation to solve the correspondence problem between both camera views and find many homologous pixel pairs. This technique is extensively discussed and explained in [3,4]. Given an intrinsic and extrinsic calibration, those pairs were then taken for triangulation to reconstruct numerous densely packed 3D points.

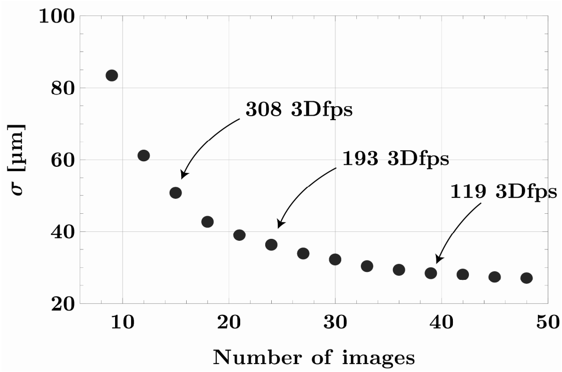

Fig. 2 Accuracy results for the laser speckle projection 3D sensor. σ denotes the standard deviation of 3D points around a fitted certified plane. For different numbers of images the achievable 3D accuracy is shown.

The quantitative results and achievable accuracies are shown in Figure 2. A certified measurement plane was placed inside the measurement volume. A plane function was fitted to the reconstructed 3D points. The point deviation around the plane function is calculated to σ and plotted for different amounts of images in Figure 2. When 15 images are used for the temporal correlation a 3D point localisation accuracy of 50 µm is reached. The relative accuracy given by the 3D point localisation accuracy divided by the measurement volume diagonal amounts to 1.9 *10^-4.

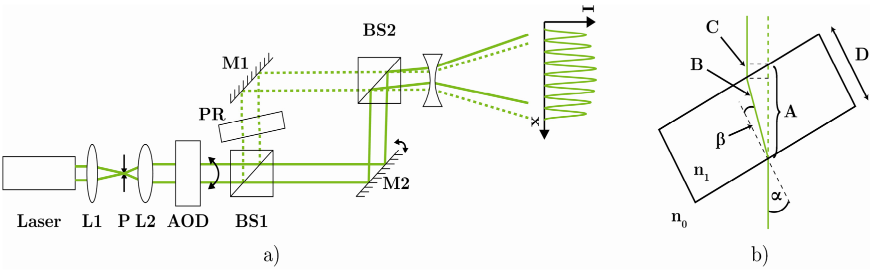

Fig. 3 Schematic drawing of the fringe-creating Mach-Zehnder interferometer including the supplementary AOD for angle switching and the glass plate for angle-sensitive phase retardation. b) shows the incidence angle dependent path delay line for phase shifting.

3 Coherent Fringe Projection by Two-Beam Interference

The aim of highspeed 3D shape measurement with structured illumination can be addressed in general in two ways. One is to increase the projection and image acquisition rate and the other is to decrease the amount of necessary patterns for one single 3D reconstruction. It has been shown that it is preferable to use fringes, since shape reconstruction can be done precisely with only 3 phase-shifted images. This can't be done by statistical pattern projection with the setup proposed in Section 2, that typically needs 9 or more patterns for one reconstruction. The second system shown in Figure 3 and 4 enables highspeed fringe shifting for 3D shape measurements by using an AOD.

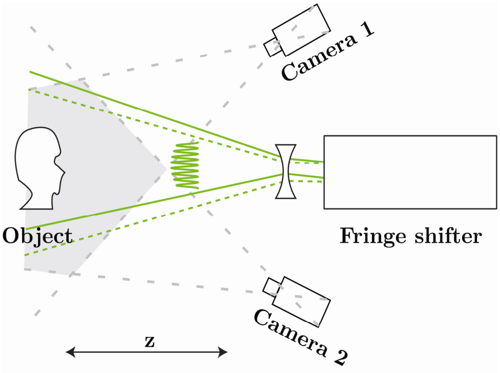

Fig. 4 Overall setup using the Mach-Zehnder interferometer inside the Fringe shifter and two cameras for stereophotogrammetric shape reconstruction

A pinhole-filtered and collimated beam passes the AOD so that the first-order diffracted beam can be altered in direction by changing the acoustic frequency within the crystal. One mirror inside the interferometer is slightly tilted, so that at the output two tilted plane waves interfere that create a sinusoidal fringe pattern depending on the tilt angle between both beams. If one changes the incidence angle of the interferometer by the AOD, the refraction law at the glass plate PR results in an non-linear path difference between both arms. By this, one can induce path differences by changing the angle with the AOD. Since this can be done at very high rates, fringe shifting can reach the aforementioned frequency of approximately 200 kHz.

To evaluate the maximum achievable accuracy we distinguished the 3D point noise at a certified measurement plane, comparable to the measurements that have been done for the first system. The results can be seen in Figure 5. The cameras (240x240 pixel, 414 Hz) with a base distance of 0.6 m and focal length of 17 mm were placed beside the fringe shifter. The measurement volume amounted to 10x10x10 cm³.

It is noticeable that the incoherent approach reaches a lower 3D noise and therefore gives more accurate 3D points. On the other hand the Fringe shifter system achieves better accuracy (σ = 532 µm for N=3, relative accuracy equals to 3*10^-3) for less images, e.g. for N=3. In this case, the incoherent approach can not be used and fringe projection is favorable. The higher noise level for more

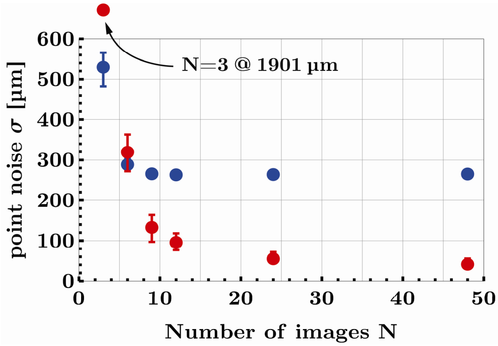

Fig. 5 Experimental results of the Fringe shifting setup (blue) in comparison to the incoherent statistical pattern projection (red) aforementioned and proposed in [5] for different amounts of images

images per reconstruction comes from the presence of subjective speckle noise that occurs when the coherently illuminated object is imaged. This is a disadvantage that can be addressed by speckle suppression techniques, but will always play a role.

On the other hand this technique allows very high fringe shifting rates as shown in Figure 6.

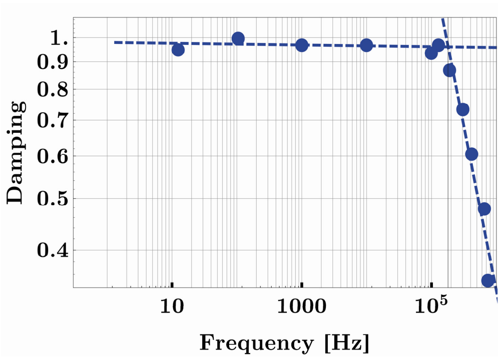

Fig. 6 Frequency properties of the AOD. At the point where the damping decreases spontaneously the maximum accessible frequency is reached.

For the experimental results shown in Figure 6 we calculated the ratio between the signal voltage applied to the piezo transducer emitting the acoustic wave into the crystal and the voltage of a photo diode placed into the stripe pattern. At the frequency where the beam deflection cannot follow the applied angle rate, the ratio decreases. By this, we extracted the maximum permissible beam deflection rate or phase-shifting rate. The value was calculated to 179,872 Hz. If one would use 3 images for one reconstruction and suitable cameras an overall 3D measurement rate of nearly 60,000 Hz would be possible.

4 Conclusion

In summary, we explained two systems for coherent, high frequency pattern projection that can be used for structured illumination within a stereophotogrammetric 3D sensor. Both systems make use of an acousto-optical deflector and can switch the pattern at approx. 180 kHz. The second system has the advantage of using fringes that allow short sequence lengths and 3D reconstructions with only 3 images necessary. On the other hand, since there is now gray-code applied, this system is restricted to steady surfaces or changes within one period length. This restriction is not given for the first system that needs more images for one reconstruction but is as accurate. Both systems show lower accuracy in comparison to incoherent projection devices, like the one we compared to [5]. This was explained to emerge from the existence of disturbing subjective speckle noise.

References

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