Active Optical Systems and Computational Imaging

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Theoretical and experimental investigations concerning the influence of coherent noise on the resolution of data measured with triangulation sensors

S. Haberl, M. Gronle, T. Haist, W. Osten

Active triangulation on rough surfaces is fundamentally limited by speckle noise. Especially for laser-based methods speckles will lead to a strong uncertainty in height measurements. Dorsch and Häusler clearly explained and analyzed the (conventional) situation where the numerical aperture of the illumination of the surface under test is lower than for the imaging onto the image sensor [1]. This situation is common for typical systems using scanning lasers points or scanning lines (“Lichtschnitt”). The other option is to use a comparatively lower numerical aperture for the imaging.

For all such speckle-limited measurement systems the typical approach is use some kind of temporal averaging to finally reduce the speckles. To this end we investigated the use of dynamic computer-generated holograms written into a spatial light modulator (here: Holoeye TN-LCD, 800 x 600 pixels). By this approach it becomes possible to directly program the wavefront of the illuminating spot of a triangulation sensor. Also, the position of the spot can be very accurately changed. Different patterns have been tested by simulation and experiment.

It turned out that for the conventional geometry (numerical aperture of illumination low) the speckle-based uncertainty can only be reduced by a small amount (approximately 20 to 30 %). However, for the case with the low numerical aperture of the imaging strong improvement is possible by using a micromovement of the illuminating spot (within the area of the diffraction limit of the imaging). This indeed is expected because different microstructures are illuminated leading to different (uncorrelated) speckles. This way, the statistical measurement uncertainty has been reduced by a factor of three using the average of ten recordings.

Apart from micromovement, different other wavefront changes in the Fourier plane have been investigated. Zernike polynomials as well as doughnut wavefronts with different integer and non-integer phase dislocations are also possible.

Fig. 1 shows the setup used for testing the improved triangulation. Fig. 2 shows measurement curves for the linear axial translation of a plane object using a piezo stage. Obviously, the micromovement method with ten times averaging considerably improves the statistical measurement uncertainty. In the future the method might be used also in combination with a rotating static computer-generated hologram. Additional errors due to the discretization of the image sensor might be eliminated using a multipoint imaging optics [2].
**Fig. 1:** Experimental setup for testing the reduction of statistical measurement uncertainties.

**Fig. 2:** Reduction of measurement uncertainty of triangulation spot for axial displacement of the test surface with conventional imaging and under different amounts of averaging using micromovements.

References:


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New setup for the characterization of image sensors with respect to fixed-pattern noise

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Fixed-pattern noise is – especially for CMOS-based sensors – one of the main noise contributions for image sensors. Whereas time dependent noise, e.g. dark current noise, photon noise, read-out noise, can be always reduced by averaging over many frames, the spatial noise contributions are not so simple to eliminate. Especially at high light levels, the so-called photo-response non-uniformity (PRNU) considerably limits the achievable signal-to-noise ratio and, therefore, the achievable measurement accuracy for different image-sensor based measurement techniques. At low-light levels, on the other hand, dark signal non-uniformity (DSNU) is the major contribution.

Of course, the sensor manufacturers already include dedicated circuits and look-up tables to individually correct the responses of the respective pixels. However, since the behavior depends on a lot of factors (e.g. wavelength, exposure time, temperature etc.), complete calibration for all applications is not possible.

We realized a setup for measuring PRNU and DSNU based on a Fourier geometry with a rotating diffusor. Compared to the standard characterization setup as proposed in the leading standard EMVA1288 [1], a better light efficiency is achieved. Also problems due to possible straylight/reflections on the sensor housing is reduced and sensor-sided telecentricity is achieved.

The setup is depicted in fig. 1. The rotating diffusor is located in a Fourier plane of the sensor. Therefore, imperfections of the diffusor (dirt, scratches etc.) will be distributed evenly on the whole sensor and, therefore, will not disturb the measurement.

Within the measurement procedure (implemented in ITOM) every frame is recorded 100 times to average out temporal noise contributions. A very stable fiber-coupled thermal light source has been used in combination with different 10 nm bandpass filters to measure the behavior of three sensors (PCO edge 3.1 scientific CMOS), Point Grey GS3-U3-23S6M-C (Sony IMX 174) and Ximea XiQ MQ013MG – E2). All sensors achieved quite good results for PRNU with the PCO edge and the Sony sensor achieving results below 0.3 %. For the DSNU, as expected, the scientific CMOS sensor of the PCO edge resulted in exceptionally high quality with DSNU values below the measurement uncertainty of our measurement setup.

Temperature dependence of DNSU for the non-cooled sensor was as expected (strongly increasing DSNU) with temperature. Also, as expected, especially for small F-numbers pollution of the cover plate of the sensor increases the PRNU.

Fig. 2 shows a typical output of the characterization software where the PRNU is shown for every column of the image sensor. In addition, maximum and minimum values for the deviations are shown and a histogram of the deviations are rendered in the background.
Fig. 1: Fourier-based setup for the characterization of Fixed-Pattern noise for image-telecentric applications with a given image-sided numerical aperture ($\sin \alpha'/F$-number).

Fig. 2: Typical measurement output showing PRNU, minimum and maximum deviations and histogram for each column of the sensor (here: PCD Edge 3.1).

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Meanwhile there is a bunch of different phase retrieval approaches available. In this project we have developed a benchmark system and a corresponding optical setup for testing the performance of different phase retrieval methods. Therefore, we are using a spatial light modulator (SLM) in the optical path for adaptively changing the characteristics of the setup. Doing so, we are able to use the setup for testing different phase retrieval methods and their parameters without any mechanical changes. Thereby, the user is supported with respect to the task-dependent selection of the most suitable phase retrieval method.

Usually, for measuring the phase of an object, an interferometric measurement setup is utilized. Beside interferometry of holography which need some reference wave for determining the phase, there are also methods which do not have the necessity of a second interfering wave. These phase retrieval methods often use multiple images and a corresponding algorithm for calculating the phase.

Because there are many different phase retrieval methods and their performance strongly depend on the phase object itself and some method specific parameters it is important to compare different methods for a given object. Therefore, we introduced a benchmark system, for objective judging of the methods [1]. Next to the pure simulation based benchmark, a practical implementation is important to verify the simulation results. Thus, we built a microscopic setup including an SLM for easy and fast parameter changing, see fig. 1. We insert a rotating diffuser in the illumination path for speckle reduction and be moving the laser in z-direction we can control the grade of coherence. After the phase object we image it via a microscopic objective and a tube lens onto half of the SLM in the intermediate image plane. There we can manipulate the object using for example some phase masks. After that the object is imaged onto the camera by a telescope where the second half of the SLM is placed in the Fourier plane, where we can correct aberrations of introduce some defocus by writing in some Zernike polynomials.

In conclusion, we developed a SLM based adaptive phase retrieval setup which is suitable to measure phase objects with different methods and parameters by proper hologram settings.

\[ \text{References:} \]


Post-processing for the compensation of chromatic aberrations in programmable microscopy

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Spatial light modulator (SLM) based microscopy [1] traditionally is performed using coherent illumination. However, problems due to speckles and other interference-based disturbances often lead to noisy images. Incoherent illumination avoids such problems. Spatial incoherence in combination with monochromaticity is hard to achieve at reasonable optical power. Therefore, often temporal averaging e.g. using rotating diffusors is employed. LEDs achieve a limited spatial and temporal coherence and are in principle good choices for microscopy. When used in combination with a diffractive optical elements and a carrier frequency (which is necessary to separate unwanted diffraction orders due to the non-ideal modulation characteristic of the SLM from the desired diffraction order) strong chromatic aberrations will occur.

The chromatic aberration will be always perpendicular to the grating structure. Therefore, it is possible to change the orientation of the PSF shape by rotating the carrier frequency grating. Then, by postprocessing it becomes possible to combine several images obtained with different orientations in order to compute one sharp image with strongly reduced overall chromatic aberrations. To this end for every pixel position it is decided which image of the acquired image stack yields locally the sharpest image. This pixel is selected to be locally used within the final image. For the decision different metrics might be used. Currently we employ a simple local standard deviation metric to decide about the local sharness.

The setup (fig. 1) uses a Holoeye Pluto modulator in combination with green light (535 nm) and a Vistek CCD image sensor. Instead of a microscope objective lens a conventional achromat with a focal length of 30 mm is used in order to achieve a long working distance. The aberrations due to the achromat are corrected by proper addressing of the SLM (modulation of the carrier frequency by the conjugate of the aberration).

Fig. 2: Chromatic aberration (here in horizontal direction) due to LED illumination

Fig. 3: Combination of 7 images to improve resolution.

References: