Unusual optical imaging systems for special applications

Stars, germs, and everything in between can be better seen by the COACH's methods

Projektbericht

Introduction

Observation is the first step along the path of understanding the world around us, and imaging is the one of the main tools of observation. Imaging technology is the collection of methods used to duplicate images from one domain to another. In the area of optical imaging, we are nowadays in the middle of the era of digital imaging, in which images are recorded by digital cameras and processed by computer software. One can appreciate the importance of digital imaging from the fact that many of us use this technology on a daily basis, when we take pictures by our smartphones. The digital optical imaging has opened the field of indirect imaging in which a non-image pattern of the observed scene is first recorded into the computer as an intermediate pattern. In the computer, the image of the scene is recovered from the intermediate pattern by digital processing. Digital holography is a typical example of indirect imaging in which the digital camera records one or more holograms of the scene. A classical digital hologram is a pattern of light intensity created by interference of light beams, where at least one of the beams contains the image information of the observed object. The image, usually the three-dimensional image of the scene, is reconstructed by the computer program. The main benefit of digital holography is the ability to image three-dimensional scene with single camera shot, or very few camera shots. Other advantages of digital

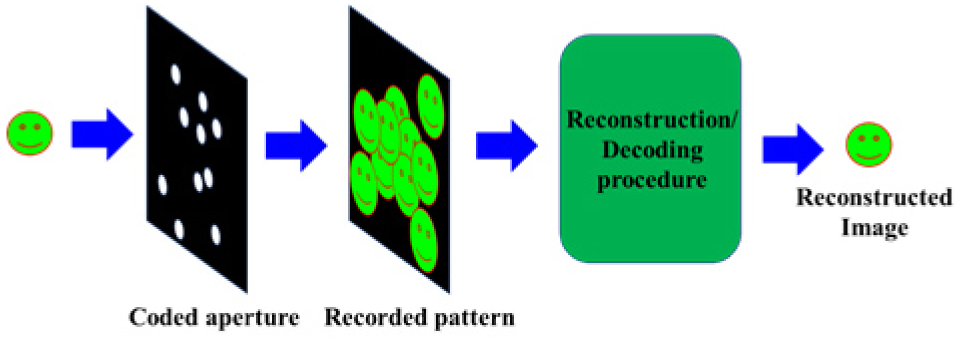
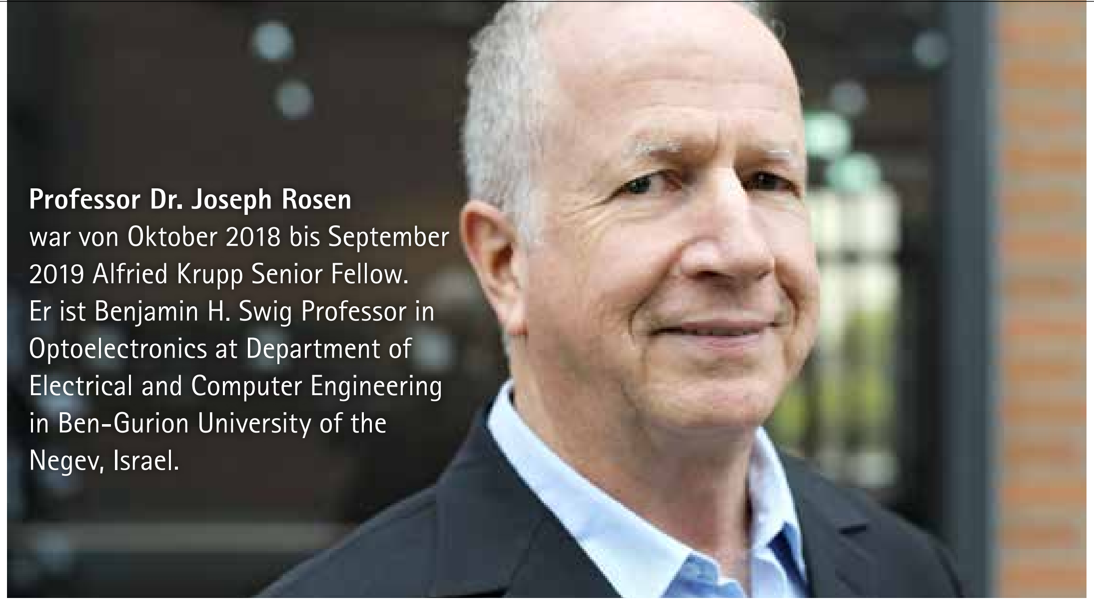


Figure 1. Coded aperture imaging system



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Fellow-Projekt

» Unusual Imaging Systems for Special Applications

Understanding the world around us begins with the observation, and optical imaging is the one of the main tools of observation in science. Optical imaging has been well-known in nature and in technology for decades. The history of imaging technology starts about a millennium ago with the emergence of the first eyeglasses in Europe. Since then, the entire optical imaging systems like microscopes, telescopes, cameras and others have full apertures usually in a shape of a disc. The reason for that is obvious; any attempt to use only part of the full aperture reduces the image resolution and blur the details of the image, originally captured by systems with the full aperture. Direct imaging is another feature of the traditional imaging systems. The image is directly displayed on the image sensor without any intermediate processing.
About three years ago we proposed a novel indirect imaging method that combines two different concepts; "coded aperture imaging" and "incoherent digital holography". This unique combination merges the merits of two different imaging modalities and opens a new world with interesting unexpected features. The new imaging concept is dubbed "coded aperture correlation holography" (COACH). In COACH at least one of the interfering light beams passes through a coded aperture mask. In the frame of the fellowship year in Alfried Krupp Wissenschaftskolleg Greifswald, we investigated new COACH-based methods of optical imaging and demonstrated their performances. In this project, we describe some of these new techniques of three-dimensional optical imaging with superior imaging performances. Possible applications for these imaging methods, ranging from space telescopes to a new generation of microscopes are discussed.

holography are the ability to image targets through a scattering medium, and the ability to resolve object details better than the resolving capabilities of other equivalent imaging systems with a similar physical aperture.

Most of the imaging tasks in optics are performed with natural incoherent light. This is true for most microscopes, all telescopes and many other imaging devices. However, holography in general, and digital holography in particular, are not widely applied to general natural light imaging, because creating holograms requires a coherent interference system in which two coherent laser beams interfere to create the pattern of a hologram. A possible solution to detour this coherence problem is the "coded aperture imaging" illustrated schematically in Figure 1. In "coded aperture imaging" the input beam is detected by a digital camera after passing through one or more optical masks. As in case of digital holography, the observed object is reconstructed by a digital algorithm. However, in "coded aperture imaging", the recorded pattern is not created by wave interference. The main advantage of the "coded aperture imaging" is its relatively high-power efficiency achieved without sacrifying the image resolution.

During my research fellowship of Alfried Krupp Wissenschaftskolleg Greifswald (AKWG), we have investigated a novel concept of indirect optical imaging which combines the two mentioned-above imaging methods; "digital holography" and "coded aperture imaging". This unique combination merges the merits of these two different imaging modalities and opens a new world with interesting unexpected features. The new imaging concept, shown schematically in Figure 2, is dubbed "coded aperture correlation holography" (COACH). The new imaging model can be implemented in many different devices like microscopes, telescopes, and other imaging systems. Hence, the research can contribute to different scientific fields like biology and astronomy. The main goal of the research has been to develop new imaging systems that have superior imaging capabilities over existing systems. Among others, the imaging properties that have been improved are the image resolving power and the immunity from inherent noise. In the following, I summarize the research of our group during my fellowship year in AKWG.

The topic of COACH since its invention by our group in 2016 is reviewed in a paper published in 2019 in the journal Applied Sciences [1]. In this review, we survey the main milestones on COACH from two main points of view. First, we review the prime architectures of optical hologram recorders in the family of COACH systems. A general optical scheme of COACH system is presented in Figure 3. Second, we discuss some of the key applications of these recorders in the imaging field in general, and for 3D super-resolution imaging, partial aperture imaging, and seeing through scattering medium, in particular.

COACH has been developed from the more comprehensive topic of holography termed self-interference holography. Self-interference holography is actually the main technique to record holograms of incoherently illuminated scenes. Incoherent holograms are holograms of objects in which there is no statistical correlation between the waves emitted from various points of objects. The historical roots of incoherent holograms are planted in the mid-1960s, where some of these pioneering systems have made use of the self-interference principle. Self-interference principle indicates that any two beams, originated from the same source point and then split into two waves, are mutually coherent, and hence they can be mutually interfered. In the case of incoherent illumination, where any two different source points are mutually incoherent, the self-interference property becomes the only way to obtain any interference pattern, and thus enables to record a hologram. The use of the self-interference principle has been continuously developed beyond the 1960s by implementing several interesting systems. In another review article [2], we survey the prime architectures proposed along more than 50 years of optical hologram recorders based on the principle of self-interference incoherent digital holography. We summarize this overview with a general perspective on this research topic and its prospective directions.

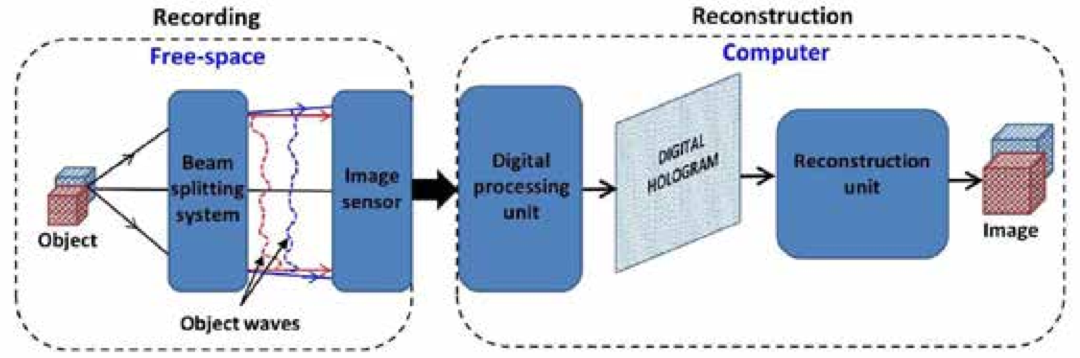

Figure 2. Recording and reconstruction of holograms in a self-interference digital holography system in general and COACH system in particular.

Analysis and design of COACH-based imager with synthetic aperture

The resolution of imaging by space and earth-based telescopes is often limited by the finite aperture of the optical systems. Imaging by a synthetic aperture is a possible method to improve the image resolution. In general, imaging with the synthetic aperture is a technique in which a relatively small physical aperture scans a relatively large (much larger than the physical aperture) synthetic aperture over time. The accumulated data in time are processed to yield an image with qualities equivalent to that of an image acquired by a single exposure of the complete synthetic aperture. Since the minimal resolvable detail of an image is inversely proportional to the aperture size, the image resulting from the synthetic aperture has better resolution than the image obtained from the physical aperture by direct imaging. Commonly, the resolution improvement is equal to the ratio between the sizes of the synthetic and the physical apertures.

We have investigated a novel synthetic aperture-based imaging system with several physical sub-apertures distributed only along the perimeter of the synthetic aperture [3]. The proposed optical configuration is inspired by a setup in which two synchronized satellites move only along the boundary of the synthetic aperture and capture a few light patterns from the observed scene. The light reflected from the two satellites interferes on an image sensor located in a third satellite. The sum of the entire interfering patterns is processed to yield the image of the scene with a quality comparable to an image obtained from the complete synthetic aperture. The minimum demonstrated two sub-aperture area is only 0.43% of the total full synthetic aperture area. The proposed system is based on the COACH

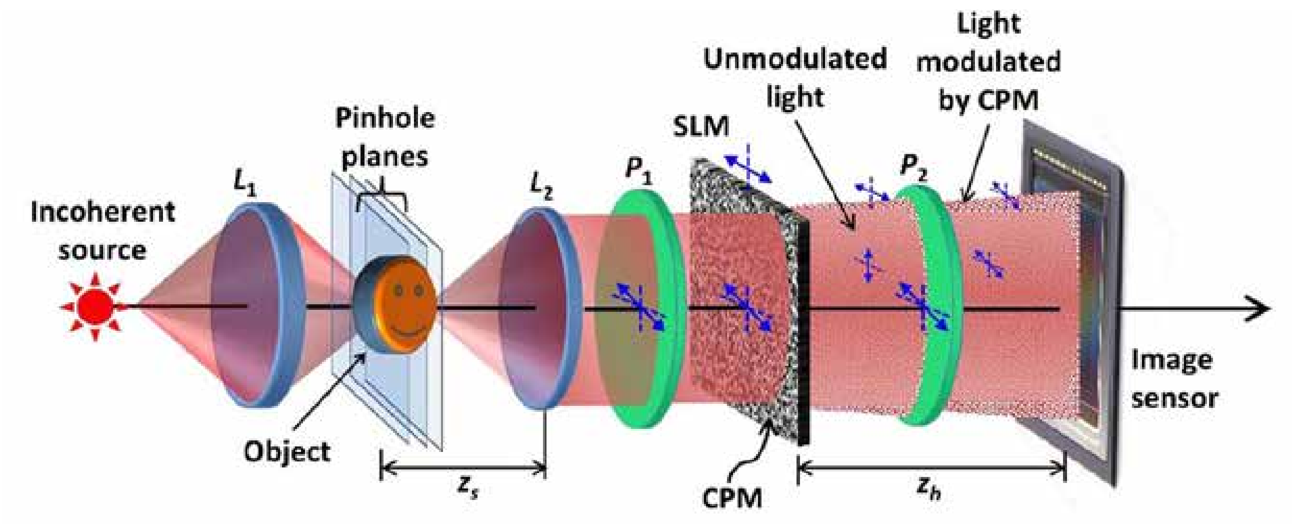

Figure 3. Optical configuration of COACH. CPM – Coded phase mask; L1, L2 – Refractive lenses; P1, P2 – Polarizers; SLM – Spatial light modulator; Blue arrows indicate on polarization orientations.

technique in which the light diffracted from an object is modulated by a chaotic coded phase mask. The modulated light is recorded and digitally processed to yield the 3D image of the object. A laboratory model of imaging with two synchronized sub-apertures distributed only along the border of the aperture was demonstrated. Experimental results validate that sampling along the boundary of the synthetic aperture is enough to yield an image with the resolving power obtained from the complete synthetic aperture. Unlike other schemes of synthetic aperture, there is no need to sample any other part of the aperture beside its border. Hence, a significant saving of time and devices is achieved in the process of the data acquisition.

Resolution enhancement by nonlinear interferenceless structured-light COACH

High image resolution enables the observer to see more fine details of the specimen and, therefore, it is usually the most significant feature in microscopy. In general, the lateral and axial resolutions of COACH are equivalent to those of conventional direct imaging with the same aperture size. One of our proposed methods to increase the lateral resolution without increasing the physical aperture of a system is to project random structured-light patterns of sub-diffraction spot arrays on the digital camera. The main component of COACH is a coded phase mask used as the system aperture. In the study published in [4], the coded phase mask has been engineered using an iterative computer algorithm to generate a random distribution of sub-diffraction spot arrays on the digital camera as the system response to a point source illumination. A library of point object holograms is created to calibrate the system for imaging different lateral sections of a 3D object. An object is placed within the calibrated 3D space and an object hologram is recorded with the same coded phase mask. The various planes of the object are reconstructed by a non-linear cross-correlation between the object hologram and the point object hologram library. A lateral resolution enhancement of about 25% was noted in the case of structured-light COACH compared to direct imaging.

Superresolution using spatial light modulator between objects and the imaging system

In papers [5,6] we introduced a novel superresolution technique for imaging objects beyond the diffraction limit imposed by the limited numerical aperture of a general optical system. A coded phase mask displayed on a spatial light modulator is introduced between the object and the input aperture of an ordinary lens-based imaging system. Consequently, the effective numerical aperture is increased beyond the inherent numerical aperture of the optical imaging system. Unlike conventional systems, the imaging in our proposed method is not direct from an object to a sensor, and the system requires a one-time calibration. In the calibration mode, a point object is mounted in the object plane, and the point spread intensity pattern is recorded. Following calibration, the system is ready for imaging an arbitrary number of objects. The intensity pattern from any object placed at the same axial location of the point object, and modulated by the same coded phase mask, is recorded once by a digital camera. The super-resolved image of the object is reconstructed by a nonlinear cross-correlation between the above mentioned two intensity patterns. The effective numerical aperture and the new resolution limit can be tuned by changing the scattering degree of the coded phase mask.

Noise suppression by controlling the sparsity of the point spread function

As mentioned above, in COACH, the light scattered from an object is modulated by a coded phase mask and then recorded by a digital camera as an object digital hologram. To reconstruct the image, the object hologram is cross-correlated with the point spread function (PSF), which is the intensity response to a point at the same object's axial location recorded with the same coded phase mask. So far in COACH systems [3,5], the light from each object point has scattered over the whole camera area. Hence, the signal-to-noise ratio per camera pixel is lower in comparison to the direct imaging in which each object point is imaged to a single image point. In paper [7], we consider the midway between the camera responses of a single point and of a continuous pattern over the entire camera area. The light in this study is focused onto a set of dots randomly distributed over the camera plane. With this technique, we have shown that there is a PSF with a best number of dots, yielding an image with a maximum product of the signal-to-noise ratio and the image visibility and a maximum value of structural similarity.

COACH-based microscope with coherent Illumination

The use of a spatial light modulator as dynamic computercontrolled optical component in COACH has been extended to the regime of coherent digital holography in our work published in [8]. Consequently, the investigated coherent hologram recorders have now the same benefits of the traditional incoherent COACH recorders with the additional capability to image and measure objects that cannot be imaged by incoherent systems. The coherent microscope is implemented on a similar setup as the incoherent microscope, with minimum changes, making the proposed microscope a multimodal device that can operate under coherent as well as incoherent illuminations. Optical recording of digital holograms by coherent light traditionally involves interference between object and reference waves, which complicates the image acquisition process and decreases the power efficiency. In this project, we take the coded aperture correlation holography technique one step forward to record coherent digital holograms of three-dimensional scenes, without wave interference and in a motionless working mode. In addition to the explicit benefits of integrating interferenceless holographic imaging systems with coherent illumination, the suggested method enables fast image acquisition implied by its inherent high signal-to-noise ratio. Experimental validation for diffusely reflective objects is also described in [8], making this relatively simple system appropriate for studying and using the speckle phenomena in coherent digital holography.

Summary

This report summarizes ten new projects [3-12] and two review articles [1,2], all were completed during the fellowship year in AKWG. Because of space limitations, not all scientific progress during the fellowship can be detailed here. Works that cannot be fully presented in the report are lengthily described in articles [9-12]. Specifically, in [9-12] we published studies about a new method of noninvasive imaging through scattering layers [9], generation of structured light by multilevel orbital angular momentum holograms [10], implementation of a speckle-correlation-based optical lever with extended dynamic range [11] and a novel way to improve the dynamic range of speckle correlation based optical levers [12]. All these works [3-12] are only beginning points and an inspiration for many ideas and projects that undoubtedly will come up in the future.

Our sincere thanks and our deep appreciation are given to the people of Alfried Krupp Wissenschaftskolleg Greifswald for their generous and dedicated support throughout my fellowship.

Am Kolleg entstandene Veröffentlichungen

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