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2 authors:


Vijayakumar Anand
University of Tartu


Joseph Rosen
Ben-Gurion University of the Negev

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Interferenceless Coded Aperture Correlation Holography: History, Development, and Applications

Vijayakumar Anand[1,2,†] and Joseph Rosen[1,3,*]
[1]Institute of Physics, University of Tartu, W. Ostwaldi 1, 50411 Tartu, Estonia;
[2]Optical Sciences Center, Swinburne University of Technology, Melbourne 3122, Australia;
[3]School of Electrical and Computer Engineering, Ben-Gurion University of the Negev, P.O. Box 653, Beer-Sheva 8410501, Israel.
[†]vijayakumar.anand@ut.ee; [*]rosenj@bgu.ac.il

ABSTRACT

Interferenceless coded aperture correlation holography (I-COACH) was developed in 2017 to achieve 3D imaging without two-beam interferences. In I-COACH, the imaging process consists of three steps: COACHing, recording and reconstruction. In the COACHing step, the point spread function (PSF) library is recorded. In the recording step, an object mounted within the axial boundaries of the PSF library is recorded, and the recording is processed with the PSF library in a computer to reconstruct the image of the object in the final step. During the past five years, I-COACH evolved rapidly into a significant incoherent holography technique breaking the limits of almost all imaging characteristics such as lateral resolution, axial resolution, spectral resolution and field of view, not to mention, the ability to sense colour with a monochrome sensor. In this invited article, some of the major milestones in the evolution of I-COACH are briefly presented.

Keywords: coded aperture correlation holography; incoherent optics; computational imaging; holography; 3D imaging.

1. INTRODUCTION

Coded aperture correlation holography (COACH) was developed at the intersection between holography and coded aperture imaging (CAI) [1,2]. In incoherent holography, one or more self-interference holograms formed between two differently modulated object waves were recorded, and the different planes of the object were reconstructed using computational backpropagation. In CAI, the point spread function (PSF) of the system is recorded in the first step. Then the object intensity is recorded under identical conditions of recording (PSF) and processed with PSF in a computer to reconstruct the object information. In COACH, light from an object was split into two parts: one part was modulated by a quasi-random phase mask and interfered with the other part of the object wave to create the hologram. Unlike its predecessor, Fresnel incoherent correlation holography (FINCH) [3], COACH does not digitally imitate the optical propagation from the hologram to the image plane. Therefore, in COACH, the CAI method was adapted, and the point spread holograms were recorded at all axial planes in the first step and used for reconstructing the 3D information from the object hologram. Hence, the name COACH was formed from CAI and FINCH. During the investigation of COACH, it was discovered that the 3D information of the object was encoded in both the amplitude and phase of the scattered wave, so two-beam interference is not necessary to record 3D information. This discovery led to the development of interferenceless COACH (I-COACH) [4], which had a significant impact in the area of imaging, as I-COACH had the advantages of holography, which is a 3D imaging capability, as well as the advantages of CAI, which is interferenceless.

After the development of I-COACH in 2017, it evolved into a powerful imaging technique [5, 6]. The first version of I-COACH required at least three camera shots with three uncorrelated quasi-random phase masks and required multiple optical components. Modified versions of I-COACH were developed, such as single camera shot I-COACH (SCS-I-COACH) [7], lensless I-COACH (LI-COACH) [8], I-COACH with non-linear reconstruction [9], resolution-enhanced COACH (RE-COACH) [10], I-COACH with an extended field of view [11] and sparse I-COACH (SI-COACH) with a higher SNR [12]. These methods simplified I-COACH and enhanced its imaging performance. The method introduced by I-COACH inspired the development of advanced imaging systems such as DiffuserCAM [13], partial aperture imaging systems (PAIS) [14], synthetic marginal aperture with revolving telescopes (SMART) [15], super-resolution imaging

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systems [16], chaos-inspired imaging technologies [17,18], non-linear imaging systems [19] and 3D imaging systems with deterministic optical fields [20, 21]. In the next sections, the optical and computational methods that led to the evolution of I-COACH are discussed.

2. EVOLUTION OF I-COACH

Although the I-COACH technique has expanded with different variations, the principle of imaging can be described using simple equations, as it is a linear shift-invariant imaging system. The intensity distribution I_O recorded for an object O can be expressed as $I_O=O\otimes I_{PSF}$, where I_{PSF} is the prerecorded point spread function and '⊗' is a 2D convolutional operator. The imaging task can be completed if O can be reconstructed from the recordings of I_O and I_{PSF}. One of the direct methods of solving the equation is by rearranging it as $O=I_O*I_{PSF}$ = $O\otimes I_{PSF}*I_{PSF}$, where '*' is a 2D correlation operator. This classical approach of reconstruction is also called correlation or matched filter [22]. The component $I_{PSF}*I_{PSF}$ is called the autocorrelation function, which samples object O. Therefore, the autocorrelation function needs to be as sharp as possible with low background noise to reconstruct the object information effectively.

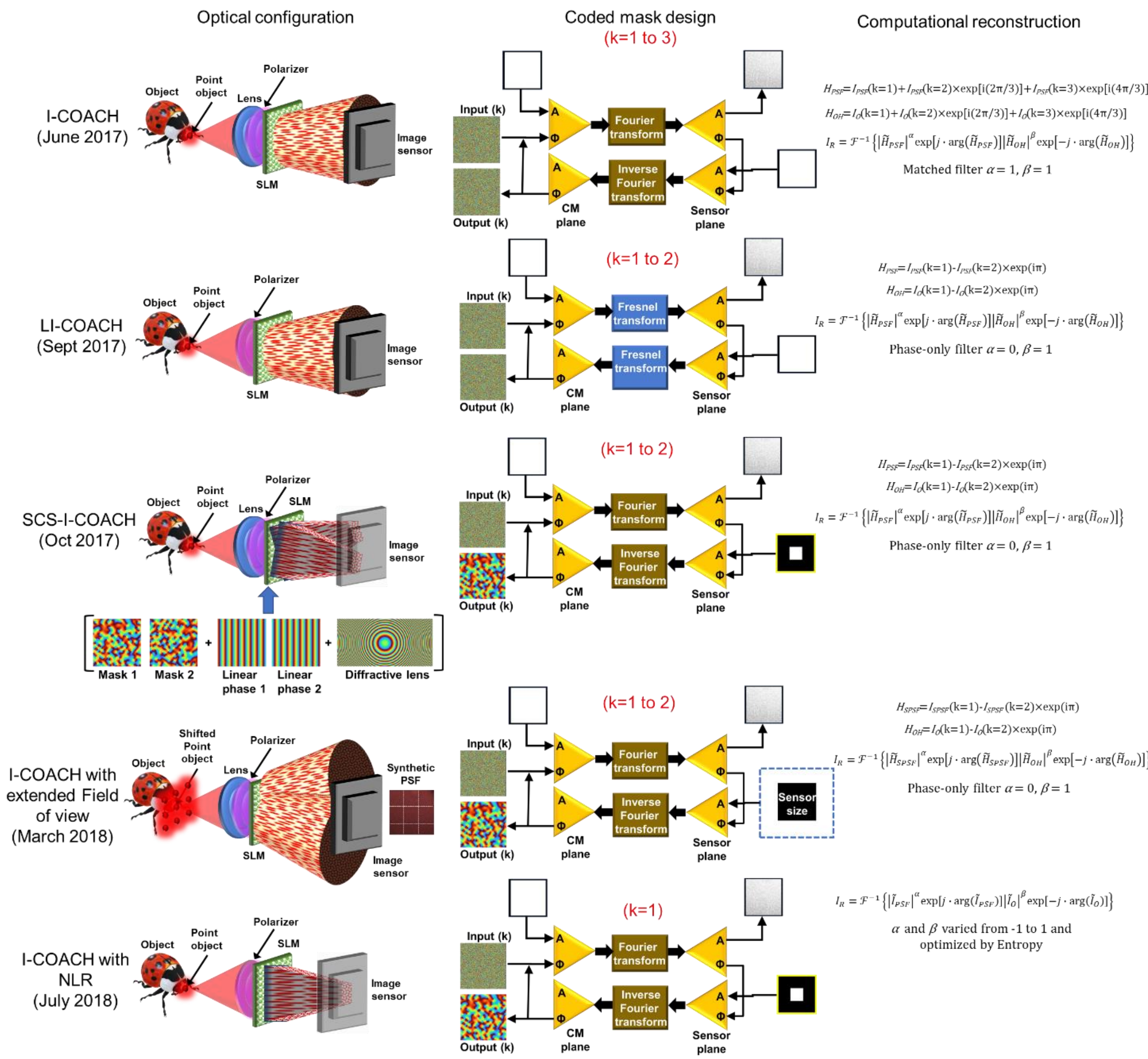

Figure 1 Evolution of I-COACH from June 2017 to July 2018. SLM – spatial light modulator; k – number of masks; A – amplitude; Φ – phase; CM – coded mask; $\mathcal{F}^{-1}$ – inverse Fourier transform; $\tilde{I}$ – Fourier transform of I.

The evolution of I-COACH starting from its first version reported in June 2017 to the version reported in July 2018 is shown in Figure 1, with developments shown in three directions: optical configuration, phase mask design and computational reconstruction. The first version of I-COACH was developed based on COACH and FINCH by modifying the polarizer's orientation from 45 degrees with respect to the active axis of the spatial light modulator (SLM) to 0 degrees, resulting in the generation of only the modulated object beam [1]. Three uncorrelated quasi-random coded masks (CM) were designed using the Gerchberg-Saxton algorithm (GSA) to generate a pure phase function at the sensor plane [23]. The light from a point object was collimated using a refractive lens, polarized along the active axis of the SLM, modulated by the CMs displayed on the SLM, and the I_{PSF}s were recorded. The three recorded I_{PSF}s were projected into a complex space with θ = 0, 2π/3 and 4π/3, and a complex-valued matrix was obtained. The pinhole was shifted to all the axial planes, and the above process was repeated. A thick object is placed within the axial boundaries of the I_{PSF}s, and three intensity distributions corresponding to the three CMs were recorded and combined to form a complex-valued matrix. The complex matrix of the object was cross-correlated with the complex PSF library to reconstruct the different planes of the object. The regular cross-correlation is also called the matched filter given by the equation $I_R = \mathcal{F}^{-1}\left\{\left|\widetilde{H}_{PSF}\right|^{\alpha}\exp\left[j\cdot\arg\left(\widetilde{H}_{PSF}\right)\right]\left|\widetilde{H}_{OH}\right|^{\beta}\exp\left[-j\cdot\arg\left(\widetilde{H}_{OH}\right)\right]\right\}$, where $\alpha = \beta = 1$. The first version of I-COACH was significantly simpler than COACH and FINCH, but compared to direct imaging, it required an active device and multiple optical components and had a temporal resolution of one-third of that of direct imaging.

The next version of I-COACH without lenses, called lensless-I-COACH (LI-COACH) using only the SLM between the object and the sensor, was reported in September 2017 [8]. The CM was designed using a modified version of GSA with a Fresnel propagator between the CM plane and the sensor plane instead of a Fourier transform. Second, the number of camera shots was reduced from three to two by replacing complex holograms with bipolar holograms with θ = 0 and π. Instead of a matched filter, a phase-only filter with $\alpha = 0$ and $\beta = 1$ was used to reconstruct the object information from the bipolar object hologram and PSF. The performance of LI-COACH was better than that of I-COACH in SNR with a reduced number of camera shots and optical components. A modified version of I-COACH called single camera shot I-COACH (SCS-I-COACH) was reported in October 2017 by improving the CM in two ways [7]. First, in the first version of I-COACH, the Fourier transform relation in GSA was not satisfied in the experiment, which was satisfied in SCS-I-COACH by including a lens function. Second, the two temporal shots of LI-COACH were converted to two spatially separated shots recorded instantly by adding two identical but opposite linear phases to two uncorrelated mask patterns. The uncorrelated masks were synthesized using GSA by applying a space constraint in the sensor plane with the pure phase constraint. The resulting multifunctional CM is composed of two uncorrelated mask patterns generated from GSA, two opposite linear phases and a lens for satisfying the Fourier transform. The recorded intensity distributions were split into two and subtracted from one another to form the bipolar distributions for the object and point object followed by reconstruction using a phase-only filter. The sharing of the sensor space between two camera shots reduced the field of view (FoV) of imaging. The SCS-I-COACH was the first demonstration of 3D imaging with the same time resolution as a direct imaging system, and an SLM is not needed.

The FoV of an imaging system is limited by the size of the image sensor. In I-COACH, the above limitation was overcome in the FoV-extended I-COACH reported in March 2018 by engineering the CM to generate a PSF much larger than the sensor area [11]. In the first step, the GSA was used to synthesize an intensity distribution larger than the sensor area. In the experiment, the pinhole was shifted laterally, and the shifted versions of the PSF were captured and computationally stitched to form a large synthetic PSF. The synthetic PSF was used to reconstruct object information beyond the FoV of the system. In [11], an FoV extension of 3 times was demonstrated, while the method is limited only by the optical power. In the FoV extended I-COACH, a phase-only filter was used for reconstruction with two camera shots. In July 2018, a novel reconstruction method called non-linear reconstruction (NLR) was reported in which the values of α and β were tuned until an optimal reconstruction defined by the least entropy was obtained. The I-COACH method with CM is engineered to generate a pure phase function within a limited area in the sensor plane along with NLR-reconstructed images with a higher SNR. I-COACH with NLR does not require an active device such as an SLM and can work with a passive CM, as only a single camera shot is needed.

The RE-COACH technique reported in January 2019 used special CMs to achieve resolution enhancement, as shown in Figure 2. A modified GSA was used to generate 3×3 arrays of sub-diffraction spots, and then it was randomized to prevent any occurrence of sidelobes in the autocorrelation function [10,24]. The sub-diffraction spot generation along with NLR reconstruction enabled sampling at higher spatial frequencies, resulting in resolution enhancement. In April 2019, a super-resolution method was developed based on I-COACH using the configuration shown in Figure 2 [16]. The resolving power of a regular lens-based imaging system is given by λ/NA. It is not possible to increase NA by moving the object close to the lens, as the distance between the lens and the object has to satisfy the imaging conditions. However, in I-COACH, the distances do not need to meet any imaging requirements, so a quasi-random CM is inserted between the object and the lens, resulting in an increase in NA and resolving power. The GSA was used to control the scattering degree of the CM and control the resolution limit. Once again, the NLR method was used, and super-resolution was achieved without any change in the temporal resolution.

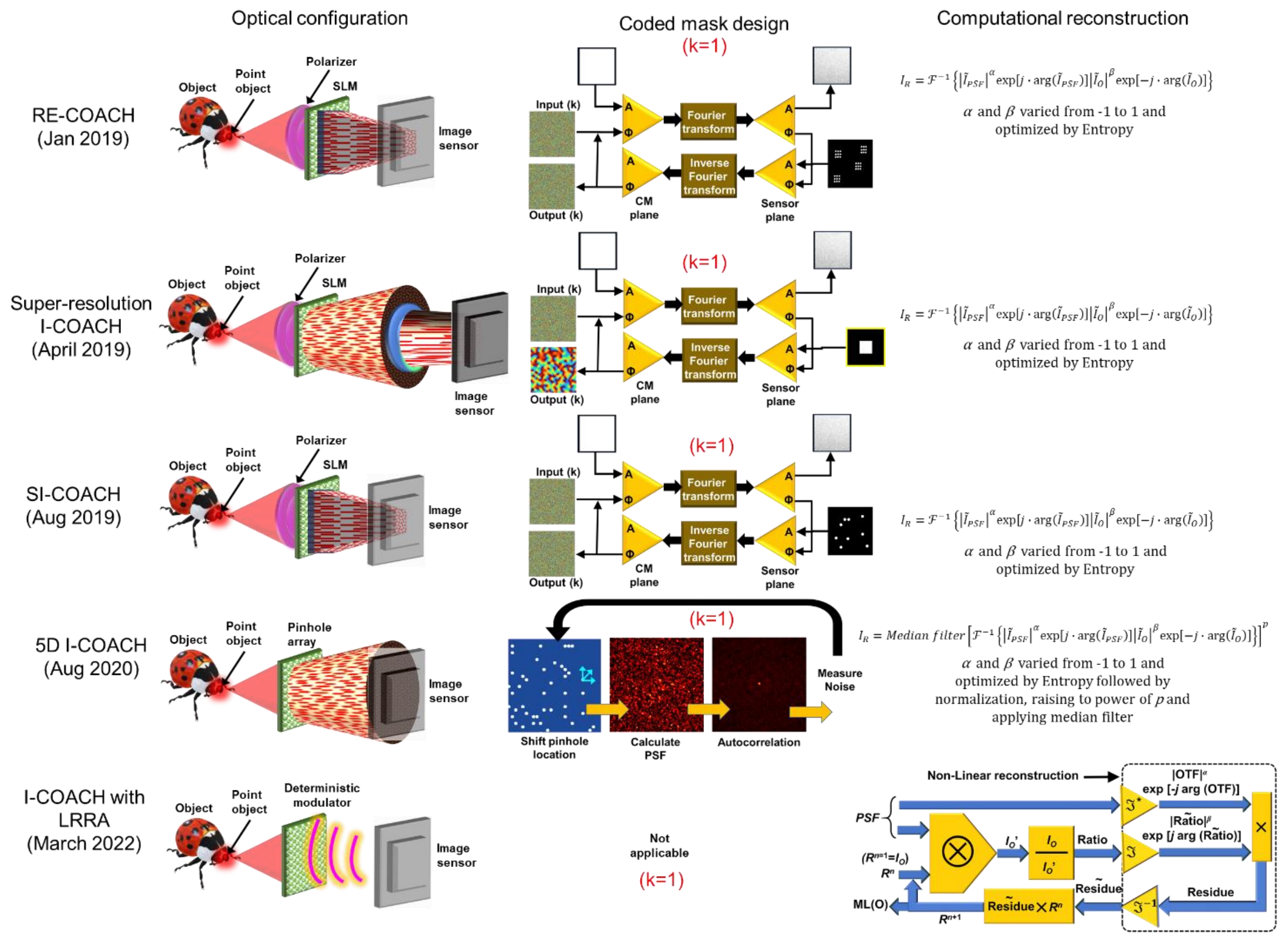

Figure 2 Evolution of I-COACH from January 2019 to March 2022. SLM – spatial light modulator; k – number of masks; A – amplitude; Φ – phase; CM – coded mask; $\mathfrak{I}$ –Fourier transform; ∗ - complex conjugate; ML – maximum likelihood; R – solution.

In all the above studies, one of the drawbacks of I-COACH in comparison to direct lens-based imaging is the low SNR associated with the scattering of light. In August 2019, a modified approach of I-COACH with improved SNR was reported, in which instead of scattering light, the CM was engineered to collect light and focus it on randomly arranged dots [12]. The amplitude constraint in the sensor plane of the GSA was modified to a few dots. The main challenge was that multiple CMs needed to be multiplexed to reconstruct object information at all planes. The same idea with dot patterns was also extended to coherent imaging with a limited FoV [25]. In all the above studies, one challenge in implementing I-COACH is the exhaustive one-time prerecording of the PSF library. In August 2020, a low-cost 5D I-COACH system was developed with a CM consisting of a random array of pinholes [17,18]. The location of the pinholes was optimized to achieve a high SNR using a two-layer search algorithm, as shown in Figure 2. In this study, the scaling factor associated with the change in PSF with different axial planes and spectra was identified. By measuring the PSFs only along the axial and spectral boundaries, the entire PSF library was synthesized in the computer. Furthermore, depth-wavelength reciprocity was discovered, which enabled recording the PSF library for different wavelengths using a single wavelength and different depths using a single depth measurement. From a single camera shot, up to 4D information in 3D space and spectrum was reconstructed with all recordings using a monochrome camera.

The I-COACH techniques were attempted at the infrared beamline of the Australian synchrotron, and during the study, the 3D imaging capability was found in some of the commonly used optical elements - Cassegrain and Schwarzschild reflective objective lenses. The intensity distributions generated by the above optical elements consisted of sharp peaks generating sharp autocorrelation functions. However, the object information could not be reconstructed with a high SNR using existing computational reconstruction methods, including NLR. Therefore, a modified computational reconstruction method called the Lucy-Richardson-Rosen algorithm (LRRA) was developed by combining the well-known Lucy-Richardson algorithm with NLR [20, 26, 27]. The $(n+1)^{\text{th}}$ reconstructed image is given as $I_R^{n+1} = I_R^n \left\{ \frac{I_O}{I_R^n \otimes I_{PSF}} \otimes I_{PSF}' \right\}$, where the loop begins with an initial guess (n=1) of O, which is I_O itself as it is a blurred version of O, and I_{PSF}' is the complex conjugate of the I_{PSF}. With LRRA, it was also possible to reconstruct 3D information using deterministic fields such as double helix beams [28] and even a refractive lens [29].

3. CONCLUSION AND FUTURE PERSPECTIVES

In this invited paper, the history and developments of I-COACH are succinctly presented. A technique that was invented with implementation difficulties similar to those of a conventional digital holography technique and an advantage of only an additional dimension has rapidly evolved with incredible capabilities. While the initial method used a random CM, as seen from the evolution, the path has drifted toward the use of deterministic optical fields. Some recent studies have suggested the possibility of realizing even non-linear imaging characteristics, such as tuning axial resolution independent of lateral resolution [19]. Based on the development of I-COACH, we believe that this method will expand more with more surprises and possibilities replacing many conventional imaging techniques in the future.

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