Binary Coded Aperture Design by Sphere Packing in Compressive Ultrafast Photography

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Abstract: This work presents a binary coded aperture (CA) design using sphere packing (SP) to determine the number of light entries in a compressive ultrafast photography (CUP) system. Our proposed approach leverages the uniform sensing that yields SP and the temporal shifting induced by the galvanometer to achieve uniform sensing.

1. Introduction

The acquisition of transcendent events is crucial in biology and physics, but capturing those events is a challenging task because the conventional sensing approaches rely on scanning the transcendent event, resulting in transmission delays, and storage costs. Therefore, ten years ago, compressive ultrafast photography (CUP) emerged as a competitive alternative for capturing transcendent dynamics by acquiring a single compressive projection and solving an ill-posed optimization problem [1, 2]. However, the main challenge in CUP systems is the high computation time of reconstruction algorithms to recover the underlying video, preventing their extension to online applications. In order to address this issue, we propose designing a coded aperture (CA) by optimizing the sampling density. The video is reconstructed using a conventional interpolation algorithm to reduce the computational cost [3].

Our approach exploits sphere packing (SP) [4], which consists of packing congruent balls in a 3D container so that each sphere is at most tangent to each other; note that the SP defines the sampling density of the binary CA. The optimal density of the equal-sized 3D spheres is $\rho_{\Lambda_3} = \frac{\pi}{\sqrt{18}} \approx 0.74$ [5], where Λ_3 denotes the face-centered cubic (FCC) lattice, and we exploit that theoretical upper bound to design our CA. Recently, systems with multiple apertures have been designed for video [6, 7] and multispectral imaging [8]. Nevertheless, those previous approaches were designed for acquisition systems with multiple CAs. In contrast, the CUP system uses a single binary CA. Therefore, in this work, we introduce a single binary sphere packing coded aperture (SPCA).

2. Methods

The single snapshot that captures the CUP system is denoted by

$$\mathbf{Y}_{(:,:,\bar{t})} = \sum_{\bar{t}}^{T-1} \mathbf{C}_{(:,:,\bar{t})} \odot \mathbf{X}_{(:,:,\bar{t})} + \boldsymbol{\eta}, \qquad (1)$$

where T is the number of frames, $\bar{t}$ denotes the temporal shifting induced by the galvanometer, $\mathbf{X}_{(:,:,\bar{t})}$ is the shifted frame of the transcendent event, $\mathbf{C}_{(:,:,\bar{t})}$ is the shifted CA, and $\boldsymbol{\eta}$ represents the additive Gaussian noise. Our approach exploits the SP to design the CA entries so that the sensing is uniform. Thus, we leveraged the temporal scanning from the galvanometer to scan the transcendent event. The reconstruction algorithm is nearest neighbor interpolation (NNI) [3].

3. Results

To demonstrate the performance of our SPCA, we use a dataset with 21 videos, whose spatial resolutions are 256×256 and 36 frames. In order to evaluate spatial fidelity, we use the peak-signal-to-noise ratio (PSNR) and structural similarity index (SSIM). As illustrated in Fig. 1, our approach recovers the video of a falling slice of orange in water, whose mean PSNR is 31.90 dB and whose SSIM is 0.88. Note that the size of the compressed measurement is considerably wider than that of the CA because of the temporal shearing. The simulation results are summarized in Table 1, where the mean PSNR and SSIM are computed and the random and designed CAs are compared. The advantage of our CA design is the uniform sampling that leverages the temporal shifting to scan the transcendent event.

4. Conclusions

This paper introduces a novel sphere packing coded aperture to reconstruct the transcendent events of a compressive ultrafast photography system. Our approach leverages the 3D-packing density of 3D congruent spheres to design a coded aperture to sample frames of transcendent events. Future work will include a test-bed setup using a rotating

Table 1: Performance of random permutation CA against the proposed SPCA on the 21 videos dataset for the NNI interpolation algorithm, where the spatial resolution is 256×256, and the number of frames is 16, 25 and 36.

		Number of frames		
Algorithm	CA	$T = 16$	$T = 25$	$T = 36$
NNI	random CA PSNR (dB) ↑	23.50 ± 4.26	22.61 ± 3.85	22.04 ± 4.12
	random CA SSIM ↑	0.76 ± 0.14	0.73 ± 0.14	0.72 ± 0.14
	SPCA PSNR (dB) ↑	24.23 ± 4.40	23.18 ± 4.30	23.14 ± 4.22
	SPCA SSIM ↑	0.78 ± 0.13	0.75 ± 0.13	0.75 ± 0.13

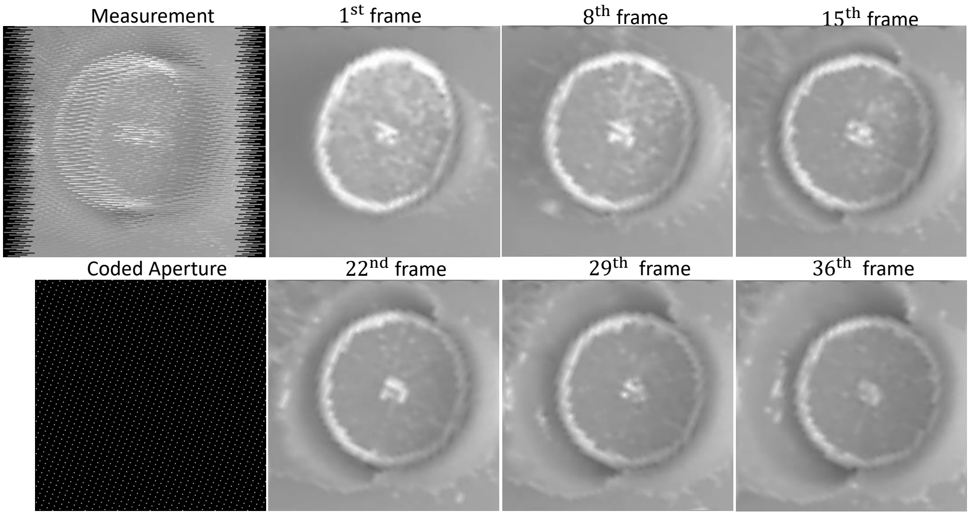

Fig. 1: Simulation reconstructions. The first row depicts the compressive measurement and the reconstructions of the 1st, 8th, and 15th frames. The second row depicts the designed CA, and the 22nd, 29th and 36th frames.

mirror-based CUP system to prove the capability of our approach [9, 10] and explore reconstruction algorithms driven by deep learning and CA that multiplex the transcendent events.

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