Inaccuracy Amplified: Compressed Sensing Under Experimental Misalignment

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***Abstract*—Compressed sensing (CS) with single-pixel detectors and optical phased arrays (OPAs) allows efficient image reconstruction by exploiting structured speckle patterns. This study investigates how spatial misalignments affect reconstruction fidelity. We numerically simulate the alignment errors of different magnitude and evaluate the reconstructed image using both the structural similarity index (SSIM) and the peak signal-to-noise ratio (PSNR). These findings highlight the sensitivity of compressed sensing to spatial misalignments, emphasizing the need for precise control in experimental setups to ensure reliable image reconstruction.**

***Index Terms*—Compressed sensing, single pixel, speckle illumination, Structural Similarity Index, Peak Signal to Noise Ratio, reconstruction errors**

I. Introduction

CS with single-pixel detectors represents an efficient solution for the acquisition of a target image. In contrast to faster but more technologically complex solutions where the target image is captured with a single acquisition, e.g. using matrix sensors, or slower but simpler approaches such as raster scanning where the target is acquired one pixel at the time, in CS the target is highlighted by a sequence of deterministic, uncorrelated speckle patterns, and the resulting signal is collected by a single-pixel detector (Fig. 1(a)). Assuming that K total speckle patterns are used, we can introduce the $N^2 \times K$ matrix $I = [I_1, I_2, \ldots, I_K]$, with I_k column vector containing the $N \times N$ samples of the $k-th$ illumination pattern, rearranged in lexicographic order; in a similar way we can introduce the column vector A with A_k values returned by the sensors for the $k-th$ acquisition. The reconstructed image $\tilde{T}$ can be obtained as $\tilde{T} = I^+ A$, with I^+ Moore-Penrose generalized inversion of I [1]. With respect to acquisitions based on raster scanning, CS is generally much faster, since the number of acquisitions K required to reconstruct the fundamental features of the target is smaller than N^2. In this scenario, it is obvious that a key ingredient is the reproducibility of the patterns that must be measured accurately before the target is processed and must be reproduced with high precision, since errors in the patterns would result in values of A_k not consistent with I_k, introducing degradation in the reconstructed image [1]. A typical device used for the generation of the speckle patterns is the OPA, which can be controlled not only to create a focused beam (e.g., for raster scanning), but also, applying proper control signals, to generate pseudo-random patterns, whose characteristic size depends mainly on the number of branches. The reproducibility of the generated pattern can be affected by the temperature and mechanical displacements of the experimental setup, but is generally very good [2]. An additional solution is represented by a nanocomposite combining electro-spinned nanofiber tissue and UV curable resin on a glass plate (Fig. 1(b)), with a total area much larger than the target image. In this way, it is possible to generate the various uncorrelated patterns simply by translating the plate in the $x-$ and $y-$ directions, using different uncorrelated areas. In this scenario, a critical aspect is the proper alignment of the plate in the expected position [1], [3]. In this study, we investigate how spatial misalignment of speckle patterns affects the quality of the reconstruction. Specifically, we simulate the illumination of the target employing speckle patterns that are intentionally shifted with a defined boundary region. This shifting emulates various angular perspectives or aperture displacements that occur during the illumination process, thereby effectively modifying the set of light paths that contribute to each measurement [4]. By modifying the maximum alignment error, we analyze the impact of these inaccuracies on the quality of the reconstructed images using quantitative metrics such as SSIM and PSNR [5].

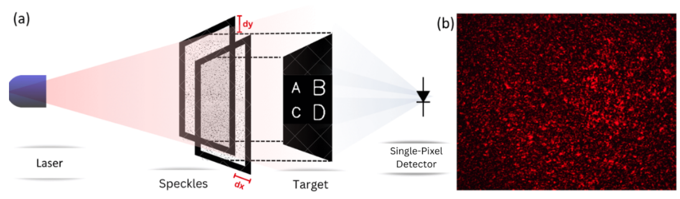

Fig. 1. (a) Conceptual illustration of the imaging process. (b) Example of speckle pattern on glass plate, acquired by a Thorlabs DCC1645C CMOS camera with resolution of 1280 × 1024 pixels and 3.6 µm× 3.6 µm pixel size.

II. Methods and Results

To numerically investigate the effects of misalignments, we consider as a target the boolean 128 × 128 or original

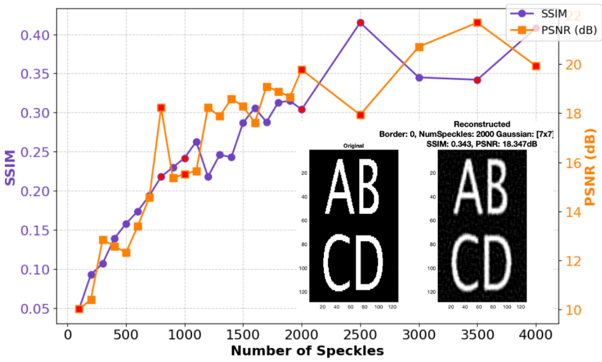

Fig. 2. Effect of number of speckle patterns on SSIM and PSNR for $R = 0$ (perfect alignment). Inset: target image (left) and reconstructed result (right) with 2000 patterns (SSIM = 0.343, PSNR = 18.3 dB).

image shown in the left inset of Fig. 2. In MATLAB, we generate realistic speckle patterns, as matrices of uniformly distributed values in the $(0, 1)$ interval. A 2D Gaussian blur with a standard deviation equal to 2 pixels is introduced to mimic the characteristic patterns found on the glass plate. In order to simulate the misalignment, when we calculate the numerical product between speckle patterns and target image, we introduce a shift dx and dy in the correct pattern, as shown in Fig. 1. The values of these two quantities, expressed in pixels, are different for each pattern and are extracted randomly from the range $[-R, R]$ following a uniform distribution. When $R = 0$, we revert to the ideal case of perfect alignment: in this ideal condition, we evaluate the quality of the reconstucted image vs. the number of speckle patterns used. The results are shown in Fig. 2, where both SSIM and PSNR increase with the number of speckles, especially in the range of 100 to 2500. Higher speckle counts improve reconstruction quality, leveling off at approximately 2000 speckles. The inset of Fig. 2 shows a representative reconstruction result of the original target using CS: while the reconstructed image exhibits some blurring effect, it fully captures the main features of the target.

To isolate the impact of spatial misalignment, we fixed the number of speckles to 2000 and varied R. As illustrated in Fig. 3, an increase in R results in a clear degradation in image reconstruction quality, as reflected in both SSIM and PSNR. The SSIM and PSNR decrease from 0.317 and 19.2 dB at $R = 0$ to 0.014 and 4.4 dB at $R = 6$, respectively, indicating a significant loss of structural similarity. Depending on the target application, it is possible to identify a quality threshold, e.g. SSIM=0.1, that specifies which is the maximum allowed alignment error.

Finally, it is interesting to observe that, when $R > 0$, the quality of the reconstructed image is not a monothonic function of the number of patterns used: Fig. 4 shows that when more than 500-1000 misaligned speckle patterns are used, then SSIM significantly decreases. In these situations, in fact, the large number of not perfectly aligned patterns increases the reconstruction noise and leads to quality degradation.

III. Conclusion

We have shown through numerical calculations that spatial misalignment can significantly amplify inaccuracies in CS. As the alignment error increases, speckle shifts cause significant structural decorrelation, harming reconstruction fidelity.

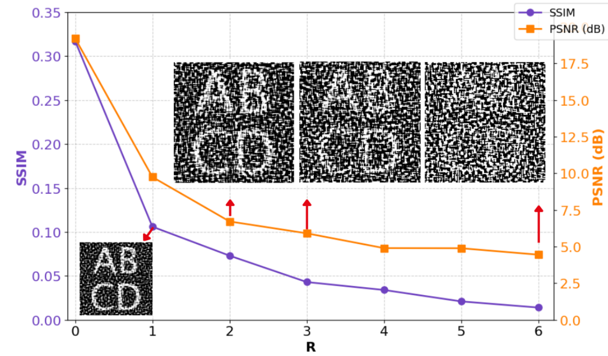

Fig. 3. Effect of misalignment R on the quality of the reconstructed image with 2000 speckle patterns.

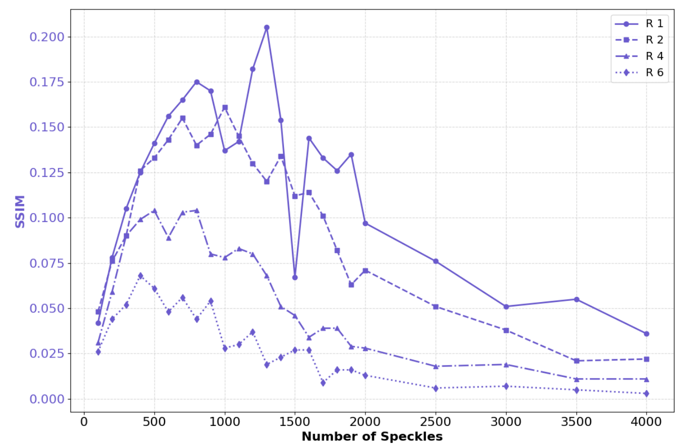

Fig. 4. Comparison of SSIM values versus the number of speckles for different $R = 1$, 2, 4, and 6.

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