Compressive Ultrafast Single Pixel Camera

Citation	Satat, Guy, Musarra, Gabriella, Lyons, Ashley, Heshmat, Barmak, Raskar, Ramesh et al. 2018. "Compressive Ultrafast Single Pixel Camera."
As Published	10.1364/cosi.2018.ctu2e.2
Publisher	OSA
Version	Author's final manuscript
Citable link	https://hdl.handle.net/1721.1/138066
Terms of Use	Creative Commons Attribution-Noncommercial-Share Alike
Detailed Terms	http://creativecommons.org/licenses/by-nc-sa/4.0/

Compressive Ultrafast Single Pixel Camera

Guy Satat[1]**, Gabriella Musarra**[2]**, Ashley Lyons**[2]**,**
Barmak Heshmat[1]**, Ramesh Raskar**[1] **and Daniele Faccio**[2]
[1]*MIT Media Lab, 75 Amherst St., Cambridge, MA, USA*
[2]*School of Physics & Astronomy, University of Glasgow, Glasgow, G12 8QQ, United Kingdom*
guysatat@mit.edu

Abstract: We experimentally demonstrate a single-pixel, time-resolved camera that, by using the temporal information, produces improved reconstruction quality and shorter acquisition times, compared to traditional, non-time-resolved, single-pixel approaches.

OCIS codes: (110.1758) Computational imaging, (110.0110) Imaging systems, (100.3010) Image reconstruction.

1. Introduction

Producing high resolution and high frame-rate cameras that operate in challenging parts of the spectrum like IR is a great challenge [1]. One notable solution to this challenge is the single pixel camera which benefits from ideas central to compressive sampling. Previous works addressed the problem of compressive sensing for lensless imaging either with a single pixel [2], or in a more general form of imaging with random masks [3]. However, these methods assume and use regular bucket detectors which integrate over all dimensions of the Plenoptic function. The result is a very long acquisition process that requires hundreds (or more) of consecutive measurements. Recently, a method that uses a time-resolved detector for single pixel cameras has been suggested [4]. Here, we experimentally demonstrate that a time-resolved single pixel camera provides superior quality when compared to traditional single pixel systems.

2. Compressive Ultrafast Sensing Framework

A target $\mathbf{f} \in \mathbb{R}^L$ with L pixels is illuminated by wavefront $\mathbf{g} \in \mathbb{R}^L$. Light reflected from the scene is measured by an omnidirectional ultrafast sensor with a time resolution of T. The time-resolved measurement is denoted by $\mathbf{m} \in \mathbb{R}^N$, where N is the number of time bins in the measurement. For a fixed time window, better time resolution (smaller T) increases N. The measurement matrix $\mathbf{H} \in \mathbb{R}^{N\times L}$ is defined by the space to time mapping that is enforced by special relativity. When the time resolution is very poor, $\mathbf{H}$ is just a single row ($N = 1$), identical to the regular single pixel camera case. The illumination operator is a diagonal matrix $\mathbf{G} \in \mathbb{R}^{L\times L}$ with the illumination pattern $\mathbf{g}$ on the diagonal.

We consider N time samples and M illumination patterns ($j = 1..M$) so the time-resolved measurement for the j-th illumination pattern, is defined by: $\mathbf{m}_j = \mathbf{H}\mathbf{G}_j\mathbf{f}$. Concatenating all measurement vectors results in the total measurement vector $\vec{\mathbf{m}} \in \mathbb{R}^{NM}$. The total measurement operator $\mathbf{Q}$ is an $NM \times L$ matrix, such that:

$$\vec{\mathbf{m}} = \begin{bmatrix} \vdots \\ \mathbf{m}_j \\ \vdots \end{bmatrix} = \begin{bmatrix} \vdots \\ \mathbf{H}\mathbf{G}_j \\ \vdots \end{bmatrix} \mathbf{f} = \mathbf{Q}\mathbf{f} \tag{1}$$

To recover $\mathbf{f}$ we invert the system defined in Eq. 1 using compressive sensing approach.

3. Experiments and Results

The experimental setup is shown in Fig. 1a. A femtosecond Ti:Sapphire pulsed source (80 MHz repetition rate, 120 fs pulse duration, 800 nm wavelength) is incident on a Digital Micro-mirror Device (DMD, Texas Instruments). The DMD is projecting the desired compressive patterns on the target and controlled by a computer. The target is imaged with a Becker&Hickl photomultiplier tube (PMT) detector and sampled with Time Correlated Single Photon Counter (TCSPC) electronics that has a measured total impulse response time of 27 ps. The compressive patterns utilized here are Hadamard patterns with a resolution of 32×32.

The first step in the experiments is the calibration of the measurement matrix $\mathbf{H}$. This step is achieved by imaging a white wall with full rank Hadamard patterns ($32 \times 32 = 1024$ in this case) that are used to recover $\mathbf{H}$. Fig. 1b shows

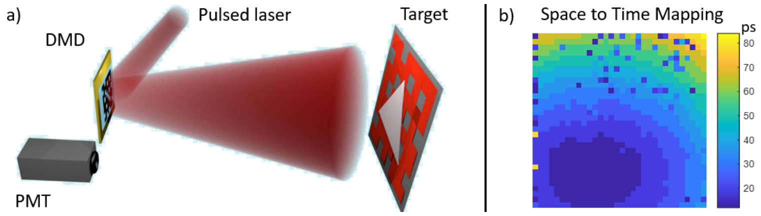

Fig. 1. Ultrafast single pixel camera. a) Experimental setup. b) Visualization of the measurement operator that maps space (pixels) to time. Color indicates the peak time of the response per pixel.

the structure of the measurement operator, the ring structure indicates the areas in the targets that are mapped to different time bins. This shows that improved time resolution encodes more spatial information and thus requires less compressive patterns for recovery of objects.

Figure 2a shows recovery results using compressive ultrafast sensing. The target is a white circle. The figure shows recovery results using the suggested approach and compares it to a traditional single pixel camera (without any time sensitivity) for different number of compressive masks. The reconstructions are evaluated with Structural Similarity (SSIM), that ranges in [0,1] (higher number indicates better reconstruction). Figure 2b also presents a plot for the complete SSIM trend as the number of used masks is reduced (more compression).

To demonstrate that these results are not unique to this particular target we use the mutual coherence. Mutual coherence is defined by: $\mu = \frac{1}{L}\left\|\mathbf{I}_L - \tilde{\mathbf{Q}}^T\tilde{\mathbf{Q}}\right\|_F^2$ where $\mathbf{I}_L$ is the identity matrix, and $\tilde{\mathbf{Q}}$ is $\mathbf{Q}$ with columns normalized to 1. Lower mutual coherence is better and provides guarantees for compressive sensing recovery. The plots in Fig. 2b show that the time-resolved measurement provides superior mutual coherence for any given number of masks. The lower mutual coherence is the reason for better reconstruction quality (higher SSIM) at all levels of compression.

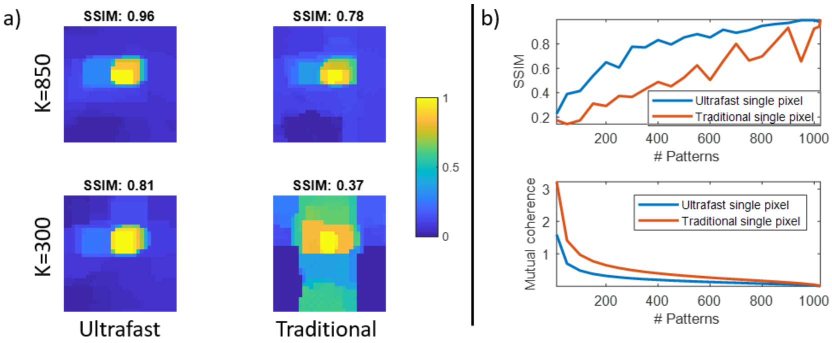

Fig. 2. Experimental results. a) Recovery of a circle shape using ultrafast (left) and traditional (right) single pixel cameras. The two rows correspond to 300 and 850 compressive masks. b) Curves demonstrating the effectiveness of ultrafast single pixel imaging as a function of number of allowed masks.

In conclusion, we experimentally demonstrate that the time-resolved single pixel camera provides significantly improved reconstruction quality with the same number of compressive masks. Alternatively, it can reduce the acquisition time as it requires fewer compressive masks to achieve a desired reconstruction quality.

References

1. G. M. Gibson, B. Sun, M. P. Edgar, D. B. Phillips, N. Hempler, G. T. Maker, G. P. A. Malcolm, and M. J. Padgett. Real-time imaging of methane gas leaks using a single-pixel camera. *Optics Express*, 4, 2017.
2. M. F. Duarte, M. A. Davenport, D. Takhar, J. N. Laska, T. Sun, K. F. Kelly, and R. G. Baraniuk. Single-pixel imaging via compressive sampling. *IEEE Signal Processing Magazine*, 25, 2008.
3. S. Bahmani and J. Romberg. Compressive deconvolution in random mask imaging. *IEEE Transactions on Computational Imaging*, 1, 2015.
4. G. Satat, M. Tancik, and R. Raskar. Lensless imaging with compressive ultrafast sensing. *IEEE Transactions on Computational Imaging*, 3, 2017.