A 2D Camera Design with a Single-pixel Detector

Abdorreza Heidari and Daryoosh Saeedkia
T-Ray Science Inc.
Waterloo Research and Technology Park
295 Hagey Boulevard, Waterloo, Ontario
Canada N2L 6R5
Emails: {aheidari,daryoosh}@t-rayscience.com

***Abstract*—A single-pixel camera for THz imaging has been proposed in [1]. In this article, we propose a new design for a single-detector THz imaging system based on Compressive Sampling (CS), which does not need raster scanning of the object in front of the THz beam. We exploit a time-efficient and cost-effective design to acquire the CS measurements. As a result, the image acquisition time in the proposed imaging system is only limited to the speed of the THz detector. The proposed approach is applicable to other types of imaging as well.**

I. Introduction

Compressed/Compressive Sampling/Sensing (CS) [2], [3] uses a fairly small number of linear projections of a multi-dimensional signal (such as image) to reconstruct the signal. It is basically an efficient sampling scheme which utilizes sparsity, and improves the acquisition process by not sampling redundant data as is done in conventional sensing methods. The CS approach has been introduced recently, yet it is revolutionizing many fields such as imaging and sensing, data acquisition, compression and coding, etc. Currently there are several active fields in imaging, including MRI, low-light and sensitive cameras, and single-pixel cameras, which are exploiting the tools that mathematicians have developed under the CS umbrella.

Consider the general linear sensing model,

$$y = Ax + z \tag{1}$$

where $x_{N\times 1}$ is the desired image vector, $A_{M\times N}$ is the sensing matrix, $y_{M\times 1}$ is the measurement vector, and $z_{M\times 1}$ is the noise vector. There are N unknowns in (1), but M equations, where $M \ll N$ is practically desirable. This problem seems mathematically insolvable as the equation is under-determined, however, it has been shown [2] that using a proper sparse representation of the signal provides a practically certain method to recover the signal from this equation system.

Here is a list of Compressed Sensing benefits. Acquisition and recovery are numerically stable. Same software or hardware implementation can be used for any compressible signal class (Universality). Conventionally acquisition process is complex, costly, and time-consuming which is not attractive for imaging applications. However, in CS, the acquisition process is fairly simple, and most processing is done at the data recovery. In other words, in conventional sensing methods, we usually have smart encoders and dumb decoders, while in CS, we have dumb encoders and smart decoders.

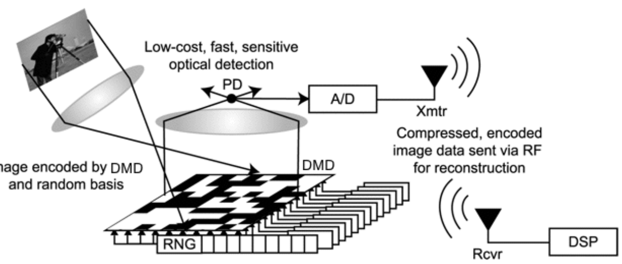

Fig. 1. Block diagram of a single-pixel camera (The picture is from http://www.dsp.ece.rice.edu/cscamera/)

II. Single-pixel Camera

A single-pixel camera [1], [4], uses a set of random masks to acquire the projection measurements. Equivalently, in model (1), A is a random matrix consisting of all the random masks. For a single-pixel camera, usually a random binary (Bernoulli) matrix is used because the ”0” and ”1” elements can be realized by a proper physical mask design which blocks or passes the light respectively. Fig. 1 shows an early implementation diagram of a single-pixel camera, which uses a DMD array as an optical mask.

To implement a conventional CS-based THz imaging system, a set of M random masks are required (which are collectively formulated in the sensing matrix A, i.e., each row in A represents a vectorized mask). In [5], an active metamaterial structure has been suggested as a THz modulator. But such materials are expensive and still have low efficiency in the THz region. In [1], M independent random binary masks are used for the purpose. The masks are printed on a uniform grid on PCBs, where ”0” means a metal deposition on the board which blocks the THz beam. Then, the masks are applied individually by an automatic translation stage. Obviously, this method is very inconvenient in practice, and only is used for the proof of concept. In the following, we propose a novel method for the mechanical mask design, and prove the feasibility.

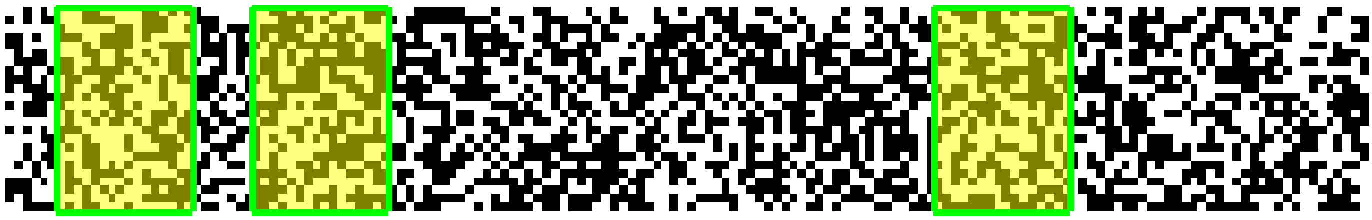

Fig. 2. A demonstration of the proposed design method

A. Our Design Method

In this article, we propose a novel design to implement the random patterns. In this design, a unified mask provides all the required measurements in a convenient way, such that no mechanical mask exchange is required. With this method, the acquisition time reaches the limit of the THz detector speed. This method is also very cost-effective, and can be used to develop flexible THz imaging systems for many applications. We show that the proposed methodology can be utilized in the recovery process to compose the image.

It has been shown that when A is a random binary matrix, the CS approach can be used to recover the image with a high probability. This case is equivalent to having an independent random mask for each measurement. However, implementing M independent random masks and applying them is not easy as explained before. Instead of this method, we choose A to have a random binary Toeplitz construction [6]. This means each row of A is a shifted version of the previous row with some new random binary elements. It has recently been shown that the CS approach is feasible in this case as well, and the performance is almost the same as the case with a random binary sensing matrix.

A Toeplitz construction of A provides a much more compact design, because consecutive masks are overlapped. Fig. 2 demonstrates how this method works. A window (shown in green) represents the image size. This window slides over the design and at each shift, a new measurement is recorded. If N_x and N_y are the window (image) dimensions, and M measurements are needed, the conventional method requires $M\,N_x\,N_y$ binary elements. However, our approach only requires $(M + N_x - 1)\,N_x$ binary elements. Assume $N_x = 42$ and $N_y = 48$, meaning a $N = 2016$ pixel image is targeted. As reported in the literature, $M \geq 1000$ measurements is enough for reconstruction of a wide range of images of this size.

The proposed approach provides a design method for different imaging setups. The same method is applicable to different imaging modes. The proposed "shift-and-measure" method can be employed in many different ways to design a flexible and fast camera. We are developing a compact mask using the proposed approach for a 2D THz camera.

III. Image Recovery

Our image recovery is performed by

$$\min_{x \in \mathbb{R}^N} \|D[x]\|_{l1} \quad \text{subject to } \|Ax - y\|_{l2} \leq \epsilon \tag{2}$$

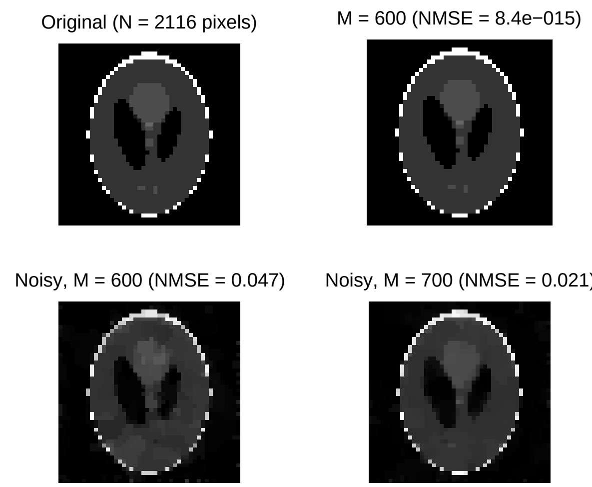

Fig. 3. A sample of recovery results with noisy sub-nyquist measurements

where $D[x]$ is an operator on the image vector x, and ϵ controls the amount of noise in the result. The $D[x]$ operator is chosen such that it can adequately signify the sparsity of the image. The problem above can be efficiently solved as long as it is a Convex Optimization problem, i.e., $\|D[x]\|_{l1}$ is convex as well. Fig. 3 shows a sample of image recovery results, when the TV (total variation) norm [7] is applied. Top-right image shows a perfect recovery for $M = 600$. The two bottom images are the recovery results for $M = 600$ and 700 (less than 1/3 of the image size) when the measurements are added with -20 dB noise (NMSE is the normalized error).

References

[1] W. Chan, K. Charan, D. Takhar, K. Kelly, R. Baraniuk, and D. Mittleman, "A Single-Pixel Terahertz Imaging System based on Compressed Sensing," *Applied Physics Letters*, vol. 93, p. 121105, 2008.

[2] D. Donoho, "Compressed Sensing," *IEEE Transactions on Information Theory*, vol. 52, no. 4, pp. 1289–1306, 2006.

[3] E. Candes and M. Wakin, "An Introduction to Compressive Sampling," *IEEE Signal Processing Magazine*, vol. 25, no. 2, pp. 21–30, 2008.

[4] M. Duarte, M. Davenport, D. Takbar, J. Laska, T. Sun, K. Kelly, and R. Baraniuk, "Single-Pixel Imaging via Compressive Sampling [Building simpler, smaller, and less-expensive digital cameras]," *IEEE Signal Processing Magazine*, vol. 25, no. 2, pp. 83–91, 2008.

[5] H. Chen, W. Padilla, J. Zide, A. Gossard, A. Taylor, and R. Averitt, "Active terahertz metamaterial devices," *Nature*, vol. 444, pp. 597–600, 2006.

[6] G. Golub and C. Van Loan, *Matrix computations*. Johns Hopkins Univ Pr, 1996.

[7] J. Romberg, "Imaging via compressive sampling," *IEEE Signal Processing Magazine*, vol. 25, no. 2, pp. 14–20, 2008.