2011 3rd International Conference on Signal Processing Systems (ICSPS 2011)
IPCSIT vol. 48 (2012) © (2012) IACSIT Press, Singapore
DOI: 10.7763/IPCSIT.2012.V48.5

A Compressive Sensing Photoacoustic Imaging System Based on Digital Micromirror Device

Naizhang Feng+, Mingjian Sun, Liyong Ma

Department of Control Science and Engineering,
Harbin Institute of Technology,
Harbin 150001, China

Abstract. In this paper, a compressive sensing photoacoustic imaging scheme based on Digital Micromirror Device(DMD) is built. In compressive sensing photoacoustic imaging, DMD is used as an optical mask. The mask is placed between a short-pulsed laser and biological tissues to realize the coded illumination. To realize the random illumination, the coded pattern of the mask should be changed for each laser pulse. Based on the DMD, random code patterns of the mask can be changed quickly by controlling a digital logical circuit. The illuminated tissue absorbs the optical energy to generate the ultrasonic waves. The generated ultrasonic waves along the same arc are compressed and detected by an unfocused ultrasonic transducer. After certain measurements, the photoacoustic image can be reconstructed by a suitable CS reconstruction algorithm.

Keywords: Photoacoustic Imaging; Compressive Sensing; Digital Micromirror Device; Micro-electro-mechanical System

1. Introduction

Photoacoustic imaging (PAI) is an emerging biomedical imaging technique and has been expanding rapidly in the past few years[1,2]. By combining strong optical absorption contrast and high ultrasonic penetration in a single modality, PAI can achieve much better spatial resolution at deeper tissues than the traditional optical modalities. In PAI, biological tissues are irradiated by a pulsed laser and absorb optic energy to generate the thermoelastic expansion. The expansion pressure propagates as ultrasonic waves, which are detected by ultrasonic transducers to form images[3-5].

The data acquisition speed of traditional photoacoustic imaging is limited by the laser repetition rate and the number of parallel ultrasound detecting channels[6]. If the image can be reconstructed from fewer measurements, the high imaging rate and low system cost will be achieved. Recently, a compressive sensing (CS) photoacoustic imaging method was proposed[9]. Based on the CS theory[7,8], an image can be reconstructed from far fewer measurements than what the Shannon sampling theory requires if the image is sparse.

Compressive sampling is a key process in the CS photoaoustic imaging, which is usually realized by an optical mask. Simply, a spin disc with high density can be employed as the mask[10]. However, it is difficult to make the high density disc and needs more long sampling time when the disc is changed. In this paper, a mask scheme based on Digital Micromirror Device (DMD) is built.

2. Digital Micromirror Device

DMD is a micro-electro-mechanical system (MEMS) device invented by Texas Instruments Incorporation in 1987. This device combines aluminum alloy mirrors, silicon based electrostatic drives, and silicon microelectronics to create a "light switch". The entire device is micro machined on a single silicon chip, each mirror is very small which is not only an opto-mechanical element but an electro-mechanical element. An

+ Corresponding author. *E-mail address*: fengnz@yeah.net

example of the device is shown in Figure 1. This is a 1280×1024 Digital Micromirror Device. The reflective portion of the device consists of 1,310,720 tiny mirrors. A glass window seals and protects the mirrors. Each mirror size is 16 um.

Figure 1. A high density DMD.

The DMD mirror structure is illustrated in Figure 2. All of mirrors are fabricated on a CMOS memory substrate. Each mirror is fabricated from aluminum. The mirror is connected to an underlying yoke. The yoke is connected by two mechanically compliant torsion hinges, which is capable of tilting the mirror ±10 degrees[11]. When a laser illuminates the DMD, light will be reflected from the mirrors to one of two directions, depending on the state of the mirror.

The mirror is pivoted through electrostatic attraction. The status of memory cells underneath the mirror structure creates a potential across the electrodes on either side of the mirror. One electrode is tied to the memory output and the other to the complementary output. When a bias voltage is applied, the yoke assembly is attracted by the electrode with the greatest potential difference. At this point, the mirror is mechanically latched because the distance from the opposite electrode to the mirror is too great to overcome the force of gravity keeping the mirror tilted, and it is stable. The status of memory cells can be changed at this time without affecting the mirror's tilt. When it is time to switch, the mirror is actually tilted further, loading the spring tips on the landing pads with potential energy. The force applied to load the springs is then released simultaneously with the change in electrode polarity. The springs give the mirror an extra boost to overcome gravity, and the electrostatic force of the other electrode pulls the mirror into its control. Each mirror of the DMD is capable of switching in this way every 20μs[12].

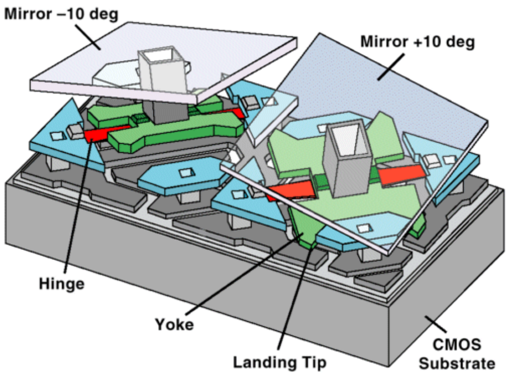

Figure 2. Schematic of the DMD mirror structure.

The DMD mirror array pictures are taken by a Scanning Electron Microscope and shown in Figure 3.

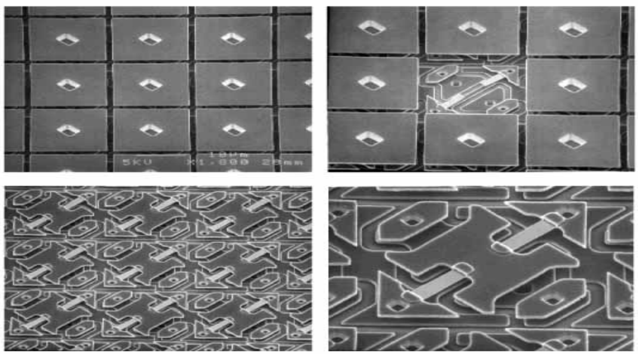

Figure 3. DMD mirror pictures by a Scanning Electron Microscope.

As described above, the mirror position depending on the status of memory cells[13]. A "one" stored in the cell will cause the mirror to move to +10 degree position. And a "zero" stored in the cell will cause the mirror to move to -10 degree position. When the memory cell is neither, no electrostatic force is applied to the mirror and the torsion hinges cause the mirror to return to 0 degrees. When a mirror is fully tilted in either direction, and has made contact with the yoke base, a bias current keeps the mirror in place irrespective of changes in the address electrode. This enables the mirror to remain in the correct position even while a new bit of data is being loaded into the cell memory.

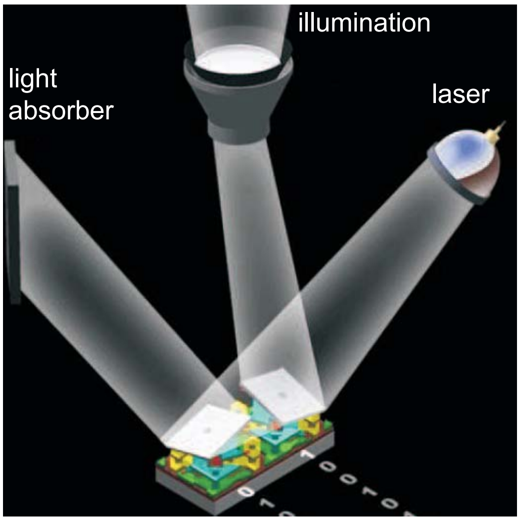

Figure 4. Realization for mask pixels in on and off state.

In CS photoacoustic imaging, the optical mask can be realized by controlling the rotation of DMD mirrors. The schematic is shown in Figure 4. All of DMD mirrors are shined by a laser. For the "off" position of the mask, the corresponding mirror is steered to a light absorber and the reflected light is absorbed. For the "on" position of the mask, the corresponding mirror is steered to testing tissues, which will be illuminated by the reflected light.

3. CS Photoacoustic Imaging Principle

The schematic of CS photoacoustic imaging based on DMD is illustrated in Figure 5.

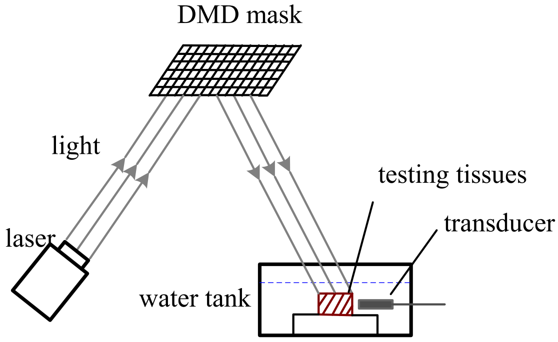

Figure 5. Schematic of CS photoacoustic imaging based on DMD

A short-pulse laser irradiates the DMD. Some of the light is reflected by the DMD mask to illuminate the tissue placed in a water tank. To realize random illumination, the coded pattern of the mask should be changed for each laser pulse. Based on the DMD, random code patterns of the mask can be changed quickly by controlling a digital logical circuit. The illuminated tissue absorbs the optical energy to generate the ultrasonic waves. The generated ultrasonic waves along the same arc arrive at the ultrasonic transducer simultaneously, so the achieved signals are the information superposition (compression) along the arc-direction. An unfocused ultrasonic transducer is used to record the arc-compressed information, shown in Figure 6.

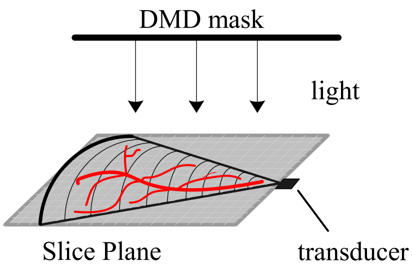

Figure 6. Reception process of CS photoacoustic imaging

The above process of laser random illumination and wave reception is called a measurement of the CS photoacoustic imaging. After certain measurements, the photoacoustic image can be reconstructed by a suitable CS reconstruction algorithm.

According to the CS theory, it is possible to reconstruct a K-sparse signal $x = \Psi s$ of length N from O(KlogN) measurements. Here, Ψ is the sparsifying transform matrix and s is the sparse representation of x. CS takes random measurements $y = \Phi x$. The measurement matrix Φ is incoherent with the sparsifying transform matrix Ψ. The signal x can be reconstructed by solving a convex optimization problem of the following form[7]

$$\hat{x} = \arg\min_x \|\Psi x\|_1 \quad \text{s. t.} \quad y = \Phi\Psi x \tag{1}$$

where $\|x\|_1$ is the l_1 norm of the signal.

Usually, photoacoustic images are sparse since only tissue angio information is displayed. Therefore the sparsifying transform matrix Ψ can be taken as an unit matrix. Then equation (1) becomes

$$\hat{x} = \arg\min_x \|x\|_1 \quad \text{s. t.} \quad y = \Phi x \tag{2}$$

The measurement matrix Φ is realized by the DMD mask. Each DMD mirror corresponds to a mask pixel. To compute CS randomized measurements $y = \Phi x$ as in equation (2), the mirror orientations Φ_m are set randomly and the corresponding measurement result is y_m. Then repeat the process M times to obtain the measurement vector y.

The CS reconstruction algorithms are generally classified into basis pursuit and greedy pursuit approaches[14]. The basis pursuit[15] approaches rely on an l_1-norm-based optimization problem that can be solved using linear programming. This linear programming, despite being quite efficient in practice, has a polynomial runtime. An alternative approach to basis pursuit methods is greedy pursuit methods. These approaches are based on thresholding and iterative recovery of signal components. Unfortunately, the exact reconstruction guarantees for greedy pursuits are not as strong as those for the basis pursuits. Nevertheless, compared to the basis pursuit approaches, the greedy pursuit algorithms such as orthogonal matching pursuit (OMP)[16] require much less computational resources and yield similar reconstruction performance in practice[17].

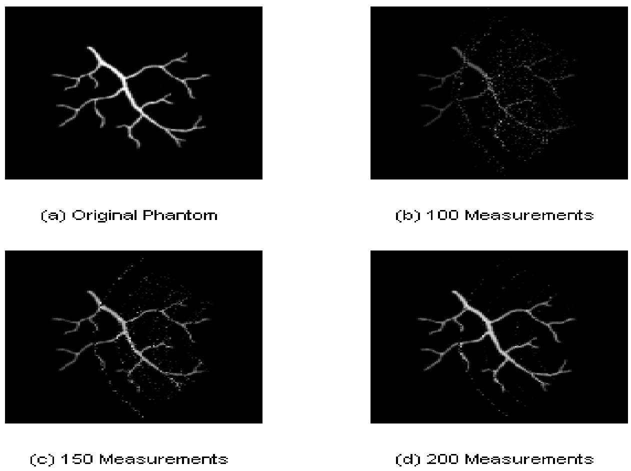

Figure 7. Reconstructed results for a photoacoustic phantom

A CS photoacoustic imaging simulation is made, in which a reasonable photoacoustic phantom is sampled and reconstructed. Based on the OMP algorithm, reconstructed results are acquired and shown in Figure 7. The orginal phantom is displayed in Figure 7(a). The reconstructed results of 100, 150 and 200 measurements are respectively displayed in Figure 7(b), (c) and (d). It is seen that the reconstructed artifacts are obvious when the measurement is not enough and become slighter as the measurement increases.

4. Conclusion

DMD is a high integrated MEMS device composed of many tiny mirrors, which can rotate in a certain scale. In CS photoacoustic imaging, the optical mask can be realized by controlling the rotation of DMD mirrors. All of DMD mirrors are irradiated by a laser. For the "off" position of the mask, the corresponding mirror is steered to a light absorber and the reflected light is absorbed. For the "on" position of the mask, the corresponding mirror is steered to testing tissues, which will be illuminated by the reflected light. The coded pattern of the mask can be changed quickly by controlling a digital logical circuit, so the random illumination becomes easier than the traditional disc mask. The mask is placed between a short-pulsed laser and biological tissues to realize the coded illumination. The illuminated tissue absorbs the optical energy to generate the ultrasonic waves. The generated ultrasonic waves along the same arc are compressed and received by an unfocused ultrasonic transducer. After certain measurements, the photoacoustic image can be reconstructed by a suitable CS reconstruction algorithm.

5. Acknowledgment

This work is supported by the National Natural Science Foundation of China (No. 30800240), Shandong Provincial Promotive Research Fund for Excellent Young and Middle-aged Scientists (BS2010DX001) and Weihai City Science & Technology Development Project (2010-3-96).

6. References

[1] L. V. Wang, “Prospects of photoacoustic tomography,” Medical Physics, vol.35, no.12, 2008, pp. 5759-5767.

[2] Z. Xu, C. Li, L. V. Wang, “Photoacoustic tomography of water in phantoms and tissue,” Journal of Biomedical Optics, vol.13, no.3, 2010, pp.036019:1-6.

[3] B. E. Treeby, B. T. Cox, “k-Wave: MATLAB toolbox for the simulation and reconstruction of photoacoustic wave fields,” Journal of Biomedical Optics, vol.15, no.2, 2010, pp.021314:1-12.

[4] H. F. Zhang, K. Maslov, G. Stoica, et al, “Functional photoacoustic microscopy for high-resolution and noninvasive in vivo imaging. Nature Biotechnology,” vol.24, no.7, 2006, pp.848-851.

[5] M. Xu, L. V. Wang, “Photoacoustic imaging in biomedicine,” Review of Scientific Instruments, vol.77, 2006, pp.041101:1-21.

[6] Z. Guo, C. Li, L. Song, et al, “Compressed sensing in photoacoustic tomography in vivo,” Journal of Biomedical Optics, vol.15, no.2, 2010, pp.021311:1-6.

[7] E. J. Candes, M. B. Wakin, “An Introduction To Compressive Sampling,” IEEE Signal Processing Magazine, no.3, 2008, pp.21-30.

[8] M. F. Duarte, M. A. Davenport, D. Takhar, et al, “Single-Pixel Imaging via Compressive Sampling,” IEEE Signal Processing Magazine, no.3, 2008, pp.83-91.

[9] J. Provost, F. Lesage, “The Application of compressed sensing for photo-acoustic tomography,” IEEE Transactions on Medical Imaging, vol.28, no.4, 2009, pp.585-594.

[10] D. Liang, H. F. Zhang, L. Ying, "Compressed-sensing photoacoustic imaging based on random optical illumination," Int. J. Functional Informatics and Personalised Medicine, Vol.2, No.4, 2009, pp.394-406

[11] D. Dudley, W. Duncan, and J. Slaughter, “Emerging Digital Micromirror Device (DMD) Applications,” Proc. SPIE ‘03, 2003, pp. 14-25.

[12] A. Sontheimer, “Digital Micromirror Device (DMD) Hinge Memory Lifetime Reliability Modeling,” Proc. 40th Annual IEEE International Reliability Physics Symposium, 2002, pp. 118-121.

[13] - "Introduction to Digital Micromirror Device (DMD) Technology," Texas Instruments Application Report:DLPA008, July 2008, pp.1-11.

[14] M. Usman, C. Prieto, F. Odille, "A computationally efficient OMP-based compressed sensing reconstruction for dynamic MRI," Phys. Med. Biol., vol.56, 2011, pp.N99-N114.

[15] D. L. Donoho,“Compressed Sensing,” IEEE Transactions on Information Theory, vo.52, no.4, 2006, pp.1289-1306.

[16] J. A. Tropp, A. C. Gilbert, “Signal Recovery From Random Measurements Via Orthogonal Matching Pursuit,” IEEE Transactions on Information Theory, vol.53, no.12, 2007, pp.4655-4666.

[17] U. Gamper, P. Boesiger, S. Kozerke, "Compressed sensing in dynamic MRI," Magnetic Resonance in Medicine, vol.59, no.2, 2008 , pp.365-73.