Image Super-resolution for Ultrafast Optical Time-stretch Imaging

Runbin Shi[1], Antony C.S. Chan[2], Edmund Y. Lam[1], Hayden K.-H. So[1]

[1] *Department of Electrical and Electronic Engineering, The University of Hong Kong, Pokfulam, Hong Kong.*
{rbshi,elam,hso}@eee.hku.hk

[2] *Department of Electrical Engineering, California Institute of Technology, Pasadena, California 91125, USA.*
antony.cschan@caltech.edu

Abstract: We report on a super-resolution scheme for optical time-stretch imaging. It is particularly applicable to ultrafast flow imaging, but suffers from low resolution in spectral-encoding. Our algorithm overcomes this by designing subpixel shifts across scans.

1. Optical Time-stretch Imaging

Many biomedical imaging applications require extremely high throughput image capture and analysis, such as in the imaging of blood flow for single-cell characterization [1]. Several ultrafast imaging techniques have been developed by various groups [2, 3], but time-stretch imaging has proved to be very competitive. In this modality, summarized in Fig. 1, 2D images are formed from stacking the spectrally-encoded line scans, although techniques have also been developed for arbitrary two-dimensional spectrally encoded pattern generation that is suitable for patterned illumination imaging [4]. The sampling rate of the digitizer is the determining factor for image resolution in the spectral-encoding direction [5]; unfortunately, high-resolution typically demands high-end digitizers, which tend to be very costly. For technical details of the state-of-the-art optical time-stretch imaging architecture and analysis, the readers are referred to Ref. [6]. The objective of the present paper is to show how we can harness the computing hardware and a simple algorithm to achieve super-resolution for optical time-stretch imaging.

2. Designing Subpixel Shifts

Fig. 2 shows the line scanning and stacking processes of 2D image formation. Across the cell flow direction, a periodic laser shines through the cell channel and emits a spectrally-encoded beam to generate one continuous image line via time-stretch. This continuous signal is then sampled by the digitizer with a fixed frequency at multiples of the laser scanning rate, as shown in (b). The sampled pixels from neighboring lines are stacked to form a 2D cell image. The spatial pixel resolution of vertical and horizontal directions should be measured respectively to represent the digitized image quality. In our previous work [7, 9], we propose that the spatial resolution along the flow direction (vertical) can be determined by the flow rate and laser pulse frequency. Thus the vertical resolution can be increased with a lower flow rate. Relatively, the spatial resolution in the horizontal direction is only determined by the digitizer sampling frequency. Thus, in this real-time ultrafast imaging system, the highest working frequency (5 GSa/s) of the analog-to-digital converter (ADC) limits the horizontal resolution. As a result, the horizontal direction is under-sampled while there are redundant pixels in the vertical direction.

Here, we propose a novel scheme to increase the horizontal resolution with fine-tuning of the ADC sampling clock. We have shown previously that subpixel shift can achieve a higher resolution by combining multiple low-

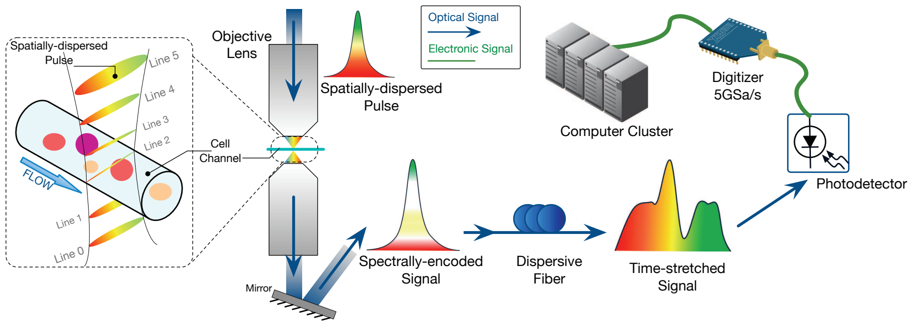


Fig. 1. A simplified diagram of optical time-stretch imaging.

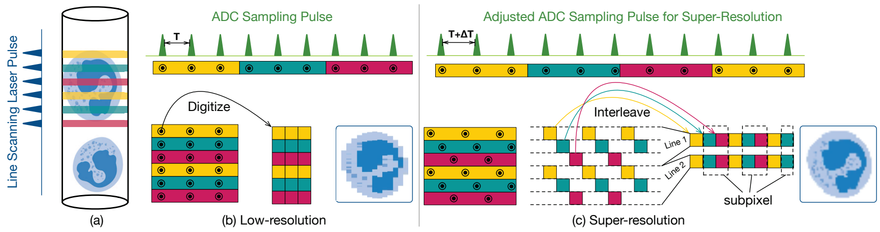
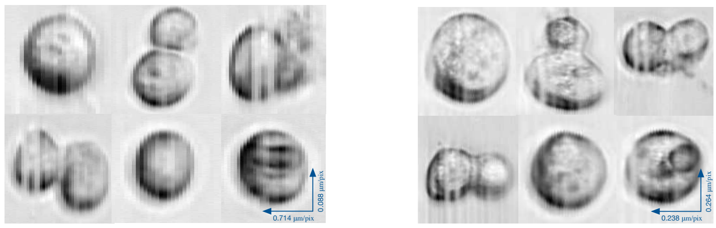


Fig. 2. Super-resolution with subpixel shift.



(a) Low-resolution (b) Super-resolution

Fig. 3. Low-resolution and super-resolution images.

resolution lines asynchronous sampled [8]; yet, the cost for real-time processing of huge amount of data in that approach is unacceptable. In contrast, the current scheme can reveal more spatial information with an even slightly lower sampling frequency. Fig. 2(c) demonstrates the process. Compared with line-aligned sampling in (b), here the sampling frequency is intentionally set to non-multiple times of line-scan laser frequency. Therefore, the sampling positions located in neighboring lines will be slightly shifted in a controlled manner. In general, $\mathbf{p}$ pixels can be uniformly sampled in every $\mathbf{q}$ lines. Thus, $\mathbf{p}$ and $\mathbf{q}$ are key parameters, where we have used $\mathbf{p} = 8, \mathbf{q} = 3$ for (c).

We then develop a line interleaving scheme for 2D image stacking. As Fig. 2(c) depicts, the pixels of every three line are interleaved during image reconstruction. Therefore, each image line has a higher resolution three times of (b). Although noise may be magnified in this interleaving process [10], experiment results show that it is acceptable if $\mathbf{q} < 6$. Otherwise, the jagged edges become apparent.

We have implemented this scheme with $\mathbf{p} = 1024$ and $\mathbf{q} = 3$. The clock synthesizer is used to generate the ADC sampling with the input source from the line-scan laser, while the line interleaving module is implemented on the Field Programmable Gate Array (FPGA) as part of the digital front end. Fig. 3 shows the cell images collected from the real-time system before and after this super-resolution scheme. Both are sampled at $\approx 4\,\mathrm{GSa/s}$. As can be seen, super-resolution indeed reveals more texture details compared with the raw image.

In summary, this paper demonstrates a super-resolution scheme for ultrafast optical time-stretch imaging. By designing the subpixel shifts and line interleaving across scans, the proposed method achieves considerable improvement on the cell imaging resolution. This work is supported in part by the NSFC/RGC under Project N_HKU714/13.

References

[1] T. T. Wong et al., “Asymmetric-detection time-stretch optical microscopy (ATOM) for ultrafast high-contrast cellular imaging in flow,” Scientific Reports **4**, 3656 (2014).

[2] L. Gao et al., “Single-shot compressed ultrafast photography at one hundred billion frames per second,” Nature **516**, 74–77 (2014).

[3] G. Satat et al., “Advances in ultrafast optics and imaging applications,” in vol. 9835 of *Proc. SPIE* (2016), p. 98350Q.

[4] A. C. Chan et al., “Arbitrary two-dimensional spectrally encoded pattern generation—a new strategy for high-speed patterned illumination imaging,” Optica **2**, 1037–1044 (2015).

[5] A. K. Lau et al., “Interferometric time-stretch microscopy for ultrafast quantitative cellular and tissue imaging at 1μm,” Journal of Biomedical Optics **19**, 076001 (2014).

[6] J.-L. Wu et al., “Ultrafast laser-scanning time-stretch imaging at visible wavelengths,” Light: Science and Applications **6**, e16196 (2017).

[7] A. C. Chan et al., “All-passive pixel super-resolution of time-stretch imaging,” Scientific Reports (2017).

[8] A. C. Chan et al., “Pixel super-resolution in optical time-stretch microscopy using acousto-optic deflector,” in “OSA Topical Meeting in Bio-Optics: Design and Application,” (2015), p. BW2A.7.

[9] A. C. Chan et al., “Pixel super-resolution of time-stretch imaging by an equivalent-time sampling concept,” in vol. 9720 of *Proc. SPIE* (2016), p. 972004.

[10] E. Y. Lam, “Noise in superresolution reconstruction,” Optics Letters **28**, 2234–2236 (2003).