Spectral Super-resolution by Image Sensor Tilting

Kazuya Kitano, Takuya Funatomi, Ryohei Yasukuni, Kenichiro Tanaka, Hiroyuki Kubo, Yoichiroh Hosokawa, Yasuhiro Mukaigawa
Nara Institute of Science and Technology, 8916-5 Takayama, Ikoma, Nara 6300192, Japan
kitano.kazuya.jy9@is.naist.jp

Abstract: We propose a spectral super-resolution method to utilize additional rows using an area sensor tilting to enhance spectral measurement. To verify our method, we conducted preliminary experiments measuring sunlight and a low-pressure mercury-vapor lamp.

1. Introduction

The spectral resolution of the multi-channel spectrometer is determined by multiple factors such as the slit width, groove of the grating, aberration of the lens and pixel pitch of the linear sensor. Konishi *et al.* [1] discussed that the main factor of the determination of the spectral resolution is the pixel pitch because the optical point spread function (PSF) in the spectrometer is smaller than the pixel pitch. They propose a super-resolution method of using two different stripes to create a Moiré pattern for limiting the wavelength bandwidth on each pixel. However, this method narrows the bandwidth of the spectrometer. We propose a method that utilizes additional rows captured by a tilted area sensor to enhance spectral measurement. By tilting the sensor slightly, each line measures a slightly different spectrum. We computationally recover the fine spectrum using the differences. This method has a better signal to noise ratio than the measurement using a linear sensor since it allows to utilize multiple rows of the area sensor.

2. Methodology

Our method targets a dispersive spectrometer as shown in Fig. 1(a). In the multi-channel spectrometer, the grating disperses an incident ray and the linear sensor samples the dispersed ray. The wavelength resolution is determined by the pixel pitch of the sensor, meanwhile, our method utilizes an area sensor as a detector.

By inserting a vertical diffuser in front of the slit, we can assume that each line of the area sensor parallel to the grating grooves outputs the same spectral measurement when the area sensor is perfectly aligned along the grating. Meanwhile, we slightly tilt the area sensor, hence each line outputs a slightly different measurement. Similar to our method, Watanabe and Furukawa [2] propose an oversampling method by tilting the image sensor in the Fourier transfer spectrometer, however, the pixel width is ignored. In this study, we take the pixel width as a blur on the spectral measurement along wavelength. The outputs are equivalent to the measurements by shifting the line sensor with subpixel accuracy. Therefore, it is straightforward to apply a sensor-shifting method [3] to estimate the super-resolved spectrum.

Specifically, the tilt angle of the sensor corresponds to the magnification of the super-resolution. The blur kernel is the line spread function (LSF) of the spectrometer, which can be estimated using a light source with known emission lines such as a low-pressure mercury-vapor lamp. The super-resolved spectrum can be recovered from a sequence of the blurred measurements on slightly shifted spectra by applying the non-negative least squares (NNLS) method [4].

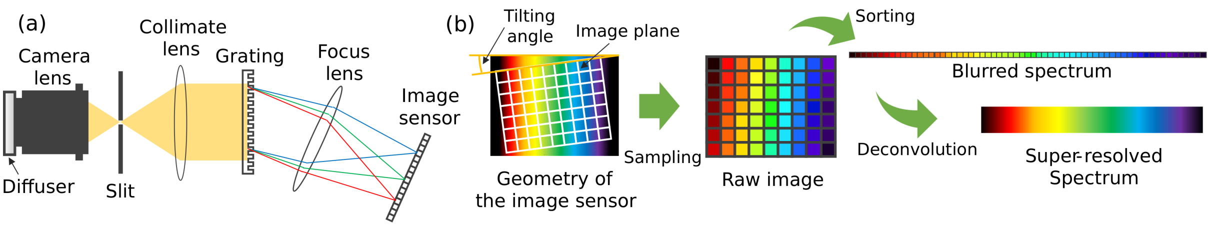

Fig. 1. (a) Optical configuration of the transmission spectrometer. (b) The process of our method.

3. Experimental results

We built a transmission spectrometer as shown in Fig. 1(a). The grating groove is 600 lines/mm, the slit width is 3 µm in experiment 1 and 15 µm in experiment 2. The area sensor can rotate around the optical axis. We validated our method through two experiments below.

3.1. Verification of the spectral super-resolution using downsampled data

Firstly, we verify our method using the downsampling that simulates a tilted area sensor. In this experiment, we downsample the measurement, super-resolve it, and compare it to the original spectrum. We use the sunlight as a light source. The original spectrum is 5472×1 pixels captured by the central row of the area sensor. The measurement is downsampled to 72×76 pixels, where the vertical row is shifted to emulate the sensor tilt. Fig. 2(a) shows the experimental result. While the downsampled spectrum does not show the exact peaks of the spectrum, the estimated result is much sharper and similar to the original spectrum.

3.2. Estimate the mercury bright lines in the Real Environment

In the second experiment, we show the effectiveness of our method by estimating the mercury lines in the real environment. In this experiment, we use the low-pressure mercury-vapor lamp. The bright line which can measure from the mercury is 576.960 nm and 579.066 nm. The width of the two bright lines is about 2 nm, and the baseline spectrometer cannot separate two peaks. The raw measurement and the estimated result are shown in Fig. 2(b). Although there should be two separate lines around 577 nm, the bright lines are blurred and cannot be observed in the ordinary measurement. In contrast, the estimated spectrum by the proposed method can successfully separate two bright lines.

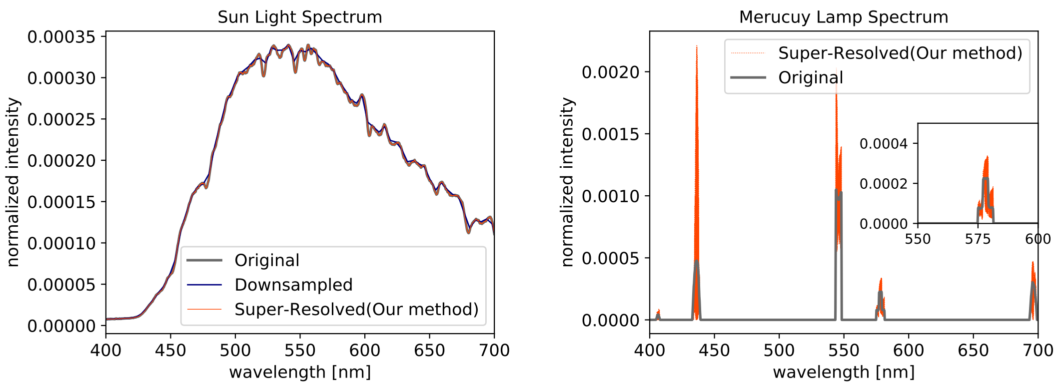

Fig. 2. Experimental results. (a) Original, downsampled, and reconstructed spectrum. The sharp spectrum is reconstructed. (b) Super-resolved spectrum of the mercury bright lines.

Acknowledgement This work is partly supported by JST CREST JPMJCR1764, JSPS KAKENHI JP19J14999 and the Grant-in-Aid for Scientific Research (C) (No. 18042069).

References

1. Tsuyoshi Konishi, Yu Yamasaki, and Tomotaka Nagashima. Super spectral resolution beyond pixel nyquist limits on multi-channel spectrometer. *Opt. Express*, 24(23):26583–26598, Nov 2016.
2. Anri Watanabe and Hiromitsu Furukawa. Super-resolution technique for high-resolution multichannel fourier transform spectrometer. *Opt. Express*, 26(21):27787–27797, Oct 2018.
3. Sung Cheol Park, Min Kyu Park, and Moon Gi Kang. Super-resolution image reconstruction: a technical overview. *IEEE Signal Processing Magazine*, 20(3):21–36, May 2003.
4. Jason Cantarella and Michael Piatek. TSNNLS: A solver for large sparse least-squares problems with non-negative variables. arXiv:cs.MS/0408029.