A Low-Cost Hyperspectral Scanner for Security Printing

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Abstract

We demonstrate a hand-held scanner that acquires two-dimensional images with up to 40 distinct wavelength channels. Light is collected through a combined slit and illumination assembly, dispersed by a diffraction grating film and analyzed using a webcam. Custom software is used to track the scanner motion and build the hyperspectral image data in real time. We tested the performance on printed fluorescent ink patterns that are of interest for security printing applications, and obtained results that are consistent with spectra acquired using a laboratory-grade spectrofluorometer.

Introduction

Identity theft, counterfeiting, warranty fraud, and forgery pose an ever-increasing threat to individuals, corporations and governments, with costs as high as $1.7 trillion projected in 2015 [1]. Easy access to high-resolution copiers and scanners, sophisticated image processing software and other digital tools have made detection and prevention extremely challenging and costly. As mobile and smart devices become more capable and with the evolution of the "internet of everything" ecosystem, wireless financial transactions and the exchange of private and personal information have become casual and commonplace. These trends have provided highly motivated and increasingly sophisticated criminals with new access points and opportunities for fraud and identity theft.

Developing innovative printing technologies for enhanced security has been a major focus of HP's Imaging and Printing businesses, leading to products such as HP's JetAdvantage Security Solutions. To address counterfeit and forgery in particular, specialty inks can be used that are difficult to copy but can be verified using specialized tools. At the forefront of security printing are techniques that combine complicated spatial patterns with unique spectral signatures using mixtures of fluorescent inks. In previous work we have demonstrated an ability to generate such patterns by thermal inkjet printing, using quantum-dot-based inks [2].

An important challenge, however, is finding an economical way to verify the unique spectral and spatial signatures. Hyperspectral imaging systems, which provide numerous channels of spectral data across a continuous image, have shown promise for ink analysis [3], but such systems are usually designed for laboratory use and cost tens of thousands of dollars. Hyperspectral imagers can be implemented by a wide variety of methods. The most common approach is one-dimensional imaging, through a slit aperture, combined with a diffraction grating to disperse light along the orthogonal axis onto a 2D sensor, with the position of the sample (or an image of the sample) scanned in time perpendicular to the slit axis. While spatial scanning approaches designed for laboratory or airborne use are typically optimized for performance, low-cost implementations have also been reported [4]. Another scanning approach involves two-dimensional imaging through a narrowband spectral filter, while the transmission frequency is swept in time. Such a tunable filter can be implemented using MEMS [7] or liquid-crystal [8] devices. Non-scanning "snapshot" approaches also exist, including approaches based on aperture arrays [5], image-mapping methods [6], or large-sets of filter mosaics [9]. While such approaches allow for faster data acquisition, they require trade-offs between spectral and spatial resolution, and may require expensive fabrication of specialized optical surfaces or integrated optical components.

Our goal in this work was to demonstrate a low-cost and compact implementation of a hyperspectral imager suitable for detecting multi-channel fluorescence patterns on a flat paper surface. Our approach uses relatively simple hardware and relies on computational methods to construct data of sufficient quality for security ink verification.

Design of the Scanner

Fig. 1a shows a schematic diagram of our hyperspectral scanner. A 3D-printed slit assembly (shown from beneath in the inset) defines a narrow rectangular region, 50 mm long, of the paper to be analyzed. The slit assembly includes a row of holes to hold LEDs that provide intense illumination from outside the slit. In our demonstration, one row contained white LEDs for reflection spectroscopy, and the other row contained UV LEDs emitting at 390 nm for fluorescence spectroscopy. The light collected through the slit is imaged by a HD 720p webcam (Logitech c310). The webcam was disassembled to remove a supporting structure and to adjust the lens focus. A low-cost film diffraction grating (Edmund) is placed immediately in front of the webcam to disperse the spectral components of the collected light into different directions. In addition, the webcam sees two regions of the paper on either side of the slit assembly, which are illuminated by separate LEDs. These unobstructed regions are used to track the motion of the scanner as it is moved manually across the paper. Figs. 1(b,c) show the exterior of the scanner, and Fig. 1d shows a typical frame captured by the webcam.

To enable real-time construction of hyperspectral data, we wrote software in C using the OpenCV library. The software includes a motion-tracking algorithm that uses cross-correlation analysis combined with continuous stitching of a reference image to track motion in each of the two regions, from which the translation and rotation (about the vertical axis) of the scanner are estimated. The spectral information along various color slices in the raw image (generally these are curved slices because of the geometry) is then translated and rotated before it is added to a set of $\sim$ 40 separate images corresponding to different color channels. The software runs at the maximum capture rate of the webcam (30 fps) on an HP ZBook laptop, but for fluorescence imaging we obtained better results when we increased the exposure to 62 ms, because of the low intensity of the signals.

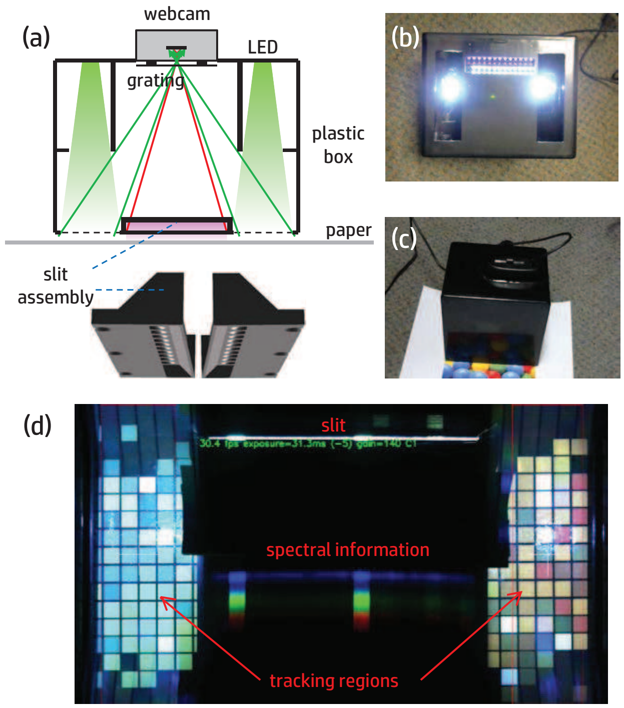

Figure 1. (a) Design of the hyperspectral scanner, including the slit assembly as seen from below. (b,c) Pictures of the completed scanner. (d) A typical frame captured by the webcam.

Imaging Results

We printed fluorescent patterns on low-fluorescence Teslin paper using a customized thermal inkjet printhead with an X-Y table system. The fluorescent inks contained three kinds of daylight fluorescent pigments, diluted 1:100 by volume in an ink vehicle consisting of 1,5-pentanediol (5% by weight), 1,6-hexanediol (5%), and deionized water (90%). A separate overlay sheet with printed characters and a central cut-out was placed on top to assist with motion tracking. Fig. 2a shows a composite fluorescence image obtained by summing over the wavelength channels of a hyperspectral image obtained with our scanner. The time required to obtain a hyperspectral image is typically 15 – 30 s. Every point in the image contains 41 channels of spectral information. Fig 2b shows spectra extracted from particular locations labeled in the image. To obtain these spectra, the hyperspectral image was corrected by subtracting reference data obtained from blank paper. This removes background fluorescence from the paper as well as longer-wavelength emission from the UV LEDs. In addition, the spectrum obtained from location 1 was subtracted from the other spectra, to remove minor additional artifacts. In the final spectra, peaks corresponding to the three pigments are clearly resolved. At locations where two pigments are simultaneously present, such as location 5, double peaks are observed, as expected. The spectra show good agreement with bulk spectra obtained using a laboratory spectrofluorometer (Fig. 2c). The excitation wavelengths using the spectrofluorometer were 365 nm, 450 nm, and 465 nm for blue, green and orange, respectively.

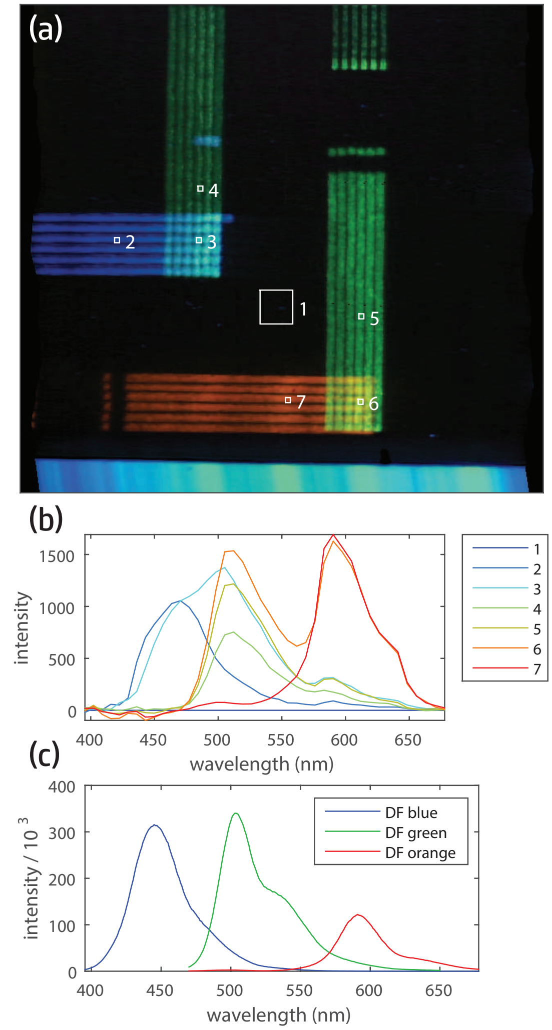

Figure 2. (a) Composite fluorescence image of a printed test pattern containing daylight fluorescent pigments. The image was obtained by summing the wavelength channels of a hyperspectral image. (b) Example spectra obtained from the locations labeled in (a). Note that the hyperspectral image contains full spectral data at every location in the image. (c) Spectra of the daylight fluorescent inks diluted in water, obtained using a laboratory spectrofluorometer.

We estimate the spectral resolution of our scanner to be approximately 10 – 15 nm. In the future it should be possible to decode complex patterns written with up to 20 different inks simultaneously, if fluorescent materials with sufficiently narrow emission linewidths can be printed. Inks containing colloidal quantum dots are promising for this purpose, since quantum dots can have ensemble linewidths as narrow as 20 nm [10]. We have successfully printed inks containing low-toxicity InP/ZnS quantum dots and imaged them with our scanner, as shown in Fig. 3. However, more work is needed to obtain narrow-linewidth emission and a large set of peak wavelengths, as needed to exceed the performance of the fluorescent pigments used in the above demonstration.

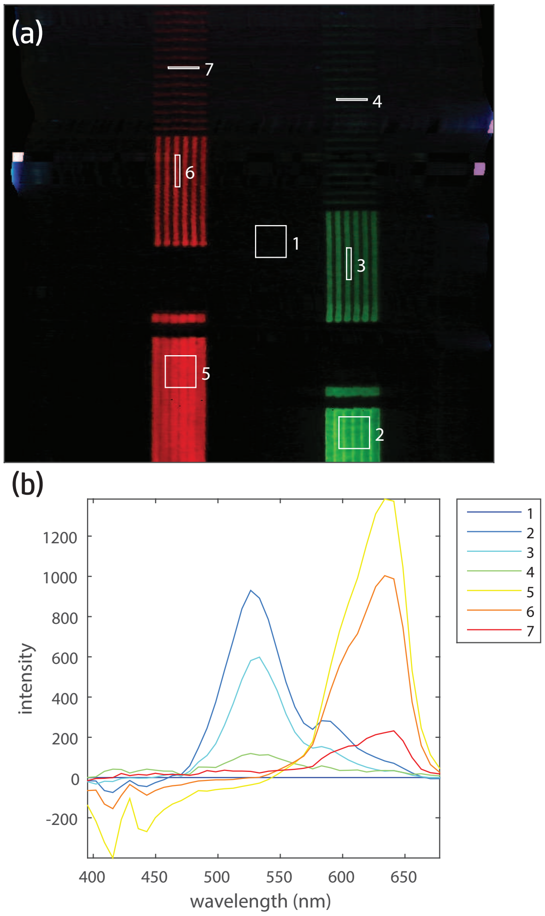

Figure 3. *(a) Composite fluorescence image of a printed test pattern containing InP/ZnS quantum dots. The image was obtained by summing the wavelength channels of a hyperspectral image. (b) Example spectra obtained from the locations labeled in (a). Note that the hyperspectral image contains full spectral data at every location in the image.*

Outlook

We have demonstrated that a simple handheld hyperspectral scanner suitable for security printing with fluorescent inks is feasible. In the future, our scanner can be optimized for smaller size, more robust motion tracking, lower cost, and faster scan speed. At the same time, improvments in quantum-dot-based fluorescent inks should allow printing of many-channel patterns which can take full advantage of a hyperspectral scanner's capabiliies.

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Charles Santori received his SB in Physics from MIT (1997) and his PhD in Applied Physics from Stanford University (2003). Since 2005 he has worked at HP Labs in Palo Alto, CA on projects related to photonics, quantum computing and spectroscopy.

