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Instrumentation challenges of a pushbroom hyperspectral imaging system for currency counterfeit applications

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ABSTRACT

Hyperspectral imaging allows the intensity of narrow and adjacent spectral bands over a large spectral range to be recorded, giving rich spectral information for each pixel in the imaged region. The spectral characteristics of each point in the imaged region can thus be detected, which is useful for quantification and classification. Hyperspectral imaging has been used in many applications such as remote sensing, quality assessment of agro-food products, biomedical imaging and document counterfeit application. This paper presents a pushbroom spatial-scanning imager, which gives a higher spectral resolution over a broad spectral range. Although a spatial-scanning imager may be slower due to the need to perform mechanical scanning, such a high spectral resolution is especially important in applications where the capability to perform classification is much more important than speed. The application of this system is demonstrated for currency counterfeit detection applications. The high spectral resolution of a pushbroom imager is able to capture fine spectral details of the samples used in this research, providing important information required for classification. Using this technique, the reflectance is acquired from specific regions of a genuine and counterfeit note. The spectra of the same region from both notes are then compared to distinguish and delineate the differences between them. The spectrum acquired from a genuine note can then be used as a reference from which future comparison can be based upon for identifying currency counterfeit and related relevant applications.

Keywords: Hyperspectral imaging, spectroscopy, reflectance, currency counterfeiting.

1. INTRODUCTION

Optical methods have been used in forensic science for the purpose of crime investigation such as fingerprint imaging^{1,2} and counterfeit applications³. Counterfeit products are often produced unlawfully, with the aim to imitate the genuine products so that they are thought to have a higher value. Such activities exist in many different industries, such as tablets in pharmaceutical industry⁴, as well as currency notes³ and credit cards⁵ in the financial industries. Counterfeiting has to be treated with high regard as it can harm the consumers and economy. In the case of combating against counterfeit currency notes, security features are usually in place for easy identification of such notes. These security features include watermarks, security thread and fluorescent features. As printing equipment advances, the differences between the genuine and counterfeit products can be reduced. This makes the identification of counterfeit notes harder, and more likely to be mistaken as a genuine note. Therefore, a precise, accurate and safe method must be available to authenticate currency notes. Hyperspectral imaging (HSI), a nondestructive method of measurement, is suitable for such applications. It is able to differentiate genuine documents from counterfeit ones³, and is also useful for many other applications such as quality assessment of agro-food products^{6,7}, disease diagnosis in biomedical applications⁸⁻¹⁰ and remote sensing¹¹.

HSI was first commonly used in airborne and spaceborne remote sensing¹¹, after the advent of electronic recording systems which replaced the film-based systems¹². HSI records the intensity of narrow and adjacent spectral bands over a large spectral range, giving a detailed spectrum of each pixel in the image. This is one of the main advantages of employing HSI over other imaging methods which capture only one or few wavelength bands^{13,14}. According to one classification criteria, HSI uses few hundreds of wavelength bands¹⁵. A HSI system can have mainly three configurations, namely the spatial-scanning, spectral-scanning and snapshot imager. Depending on the applications, the configuration can be selected based on its own benefits and limitations. Although there are different configurations, they are used to achieve the same type of data set, known as datacube. A datacube is a collection of intensity-related values stored in a spatial-spatial-spectral domain. Each value in the datacube represents the intensity of a wavelength band

belonging to a particular spatial point in a two dimensional (2-D) image. The spatial-scanning imager and in particular, the pushbroom imager is the configuration adopted in this work for configuring the system for the targeted application which is the subject focus of this paper.

A spatial-scanning imager usually uses dispersive element¹⁶ to separate the incoming light into constituent wavelength bands to be detected by the detector array. A point-scanning spectrometer records the spectrum of a spatial point in each scan to give one-dimensional spectral information. The scan is repeated across multiple points in a 2-D area before a datacube is formed. This is also known as a whiskbroom imager¹². A faster spatial-scanning imager is the line-scanning or pushbroom imager¹⁷. It is able to capture the spectrum of every point across a line of the sample in each scan. Each image captured by the detector has one spatial and one spectral dimension. After a scan is completed, a relative motion perpendicular to the detector's line of view of the sample is introduced. Another scan is taken and this process repeats until the entire region of interest (ROI) is imaged. The stacking of multiple 2-D spatial-spectral images forms the datacube. Compared to the whiskbroom imager, the data acquisition time is greatly reduced using a pushbroom imager, as lesser number of scans is required to form the same datacube. Analysis of the spectrum acquired can be performed using a variety of algorithms such as linear discriminant analysis¹⁸, principle component analysis¹⁹ and minimum volume based unmixing techniques⁴. Using a reference library, the spectral information can be used for classification and quantification.

This paper focuses on a pushbroom HSI system with a video camera that can enable the user to choose a ROI from the full view of the video camera. The reflectances of two ROIs of a genuine Singapore \$10 polymer note are used as target areas of measurement. A spectrum is then acquired from a specific spot in each ROI as the genuine spectrum. The colored-printed ROIs are used as the counterfeit notes in this study. The spectra are acquired from the same spots representing the counterfeit spectra, and compared to the genuine spectra to demonstrate the use of HSI to distinguish between genuine and counterfeit currency notes. There are benefits in measuring reflectance, instead of just taking the intensity count. Measuring reflectance allows changes to be done in the experimental setup without affecting the results.

2. EXPERIMENT

Figure 1: Experimental setup.

The proposed pushbroom HS imager's design and configuration is shown in Figure 1. Two light sources are used in this setup, VIS (broadband pigtailed source, Edmund Optics MI-150) and NIR (infrared lamp, Philips HP3616). Both sources are stabilized by warming up for at least 10 minutes before any measurement is taken. The imager consists of a 3-axis motorized stage to position the sample and to move it between each scan. Light from the sample then passes through the forelens, placed in a fine focus adapter. This adapter is attached to the bottom side of the quadrocular adapter housing a sliding mirror. The sliding mirror is initially pushed into the quadrocular adapter and directs light towards the video camera (Path 1 in Figure 1) during the selection of ROI. The video camera allows direct video imaging from which user can choose a particular region within the field on view of the video camera as the ROI. After selecting the ROI, the sliding mirror is pulled out of the quadrocular adapter for the light to travel straight towards the spectrograph and the detector camera (Path 2 in Figure 1). Line-scanning begins after the sliding mirror is pulled out. The spectrograph disperses the light entering the system and the detector camera records the spectral information.

A custom developed software based on LabView® is used for the interfacing of the video camera, detector camera and the 3-axis stage. After calibration and entering the user-defined parameters (ROI, integration time, etc.), scanning can begin.

This system offers a spatial resolution of $\sim 40 \mu\text{m}$, spectral resolution of $\sim 3 \text{ nm}$ and a spectral range of 400-1000 nm (visible light to near-infrared) with 756 spectral bands. The video camera has a full field of view of $\sim 4.32 \times 5.76 \text{ mm}^2$ with a working distance of $\sim 21.5 \text{ cm}$. A ROI of any size smaller than this full field of view can be selected. The data acquired from the ROI is referenced against the data collected from a 99% reflectance standard to acquire the hyperspectral reflectance of the ROI. The calculated reflectance then undergoes an 11-point moving average in the spectral direction for smoothing.

3. RESULTS AND DISCUSSION

3.1 Results from genuine currency note

Two ROIs (each of varying size) from a genuine Singapore \$10 polymer note are imaged using the HSI system, as shown in Figure 2 (Dot: top right corner of front design and Number: bottom of back design).

Figure 2: Location and ROI of a) Dot and b) Number.

For each ROI, a reflectance datacube is acquired. Each horizontal slice of the reflectance datacube can be extracted to show the reflectance of different parts of the ROIs at different wavelengths. A total of 756 reflectance mapping is available for each datacube. Figure 3 shows four of the selected reflectance mapping of Number, ranging from 400 to 1000 nm.

Figure 3: Reflectance mapping of Number using four selected wavelength bands.

A reflectance spectrum is acquired from each ROI by performing an average from 5×5 spatial points of the datacube, which corresponds to an area $\sim 54 \times 52 \mu\text{m}^2$ on the ROI. The spot from which the reflectance spectrum is acquired for each ROI is indicated by the center of the white squares in Figure 2. The spectra are presented in Figure 4, and it shows that HSI can differentiate one part of the note from another as the measured reflectance spectra are unique.

Figure 4: Reflectance spectra from genuine note.

3.2 Results from sample counterfeit currency note

The locations of the two ROIs shown in Figure 2 (left image of each sub-figure) are color-printed and are used to represent the counterfeit currency note. The ROIs from the counterfeit currency are shown in Figure 5, and the white square within each ROI represents the location from which the reflectance spectrum of the ROI is acquired. The region of interrogation for collecting the reflectance spectra from the counterfeit note is kept the same as the genuine note. The reflectance spectra from the counterfeit note are shown in Figure 6.

Figure 5: ROI of a) Dot and b) Number from a counterfeit note.

Figure 6: Reflectance spectra from counterfeit note.

3.3 Comparison of spectra between genuine and counterfeit currency notes

For each ROI, a comparison between each pair of spectra from the same ROI is made to demonstrate the use of HSI to differentiate a genuine and counterfeit note. Figure 7 shows the comparison and it can be seen that the spectra from the genuine note are easily distinguishable from that of a counterfeit note, even when the spectra are acquired from the same ROI.

Figure 7: Reflectance spectra from Dot and Number.

The amount of difference between each pair of spectra can be defined using root mean squared error (RMSE). Dot has a RMSE of 0.097, while Number has a RMSE of 0.053, only about half the RMSE of Dot. Therefore with reference to this particular counterfeit currency note, capturing and analyzing the spectrum of Dot is more suitable than Number to authenticate currency notes. However, the possibility of having other types of counterfeit notes means that spectra from other ROIs should also be captured and analyzed.

4. INSTRUMENTATION CHALLENGES

HSI can be used to capture a broad spectral range of a few hundred nanometers. This implies that the illumination source would need to be adequately powerful and broad to cover the entire spectral range. Also, the detector camera needs to have sufficiently high quantum efficiency (QE) within this spectral range. An illumination source, which is weak and coupled with a detector camera with a low QE in the same spectral range, result in a very low signal-to-noise ratio (SNR), giving poor image contrast and spectral results.

In this paper, two illumination sources, VIS and NIR, are used simultaneously when measuring reflectance. VIS and NIR provide light source from a quartz-halogen bulb and infrared lamp respectively. The intensity of the light source is measured using the same reflectance standard, both separately and combined. The results are shown in Figure 8.

Figure 8: Intensity counts of light sources.

A light source like VIS is commonly used in a laboratory-based HSI system as it is readily available and cheap. However, the intensity count from ~500-850 nm captured by the detector camera is much higher compared to those outside this range. This makes the image quality from the center wavelengths better. To further improve the SNR at both extremes of the entire spectral range, one can increase the intensity of VIS, or to bring the source closer to the sample. However, doing so will also increase the intensity count in the central portion of the spectral range and the detector camera may be saturated. Therefore, other sources that provide strong illumination only outside 500-850 nm are required. This will boost the intensity counts of extreme wavelengths without getting the detector camera saturated. NIR is then used simultaneously with VIS to boost the intensity count of the higher wavelengths, for a better SNR. The spectrum of the combined sources (VIS + NIR), as seen in Figure 8, shows that the ratio of the intensity counts of 400: 674: 1000 nm is about 1: 31: 5. This ratio can be used to explain why the image quality increases from near 400 nm, to near 900 nm and to the other wavelengths. This is evident in Figure 3, where the 400 nm gives a speckle-like image, with 1000 nm having a comparatively better image quality and the center wavelengths (for example 550 nm and 775 nm) giving images with better contrast. A light source that gives an adequately high intensity count across the entire spectral

range when captured by the detector camera of the HSI system, is difficult or expensive to find. Although this can be overcome using multiple suitable sources simultaneously, it can make the setup bulky and not user-friendly for specific applications.

5. CONCLUSION

The instrumentation challenges of a pushbroom HSI system were elaborated. The designed and developed HSI is illustrated by proving its efficiency in currency counterfeit applications. The developed HSI system has an integrated video camera allowing user to choose a particular area within the full field of view of the video camera as the ROI. Using a reflectance standard, a reflectance datacube is acquired from each of the two ROIs from a genuine Singapore \$10 polymer currency note. Each pair of spectra representing the designated ROI of the genuine and counterfeit notes is compared to each other. Based on the illustrated results, it is envisaged that this proposed HSI system can therefore be used for currency counterfeit applications.

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