Multispectral Stereoscopic Imaging Device: Simultaneous Multiview Imaging from the Visible to the Near-Infrared

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***Abstract*—We have designed a hand-held imaging device which is capable of capturing images of multiple spectral bands, spanning the visible to the near-infrared (NIR), as well as imaging multiple perspective views of an object simultaneously on one detector. This concept utilizes a set of mirrors positioned obliquely to the principle axis of the imaging device that present different perspective views, of a target, and simultaneously bandpass filters those views before the light enters the device. In its current state, our instrument is capable of simultaneously imaging nine independent spectral bands and three different perspective views. The device allows for measurement of multispectral properties of different material enabling multispectroscopic science as demonstrated by studying the separability of four types of black ink. Exploiting the stereoscopic imaging capability of the device, we are able to construct three-dimensional surface features of a target.**

I. Introduction

MULTI-SPECTRAL (MS) imaging is a method of capturing images of different and specific wavelength ranges on a camera. The human eye is capable of observing the visible wavelength ranges of the spectrum; a very small portion of the electromagnetic (EM) spectrum. If a broadband white light source, such as the Sun, is illuminating an object, that object would remit light of wavelengths other than the visible. Measuring the properties of the light remitted by an object can provide clues about the object's intrinsic properties. These properties can include the physical state or the molecular composition of the object observed, along with many other derived properties. The use of MS imaging has become common practice in many fields such as science, defense, security, food inspection, quality control, criminology, remote sensing, and medicine. The number of applications for such imaging systems is continuously growing.

There are several methods enabling MS imaging. The simplest method is to dissociate a color image, captured using a polychromatic camera, into its red, green, and blue (RGB) channels [1]. This method sub-divides the visible spectrum into three independent spectral bands. The spectral bands are highly dependent on the spectral response of the detector and will vary between different detectors. This method is not a very accurate radiometric representation of field of view (FOV) because polychromatic detectors use the Bayer filter [2] to acquire the three channel RGB information and interpolate the missing spectral information in a given detector pixel using its neighboring pixels which do not contain similar spectral information.

There exist two alternate, and perhaps more accurate, methods for multispectral imaging. The first method employs a series of bandpass filters combined with a monochromatic camera. These filters are designed to accurately transmit a wavelength range of interest while suppressing all other wavelengths. The filters can be placed in the path of the light entering the camera using a motorized filter wheel [3], or liquid-crystal tunable filters [4], or acousto-optical tunable filters [5]. The second method uses a series of light sources that can illuminate the target with light of a specific wavelength range. In this case the remitted light is acquired on a monochromatic camera [6], [7]. Both of these alternate methods require sequential imaging of the FOV which can be time consuming and non-preferential when imaging dynamic FOVs.

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The authors would like to thank Parthipan Siva for his guidance in processing the data and helpful discussions. This work was supported by AGFA Healthcare Inc., the Natural Sciences and Engineering Research Council of Canada, Canada Research Chair Program, and the Ontario Ministry of Economic Development and Innovation.

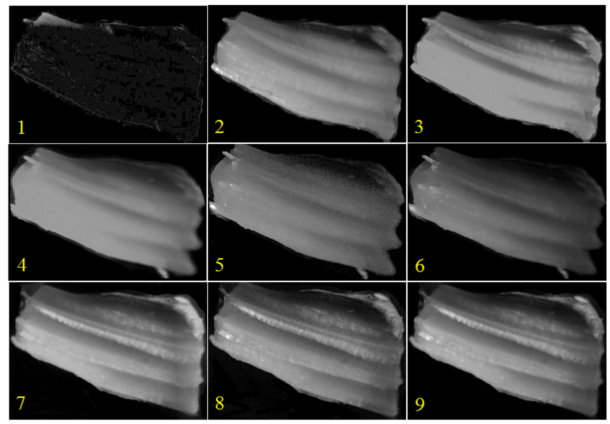
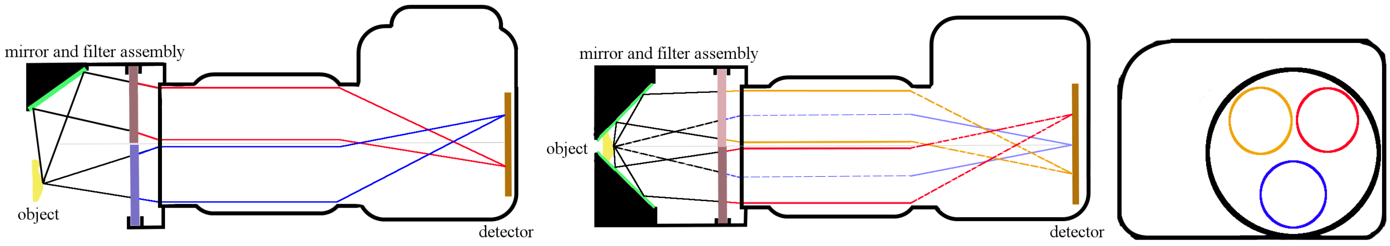


Fig. 1. A nine-band MS image of a piece of celery acquired using MSID. High reflectivity of NIR light, due to cellular structure of celery, is apparent in Channels 4 - 6. Channel 1 image has extremely low SNR due to a combination of deficit of blue photons and low quantum efficiency and low spectral response of the detector.

Simultaneous imaging is possible using various beamsplitter arrangements while imaging each spectral region on its own respective camera system [8]. Alternatively, a series of cameras, each with their own filters, can be used to image the FOV at different viewpoints [9], which requires post-processing to register the acquired images.

We aim to devise a handheld instrument for terrestrial applications that is (1) capable of simultaneous imaging of multiple spectral bands (visible to NIR) and (2) capable of acquiring stereoscopic images of a FOV, allowing for three-dimensional surface topology reconstruction on a single detector while circumventing custom camera design. The only handheld MS imager for terrestrial applications on the market is the ADC by TETRACAM Inc. [10]. This device is capable of imaging three spectral bands spanning the visible to the NIR spectral range. There are reports of other hand-held multispectral imaging devices [11], [12], but these systems only operate either in the visible or in the NIR spectral range and are not capable of stereoscopic imaging.

A recent publication by Manakov *et al.*, [13], shows promise in developing a handheld MS imager using an augmentation to digital single lens reflex (DSLR) cameras, although this goal is yet to be attained. Their instrument uses the working principles of a kaleidoscope to reproduce the image of the FOV of the camera many times and uses a bandpass filter array to filter each reproduced image before camera acquisition. Their device acquires multiple spectra for a single viewpoint which provides the benefit of not needing to register the array of images post-acquisition. This instrument is



(a) right view (b) top view (c) front view

Fig. 2. The optical design of MSID. The complex lens system of the camera and beam propagation through it is not shown to avoid cluttering. The dashed lines are representative of beams underneath others. (a) is the right side-view of MSID, the blue beam is the 400-700 nm light and the red beam is the 850-1100 nm light after traveling through their respective bandpass filters. (b) is the top view of MSID, the orange beam is the 700-850 nm light after traveling through its bandpass filter; and (c) is the front view of MSID without the mirror and filter assembly.

limited in performance since it only operates in the visible region of the EM spectrum, has low spatial resolution, is not capable of stereoscopic imaging, and optical aberrations are present in the images which degrade the quality. These shortcomings are direct result of the design choices in the system.

Our proposed instrument, uses $N-1$ mirrors in concert with the observed FOV of a camera to produce N points-of-view of a target object, each projected to a different location on the detector. These views are then independently and simultaneously bandpass filtered at different EM spectral ranges before they enter the camera. The N points-of-view are detected by detector pixels coated with one of three possible Bayer pattern filters. Due to the different spectral characteristics of N bandpass filters and the three Bayer pattern filters, the N multispectral images can be dissociated into $3N$ multispectral images with more discrete spectral range. The number of spectral bands imaged using bandpass filters is strictly dependent on the particular application and can be as many as desired. Having access to multiple view points of the same object will enable 3-D topological reconstruction of that object.

II. System Design

The multispectral stereoscopic imaging device (MSID) proposed, allows for imaging of multiple spectral bands as well as stereoscopic imaging of a target simultaneously on a single detector.

Stereoscopic imaging capability of MSID is achieved by using mirrors placed at oblique angles to the monocular FOV of the camera, creating a polyocular camera. These mirrors enable the virtual translation and rotation of the camera in space to image the FOV from a different vantage points. In this sense, the imaging device can be used as a stereoscopic imager, therefore, allowing for 3-D reconstruction of the surface of an object. This will be further discussed in the next section.

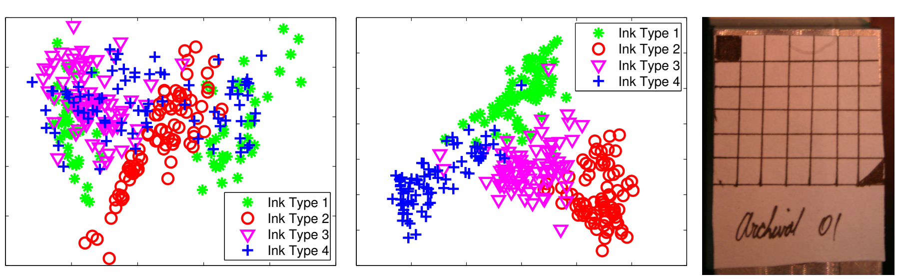
Given the Bayer pattern filters, each of the N views is further disassociated into three components, ergo creating $3N$ spectral bands in total, where N is the number of filtered views. For MS radiometric analysis of a target, the perspective views are registered based on extracted features. An example of MS radiometric application is discussed in the following section.

III. Preliminary Results and Discussion

To demonstrate the effectiveness of MSID, we implemented it on a modified PENTAX K100D Super DSLR camera using two mirrors and three bandpass filters. We illuminated the target with a broadband light spanning from the visible to short-wave-IR (400 - 2500 nm) wavelength range of the EM spectrum. The DSLR was modified by removing the IR cut-off filter from the detector and based on its quantum efficiency is able to detect light of wavelength range 400-1100 nm. The three perspective views captured by the camera were individually bandpass filtered into three smaller bands: 400 - 700 nm (channels 1, 2, and 3), 700 - 850 nm (channels 4, 5, and 6), 850 - 1100 nm (channels 7, 8, and 9). The device captures each perspective image, of an object, in one of the three previously mentioned spectral bands. Figure 2 shows a schematic of the MSID. More specifically, Figure 2c demonstrates what portion of the camera lens is used by each one of the three perspective views and thereby spectral bands. As shown in Figures 2a and 2b the mirror and filter assembly is directly attached to the front of the camera and is a permanent addition to it. The marginal optical beams passing through the system are shown in Figure 2 to demonstrate the light path through the device.

A MS image of a piece of celery was acquired using MSID, shown in Figure 1. Our instrument was able to simultaneously acquire all nine spectral channels. The three different perspective views were manually registered to simulate a common perspective. The registration was performed by manually selecting corresponding feature points across the perspective views and then fitting a model to align them to a common perspective. Note that the structure of celery beneath the superficial skin layer can be observed in channels 6 - 8 due to higher penetration of light at these wavelengths. A combination of low quantum efficiency of the detector, low spectral response of the detector, and lack of blue photons resulted in extremely low SNR in the channel 1 image.

We investigated the efficacy of our system in differentiating between four black pens, each using different type of ink. We acquired MS images of a grid pattern drawn using each of the pens, an example is shown in Figure 3c. Each pen in our sample uses a different solute and solvent combination and although they appear



(a) PCA coefficients, channels 1-3 (b) PCA coefficients, channels 4-9 (c) Grid pattern

Fig. 3. PCA was used to demonstrate (a) the poor separability of four ink types in visible channels 1 - 3 and (b) definite separability of the four ink types using the NIR channels 4 - 9. (c) Example of the grid pattern drawn using one type of black ink.

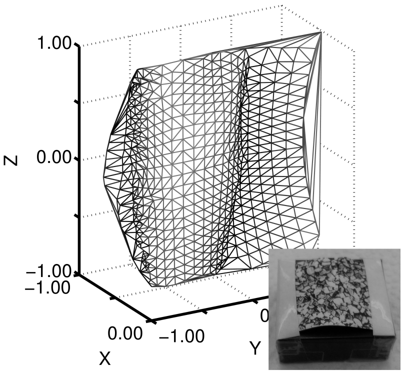


Fig. 4. Rendered 3D representation of a test object using texture extracted from different spectral band images, showcasing the stereoscopic imaging capability of MSID.

to be similar by visual inspection, they can be discriminated using a MS approach. Performing a principal component analysis (PCA) on the MS radiometric data, Figure 3a shows that using the visible channels the ink types are poorly separable. In fact, ink type 1 has a bimodality in this PCA space. By using the NIR channels, the four ink types are better separated as demonstrated in Figure 3b.

The mirror design of MSID provides simultaneous viewing of multiple perspectives of an object, in one image, mimicking a stereoscopic imaging system with multiple cameras [14]. Such a system allows for future applications with the ability to reconstruct the 3-D structure of objects and to generate additional geometrical information besides the views in different spectral bands. To extract geometric information of the object, our approach extracts SURF features [15] in all views and performs feature matching to find a geometrical relationship between the multiple views. This relationship is determined by estimating the fundamental matrix [16] based on RANSAC [17] filtering for outlier removal. It then uses the estimated fundamental matrix to rectify the images taken at different views [18] and performs disparity map computation using a sum of absolute difference approach block matching and refinement based on semi-global matching [19]. The resulting disparity map is used to compute the 3-D structure of the object. Figure 4 shows the polygonal mesh-based representation of a test surface that has been rendered using the texture extracted from different spectral bands.

IV. Summary

We have introduced a multispectral stereoscopic instrument for imaging multiple spectral bands and multiple perspective views on a single detector, simultaneously. Our results demonstrate that MSID is a competitive instrument in the field of multispectral imaging with qualities that surpass some of its counterparts. Multispectral data can be acquired simultaneously on one detector and does not suffer from the short-comings and aberrations associated with the existing aperture- or amplitude-splitting parallel imaging systems. The MSID, however, does sacrifice imaging spatial resolution since a single detector is being used to image different perspective views (images) of the same FOV. As a consequence of our design, MSID can be used as a stereoscopic imaging camera to produce 3-D topological/surface reconstructions. This capability presents a plight with the MSID's design which is that objects at one specific distance from the camera lens will be observed and perfectly in focus. In other words, the system, in its current configuration is only capable of imaging objects that are placed at the correct distance from the camera and that the perspectives imaged via the mirrors will be slightly defocused. In the current design extreme care was given in the mirror placement to minimize the defocusing exploiting the depth-of-field of the camera. Future iterations of MSID will investigate these issues in detail and aim to compensate and alleviate them.

The instrument proposed here was designed and built for applications in biomedical imaging, specifically to assist with detection and diagnosis of skin cancer, however, MSID has potential for use in various other fields.

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