Low-cost multi-spectral imaging camera array

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Abstract: Snap-shot multi-spectral imagers remain prohibitively expensive for many applications. A 5x5 array of miniature, low-cost camera modules record discrete spectral bands from which, with aid of calibration, a co-registered spectral data-cube may be reconstructed.

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1. Introduction

The rapid uptake of multi-/hyper-spectral imaging technologies has prompted investigations into techniques that capture spatial and spectral scene information in a single exposure [1, 2]. This so called snap-shot property allows for live video without the motion artefacts that can arise from time-sequential techniques. Existing systems that capture spatial and spectral information are available to specialist users at relatively high cost [1, 2] but as of yet, few low-cost solutions for larger markets have been realised to date. We aim to develop a system that uses an array of mobile camera modules to record images in distinct and arbitrary bands in the UV-to-NIR region of the electromagnetic spectrum. The spectral sampling will be performed by an array of narrow-band-pass filters where each filter is coupled to an individual camera module. As each module is capable of video-rate image capture, the end goal is to demonstrate a 25 spectral-band, high spatial resolution, wide field-of-view (FoV) video. This technique is made attractive by the very low cost of mass-produced camera modules and the absence of some technique for spectral scanning. There is however the challenge of spatially coregistering the multiple images recorded from slightly different viewpoints. This is common to the use of multi-aperture imaging at finite-conjugates [3]. We will discuss the steps taken so far in realising this concept and proving its feasibility.

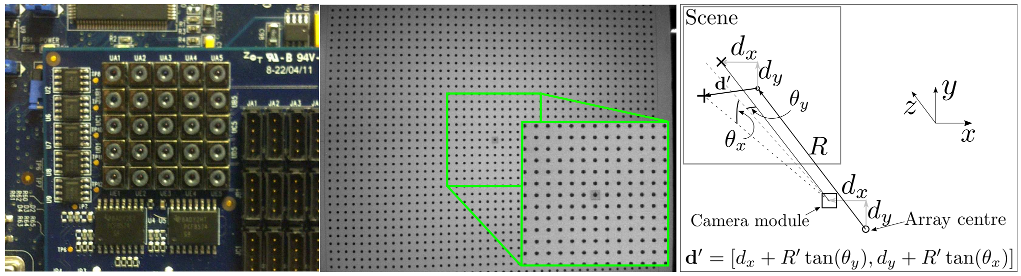
2. Camera array

The camera array (Fig.1a) is composed of 25 CMOS camera modules (STMicroelectronics) designed for use in mobile imaging applications. The physical construction of the modules enables the devices to be mounted in close proximity so that in this example, there is a pitch of ≈ 5.2mm between each aperture in both x and y dimensions. The camera modules consist of a 52° horizontal FoV focussing objective over a 2MP Bayer-sampled (RGB) sensor array. In this proof-of-concept system, the readout from the camera array is sequential, that is, each camera is activated individually and captures an image before the next camera is enabled. The intention of this platform is to act as a stepping stone to a real-time system so that image processing tools and feasible applications may be developed.

3. Image registration

Each camera in the array images using a distinct spectral band and does so from a unique spatial perspective with respect to the array centre and unique rotation with respect to normal of the array plane. As it cannot be guaranteed that features in the scene will persist throughout the spectral data cube it is necessary to infer rules from which accurate registration of the images may be achieved through a calibration step.

Imaging a regular grid of points with each camera yields sufficient information about the unwanted shift and rotation of each camera relative to the array –due to uncertainty in manufacture– so that subsequent images of a scene may be registered. Fig.1b shows an image of the chart from which the measurements are made. Distortion and rotation about z is corrected by finding a polynomial transformation that maps the imaged points to a regular grid. Using the geometry in Fig.1c, camera rotation about x and y may be inferred from the offset of the actual image centre ('$+$') to the ideal image centre ('$\times$'). By defining the desired distance of registration, the distance from the camera array to the plane in the scene which is to be registered, R', the relative offset of each image may be computed by the relationship:



(a) (b) (c)

Fig. 1. (a) The low-cost miniature camera array. (b) Image of the calibration chart. Close observation shows that there is a degree of visible distortion in the system. (c) Geometry for infering camera module rotation about *x* and *y*.

$\mathbf{d}'_k = \left[d_{kx} + R' \tan(\theta_{ky}), d_{ky} + R' \tan(\theta_{kx})\right]$ for $k = 1, 2, ..., N$ where N is the number of cameras in the system. Applying the respective offset to each of the images in the reconstruction stage gives the correct registration.

4. Experimental application

The first step in demonstrating the feasibility of an array of CMOS camera modules for multi-spectral imaging applications is to demonstrate acceptable sensitivity and the ability to accurately co-register images into a spectral data cube.

4.1. Imaging scenes with narrow bandwidths

As an initial assessment of this technique and as the filter array is not yet fabricated, the camera array is used to image scenes with spectrally filtered illumination, whereby each camera module in the array images the scene for a different illumination wavelength. Scene illumination employed a halogen light source filtered with a liquid-crystal-tunable-filter (LCTF) at twenty five bands between 490nm and 682nm with a separation of 8nm.

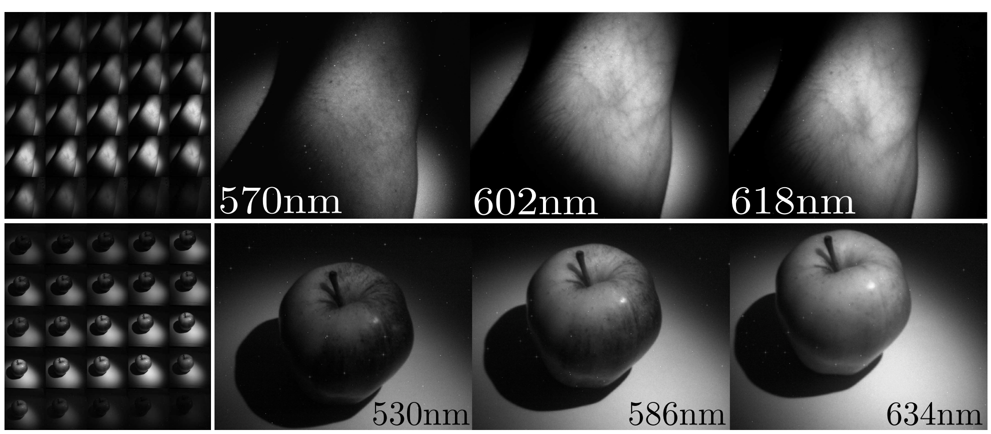
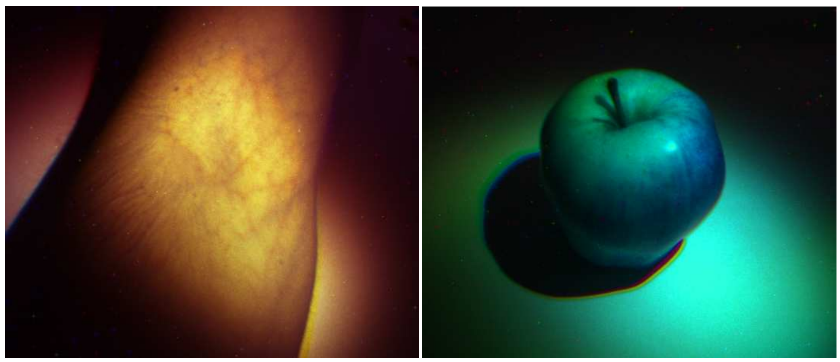


Fig. 2. Entire data set and selected bands: (Top row) of authors arm; (bottom row) of an apple.

The scenes shown here are chosen as demonstrations of the system in promising applications: hand-held multi-spectral imagers have been used in early detection of diseases in skin such as malignant melanomas [4]; multi-spectral imaging is used in quality control for agricultural produce [5].

The top row of Fig.2 shows images of the author's arm at bands centred on 570, 602 and 618nm. As wavelength is increased, the deeper into the tissue observations may be made and we see different structures at varying tissue depths in the presented images. The bottom row of Fig.2 shows how the wavelength dependent reflectance in fruit may be observed with this device. Studies on measuring the suitability for consumption of agricultural produce using multi-spectral imagers rely on the spectral resolution of the system to be sufficient so that imperfections in fruit tissue may be identified [5].

Fig.3 shows false colour representations of the data shown in Fig.2. Using the properties computed by the calibration step, it is shown that post capture registration is possible without knowledge of the scene in hand. As the images are captured $\approx$ 200mm from the array, parallax is a significant issue in the regions where the registration rules are not valid i.e. if the plane of reconstruction corresponds to the top surface of both subjects shown in Fig.3, the plane on which the shadows are cast will not be correctly registered, which is visible in the images. Improved registration can be achieved by deduction of three-dimensional shape. Although this is a challenge it also provides a new potential for understanding the effects of three-dimensional spectral illumination (the proximity effect) and consequently introduces potential for improved spectral imaging of three-dimensional scenes. At infinite conjugates registration will be essentially perfect throughout the reconstructed image field.



(a) (b)

Fig. 3. False colour images of the data shown in Fig.2 using registration parameters inferred from the calibration step.

5. Discussion

Using an array of camera modules that are intended for mobile applications (Fig.1a) and a filtered source of scene illumination; a proof of concept for a low-cost, multi-spectral, high spatial-resolution snapshot imaging system is demonstrated. In this experiment we are constrained by the spectral properties of the camera modules to image in the visible spectrum, despite this the results are promising. The aim now is to remove the visible band pass filter within the objective optics and couple each camera in the array to one of twenty-five narrow-band-pass filters arranged in a complementary array. This will allow measurements to be made between 650nm and 910nm, a region of the electromagnetic spectrum to which CMOS is sensitive and which yields significant information on biological systems. Furthermore, development of our image processing to infer scene depth could enable normalisation of spectral radiance, hence nullify the proximity effect and improve spectral imaging of three-dimensional scenes in the near field.

References

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