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A liquid crystal tunable filter based shortwave infrared spectral imaging system: Calibration and characterization

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ABSTRACT

Calibration is a critical step for developing spectral imaging systems. This paper presents a systematic calibration and characterization approach for a liquid crystal tunable filter (LCTF) based shortwave infrared (SWIR) spectral imaging system. A series of tests were conducted to validate the linearity of the system output, measure the field of view of the spectral imager, increase the system spectral sensitivity, test the spatial and spectral resolution of the system, evaluate the system stability and image distortion, and reduce the spectral noise of the system output. Results showed that the system had an angle of view of 6.98° and a spatial resolution of 158 μm. The spectral sensitivity of the system was corrected by controlling the camera exposure time and gain, which increased the signal to noise ratio of the system by 16.5%. Test results also verified the system spectral accuracy and linearity ($r > 0.999$). The system output was proven to be stable and image distortion was not perceivable. Results of calibration tests indicated that this system satisfied the design criteria in both spatial and spectral domains. The calibration methods presented here are applicable to the LCTF-based spectral imaging systems in other applications.

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1. Introduction

Spectral imaging, including hyperspectral imaging (HSI) and multispectral imaging (MSI), has been increasingly used in nondestructive inspections for food quality and safety in the past decade (Sun, 2010). Spectral imaging integrates major advantages of conventional imaging and spectroscopy methods by simultaneously acquiring the spatial and spectral information of the test object (Lu and Chen, 1998). Currently, two types of spectral imaging systems are primarily used for food quality and safety inspections: the line-scan or pushbroom spectral imaging system, and the electronically tunable filter (ETF) based spectral imaging system (Gowen et al., 2007; Wang and Paliwal, 2007). The line-scan system uses a prism-grating-prism unit to disperse the light into different wavelengths and projects the dispersed spectrum on a CCD detector. The line-scan imager scans one line at a time of the test object and then assembles all scanned lines to a spectral image (Lu and Chen, 1998). The ETF-based spectral imaging system utilizes electronically tunable filter(s) to select narrow bandpass wavelengths and takes images of the test object at each selected wavelength (Gat, 2000). The ETF-based spectral imaging system has no moving part and is applicable to stationary or field applications.

An LCTF-based spectral imaging system is a complex integration of many electrical, optical, and mechanical components. To achieve the best performance, many aspects of an LCTF-based spectral imaging system should be tested and calibrated, including spectral accuracy, sensitivity, resolution, linearity, spatial resolution, field of view, uniformity, and image distortion (Wang and Paliwal, 2007; Lu and Chen, 1998). Ideally, every major hardware component should be calibrated before system integration. However, calibrating every hardware component of a spectral imaging system requires comprehensive tests with particular calibration tools, which is a formidable task beyond the capability and scope of most laboratories. Thus, a practical and effective method for calibrating the LCTF-based spectral imaging system needs to be developed to accomplish all calibration goals.

Morris et al. (1994) evaluated the performance of the LCTF and acousto-optic tunable filters (AOTF) as they were used in a fluorescence microscopy imaging system. The filters were characterized by using monochrome lasers and the USAF 1951 resolution target to test the light transmittance and the spatial resolution, respectively. Their study evaluated several most critical but limited characteristics (peak transmittance, bandpass, and spatial resolution) of the LCTF. Evans et al. (1998) demonstrated a calibration approach for leveling an LCTF-based spectral imaging system's sensitivity using linear and logarithmic methods. But calibrations for other aspects of the system such as spectral/spatial accuracy and resolution were not considered in

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the paper. Gebhart et al. (2007) presented a procedure to quantitatively characterize their LCTF-based fluorescence and diffuse reflectance spectral imaging system in the spectral region of 400-720 nm for biomedical applications. However, there was no calibration process presented in the paper. Other reported LCTF-based spectral imaging applications in food quality and safety inspections, similarly, often conducted limited system calibrations, such as using percent reflectance to correct the uniformity of the lighting, or utilizing spectral calibration lamps to calibrate the system's spectral accuracy.

Some calibration techniques reported for calibrating the line-scan spectral imaging system are also applicable to the LCTF-based spectral imaging system. The most common calibration approach is to convert raw spectral reflectance images to percent reflectance images by using "dark" images and "white reference" images (Lawrence et al., 2003; Lu and Chen, 1998). Methods of testing the system's spectral accuracy, spectral/spatial resolution, and the CCD responsivity for the line-scan spectral imaging system can be found in the literature (Mehl et al., 2004; Lawrence et al., 2003; Kim et al., 2001; Lu and Chen, 1998). Spectral smoothing techniques were also reported to reduce the noise in hyperspectral images (Schmidt and Skidmore, 2004; Shafri and Yusof, 2009). All above methods can be applied to the calibration of an LCTF-based spectral imaging system. Furthermore, Polder and Van der Heijden (2001) discussed the method for quantifying the sensitivity and the signal to noise ratio (SNR) of a spectrograph. Lawrence et al. (2003) demonstrated a general procedure of calibrating a pushbroom spectral imaging system. However, compared to the line-scan spectral imaging system, the LCTF-based spectral imaging system has its unique requirements on system calibration. For instance, LCTF-based spectral imaging systems can adjust the camera exposure time during scanning, which makes the LCTF-based system more flexible to correct the system's sensitivity than line-scan systems. Moreover, the angular field of view of the LCTF-based spectral imaging system also enables users to test the system field of view (FOV) and image distortion using methods different than line-scan spectral imaging systems. Therefore, calibration and characterization procedures reported by the line-scan spectral imaging applications are also not sufficient for the LCTF-based spectral imaging system.

This research aimed to demonstrate a systematic and practical approach to fully calibrate and characterize an LCTF-based shortwave infrared (SWIR) spectral imaging system for food and agricultural products inspection. Specifically, the objectives of this research were to test and calibrate: the spectral accuracy, resolution, sensitivity, linearity, stability, spatial resolution, FOV, and image distortion of the LCTF-based spectral imaging system.

2. Materials and methods

2.1. The LCTF-based spectral imaging system

Our LCTF-based shortwave infrared spectral imaging system mainly consists of an LCTF-based SWIR spectral imager, an illumination system, a frame grabber, a computer, and data acquisition software. The SWIR spectral imager includes an LCTF (Model Varispec LNIR 20-HC-20, Cambridge Research & Instrumentation, Cambridge, MA, USA), an InGaAs camera (Model SU320KTS-1.7RT, Goodrich, Sensors Unlimited, Inc., Princeton, NJ, USA), and a lens (Model SOLO 50, Goodrich, Sensors Unlimited, Inc., Princeton, NJ, USA). The InGaAs camera has a 320×256 pixels focal plane array (FPA) with 25 μm pitches. The spectral response region of the camera is from 900 nm to 1700 nm. The lens is a high performance SWIR lens (50 mm focal length, f/1.4), which was designed for imaging in the spectral region from 700 nm to 1700 nm. The LCTF placed in front of the lens has 20 nm (on average) bandwidths and can be tuned between 850 nm and 1800 nm. A $600 \times 600 \times 2000$ mm ($L \times W \times H$) chamber was built as a darkroom for the system. A curtain and a top cover were made by black commando cloth to completely block the outside ambient light. A heavy-duty camera bracket is mounted on a 2 m long stainless steel tube and the spectral imager is attached to the bracket. Four quartz halogen lamps (Model S4121, Superior Lighting, Fort Lauderdale, FL, USA) are mounted on the horizontal aluminum beams to provide a shortwave infrared lighting source. A software program was written in LabVIEW graphical programming language (National Instruments, Austin, TX, USA) to control the system. The software also provides several advanced functions to enhance the quality of the acquired spectral image, such as spectral sensitivity correction, denoising, and selection of region of interest (ROI). The detailed description of the system can be found in our preceding paper (Wang et al., 2012).

2.2. The system design criteria and calibration scheme

The LCTF-based spectral imaging system was designed for the safety and quality inspection of onions at an indoor environment. The major design criterion for the system was to capture SWIR spectral images of a typical onion bulb completely and accurately in a distance of 0.5–1.5 m. Other key design criteria included an accurate and linear spectral response, high image resolution, and high signal to noise ratio. To simplify the calibration task, the LCTF-based spectral imager was treated as a single unit in calibration tests, without considering the camera, the lens, and the LCTF separately. With these premises, the LCTF-based spectral imaging system was fully calibrated in both spectral and spatial domains. In all calibration tests, spectral images were collected after the system was turned on for 30 min so that the spectral output of the halogen lamps was stable.

2.2.1. Relative reflectance

An LCTF-based spectral imaging system often has significant responsivity variations, which are caused by the nonuniformity of the illumination and the FPA of the camera, known as 'pattern noise' (Chang, 2007). In this research, this kind of error was corrected in the image pre-processing stage by using the relative reflectance (flat-fielding) correction, which converted raw spectral images to percentage spectral images using 'white-reference' and 'dark' images (Kim et al., 2001; Lu and Chen, 1998). A 99% Spectralon diffuse reflectance target (Model SRT-99-050, Labsphere, Inc., North Sutton, NH, USA) was used to collect the white reflectance images, which recorded the spectral and pixel variations of the system's responsivity. The camera internal noises caused by the dark current were stored in dark images, which were acquired by completely covering the optical entrance of the spectral imager. In most following calibration tests, acquired raw reflectance spectral images of the test object were converted to relative reflectance spectral images using the equation (Lu and Chen, 1998):

$$I = 100 \times \frac{T - D}{W - D}, \tag{1}$$

where T is the spectral image of the test object, W is the white reference image acquired from the 99% Spectralon diffuse reflectance target, D is the dark current image, and I is the converted relative spectral image. Before each calibration test, W and D were collected using the same spectral and spatial dimensions as the collected spectral images of the test objects (T).

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