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Summary

This paper presents an optimal emission filter of the fluorescence imaging system to detect skin tumors on poultry carcasses. The secure production of disease-free meat is crucial in the mass production environment. The fluorescence spectra have been gaining the practical use in many areas because the fluorescence response is very sensitive in detecting trace elements. The spectral features of the specimen are embedded across broad spectral bands and have been analyzed in various methods. We apply the linear discriminant analysis to determine the emission filter of fluorescence imaging system. It provides the optimal attenuation of emission wavelengths in terms of discriminant power. The attenuation values prioritize wavelengths to select significant spectral bands. With the optimal filter, skin tumor parts of chicken carcasses are enhanced saliently in resultant fluorescence images.

Key words: emission filter, hyperspectral imaging model, image enhancement, linear discriminant analysis, poultry skin tumors, spectrofluorimetry.


Resumen
La producción de carne libre de enfermedades es crucial en producción pecuaria intensiva. Los espectros de fluorescencia se han estado usando en forma práctica en muchas áreas, ya que la respuesta de fluorescencia es muy sensible para detectar elementos traza. Este artículo presenta un óptimo filtro de emisión para el sistema de imágenes de fluorescencia utilizado para detectar tumores cutáneos en canales de pollo. Las características espectrales de la muestra --insertas en bandas espectrales amplias-- se han analizado por varias metodologías. En este artículo aplicamos el análisis lineal discriminante para determinar el filtro de emisión del sistema de imágenes por fluorescencia, mediante el cual se obtiene la atenuación óptima de las ondas de emisión en términos de poder discriminante. Los valores de atenuación priorizan las longitudes de onda para seleccionar las bandas espectrales más significativas. Gracias a la utilización de este filtro optimizado, los tumores cutáneos existentes en la canal de pollo son magnificados, de modo que se alcanzan a diferenciar perfectamente en las imágenes de fluorescencia resultantes.

Palabras clave: análisis discriminante lineal, espectrofluorimetría, filtro de emisión, mejoramiento de imagen, modelo de imagen hiperespectral, tumor cutáneo en aves.

Resumo
A produção de carne livre de doenças é crucial em produção pecuária intensiva. Os espectros de fluorescência tem-se estado utilizando em forma prática em muitas áreas, já que a resposta da fluorescência é muito sensível para detectar elementos traza. Este artigo apresenta um óptimo filtro de emissão para o sistema de imagens de fluorescência utilizado para detectar tumores cutâneos em carcaças de frangos. As características espectrais da amostra, insertas em bandas espectrais amplas são utilizadas por várias metodologias. Neste artigo aplicamos a análises linear discriminante para determinar o filtro de emissão do sistema de imagens por fluorescência, mediante o qual obtém-se a atenuação óptima das ondas de emissão em termos de poder discriminante. Os valores de atenuação dão prioridade às longitudes de onda para selecionar as bandas espectrais mais significativas. Graças à utilização do filtro optimizado, os tumores cutâneos existentes na carcaça de frango são magnificados, de fato que são diferenciados perfeitamente nas imagens de fluorescência resultantes.

Palavras chave: análises discriminante lineal, espectrofluorimetria, filtro de emissão, melhoramento de imagem, modelo de imagem hiperespectral, tumor cutâneo.

Introduction
Automatic inspection systems of live and slaughtered poultry have been requested for food safety as poultry production and consumption increased (Bilgili, 2001; United States Department of Agriculture, 2006). Market forces are encouraging the use of more sophisticated technology for food safety along with an expanded array of food safety practices (Park et al., 2003; Gowen et al., 2007). The use of computer vision, hyperspectral imaging, and optical systems for poultry inspection are prevailing to discriminate wholesome from unwholesome chicken carcasses (Park et al., 2002; Lawrence et al., 2003). In particular, the hyperspectral imaging technique provides powerful process analytical tools for non-destructive food analysis even though this technique is originated from remote sensing (Gowen et al., 2007; Kim et al., 2004). A laboratory−based hyperspectral imaging system which employs a pushbroom method was developed (Kim et al., 2001). Recently, a hyperspectral imaging model and an applied linear discriminant analysis were developed to determine system parameters of hyperspectral inspection system for poultry feces on chicken carcasses (Kim et al., 2008).

Hyperspectral fluorescence imaging offers an instant, noninvasive inspection method for detecting skin tumors (Chao and Chen, 2002; Zhang et al., 1999). Poultry skin tumors are ulcerous lesions that are surrounded by a rim of thickened skin and dermis. Tumorous carcasses often demonstrate swollen or enlarged tissue caused by the
uncontrolled growth of new tissue. Tumor is not as visually obvious since its spatial signature appears as shape distortion rather than discoloration.

The objective of this study is to propose a mathematical model of hyperspectral fluorescence imaging system, design its optimal emission filter, and synthesize the hyperspectral images into a single-spectral image for poultry skin tumors.

**Material and methods**

*Chickens carcasses*

Hyperspectral images of chicken carcasses collected in Du and Kong (2007) were used to design an emission filter and summarized here shortly. Twelve chicken carcasses were collected from a poultry processing plant (Allen Family Foods, Inc., Cordova, MD) in March and May 2002. A Food Safety and Inspection Service veterinarian at the plant identifies the condition of the poultry carcasses.

**Hyperspectral fluorescence images**

A laboratory-based line-by-line hyperspectral imaging system capable of reflectance and fluorescence imaging for uses in food safety and quality research was developed by Instrumentation and Sensing Laboratory (ISL) at Beltsville Agricultural Research Center (Beltsville, MD) (Zhang et al., 1999; Kong et al., 2004). The system employs a pushbroom method in which a line of spatial information with a full spectral range per spatial pixel was captured sequentially to cover a volume of spatial and spectral data. The ISL hyperspectral imaging system was equipped with a charge coupled device (CCD) camera, a spectrograph, a sample transport mechanism, and two lighting sources for reflectance and fluorescence sensing (Figure 1)(Du and Kong, 2007).

![Figure 1. Multispectral imaging system.](image)

Two fluorescent lamp assemblies were installed to provide a near uniform UV-A (365 nm) excitation to the sample area for fluorescence measurements. A short-pass filter placed in front of the lamp housing were installed to prevent transmittance of radiations greater than approximately 400 nm, and thus eliminate the potential spectral contamination by pseudo-fluorescence. The system acquires the data via line-by-line scans while transporting sample materials via a precision positioning table.
A hyperspectral image of chicken carcasses consists of 460*400 pixels with 65 spectral bands. The spectral band had discrete wavelengths from 425.4 nm to 710.7 nm. The representative emission plot of poultry skin and tumor are shown in Figure 2.

![Fluorescent spectra of poultry skin and tumor. (a) Chicken carcass: skin tumor (red circle) and normal skin (blue box); (b) Fluorescent spectra: skin tumor (red solid lines) and normal skin (blue dotted lines).](image)

**Figure 2.** Fluorescent spectra of poultry skin and tumor. (a) Chicken carcass: skin tumor (red circle) and normal skin (blue box); (b) Fluorescent spectra: skin tumor (red solid lines) and normal skin (blue dotted lines).

**Multispectral Analysis**

Hyperspectral imaging techniques have been utilized in many scientific disciplines, from microscopic studies to airborne remote-sensing applications. Hyperspectral data are three-dimensional data containing two-dimensional information measured at a sequence of individual wavelengths across a sufficiently broad spectral range. The optimal emission filter is designed for poultry skin tumors through linear discriminant analysis (LDA). A mathematical model for a hyperspectral imaging system is proposed and its emission filter is optimally determined by LDA. A fast numerical scheme is presented for numerical implementation. Spectrofluorimetric data of organic materials and feces of chicken carcasses were analyzed by LDA.

The multi-spectral imaging system for spectrofluorimetry of poultry skin tumors consists of a light source, emission filter, and camera as shown in Figure 3 (Reichman, 2000). The light source is assumed to be fixed and the camera has the uniform sensitivity for all wavelengths. Spectral signature reveals the characteristics of the different types of tissues. Figure 2 shows the relative fluorescence intensity of hyperspectral image data at each spectral band for normal tissues and tumors (Kim et al., 2004). Suppose that a specimen shows its own hyperspectral response $r(v)$ with random noise $n(v)$. Its spectrofluorimetric response is:

$$s(v) = r(v) + n(v)$$

The noise characteristic of hyperspectral response was investigated. The noise $n(v)$ is assumed to be a Gaussian random noise:

$$n(v) \sim N(0, \sigma^2(v))$$
where $\sigma^2(v)$ is variance at $v$. The intensity $g$ through a filter $f(v)$ is:

$$g = \int f(v)s(v)dv$$

$$= g_s + g_n,$$

where $g_s = \int f(v)r(v)dv$ and $g_n = \int f(v)n(v)dv$ be a signal and a noise of intensity, respectively. The sample mean and variance of intensity are obtained by:

$$\bar{g} = E[g] = g_s$$

$$= \int f(v)r(v)dv$$

$$\sigma^2 = Var[g] = Var[g_s]$$

$$= \int_0^\infty f^2(v)\sigma^2(v)dv$$

For multiple specimens the sample mean and variance of the intensity of the $i$th specimen are

$$\bar{g}_i = E[g | \omega_i]$$

$$= \int f(v)r_i(v)dv,$$

$$\sigma^2_i = Var[g | \omega_i]$$

$$= \int_0^\infty f^2(v)\sigma^2_i(v)dv,$$

where $\omega_i$ denotes the $i$th specimen, $r_i$ and $\sigma^2_i$ are mean and variance of spectrofluorimetric response of $\omega_i$. The total mean of intensity is:

$$\bar{g} = \sum_{i=1}^c p_i \bar{g}_i,$$

where $p_i$ is prior probability of the $i$th specimen. The within and between variances are obtained by (Duda and Stork, 2001):

$$S_w(f) = \sum_{i=1}^c p_i \sigma^2_i$$

$$= \int f^2(v)\left\{\sum_{i=1}^c p_i \sigma^2_i(v)\right\}dv$$

$$S_b(f) = \sum_{i=1}^c p_i (\bar{g}_i - \bar{g})^2$$

$$= \sum_{i=1}^c p_i \left[\int_0^\infty f(v)\{(\bar{r}_i(v) - \bar{r}(v))dv\right]$$

The emission filter should be chosen to maximize the discriminant power of specimens. The discriminability in LDA is defined by

$$J(f, s) = \frac{S_B(f, s)}{S_W(f, s)},$$

The discriminability varies with form of $f$ but not scalar product. Their function space is restricted to positive unit functions:

$$f^* = \arg \max_{f \in B(\cdot)} J(f),$$

where $B(\cdot)$ is a collection of all positive unit functions. The optimal emission filters is obtained numerically.

**Results**

MATLAB software was used to calculate discriminability from spectral data of seven specimens and to obtain the optimal emission filter. Continuous $f$ were discretized by the same resolution, initialized with constant functions, and obtained by solving a generalized eigenvalue problem. The relative attenuation of optimal emission filter is shown in Figure 4. The proposed method provides continuous forms, while previous research presented selective bandwidths. A band-pass filter with 425-475 nm bandwidth was most appropriate.

![Figure 4. Optimal emission filter for poultry skin and tumor.](image-url)
The optimal emission filter of a multispectral imaging system for poultry skin tumor is consistent with what experts provided in previous research. With this emission filter, the fluorescent image was synthesized from all bands of hyperspectral fluorescent images (Figure 5). The filtered image has much better contrast than all hyperspectral images and enhances the part of skin tumors.

Discussion

The resultant spectra can be used, in principle, to characterize and identify any given material, but the hyperspectral imaging system will be downsized by reducing the spectra. The design of optical filters is crucial to build a hyperspectral imaging system. Many researchers focus on selecting significant bands for their purposes (Cho and Kim, 2007). Principal component analysis technique was employed to find an effective representation of spectral signature in a reduced dimensional
feature space and a support vector machine to
make a decision whether each pixel falls in normal
or tumor categories (Fletcher and Kong, 2003).
A method for detecting skin tumors on chicken
carcasses using hyperspectral fluorescence imaging
data was proposed (Kim et al., 2004). A spectral
band selection method for feature dimensionality
reduction in hyperspectral image analyses was
presented for detecting skin tumors on poultry
carcasses (Du and Kong, 2007). However, the
proposed method estimates the weight of each band
according to its discriminability and provides a
systematic way to design the emission filter.

The optimal emission filter was designed
for poultry skin tumor using linear discriminant
analysis. A mathematical model for hyperspectral
imaging system was proposed and its system
parameter, i.e., emission filter was optimally
determined by linear discriminant analysis. The
optimal emission filter was obtained by solving a
generalized eigenvalue problem from its positive
nature. The optimal emission filter was validated
to enhance the original hyperspectral images in
an effective way. Physical implementation is also
important because of limitation in the emission filter.

The proposed method can be use to select
significant wavelengths and provides a continuous
priority of selected bands. The relative attenuation
of the wavelength can be interpreted as its relative
significance so that the selection priority is
determined by sorting the relative attenuation.
Larger number of selected bands always contains
the small number of bands while selected bands
changes depending on their number in Du and
Kong (2007).

Lighting sources are also important design
parameters to improve the discriminability of
the fluorescence imaging system. Experts and
experienced researchers often determine light
sources by intuition. For example, in many cases
fluorescent lamps of UV-A (365 nm) are used to
provide excitation to the sample for fluorescence
measurements. The discriminability of the
classes can be derived by the excitation filter and
maximized in a similar way that developed in 2.3.

The study suggests that a systematic method
to determine the optical filters of fluorescence
hyperspectral imaging systems to maximize the
discriminability of poultry skin and tumor. The
resultant image through the optical filter has the
larger contrast than any other single band images.
The proposed method is applicable for other
agricultural products which are distinguishable by
their spectral properties.

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