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Research Paper

Image analysis operations applied to hyperspectral images for non-invasive sensing of food quality – A comprehensive review

Gamal M. ElMasry [a,b,*], Shigeki Nakauchi [a]

[a] Department of Computer Science and Engineering, Toyohashi University of Technology, 1-1 Hibarigaoka Tenpaku, Toyohashi 441-8580, Japan

[b] Suez Canal University, Faculty of Agriculture, Agricultural Engineering Department, Ismailia, Egypt

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Image analysis involving mathematical, statistical and software programming approaches are the essential elements of any computer-integrated hyperspectral imaging systems. The theoretical and practical issues associated with the development, analysis, and application of essential image processing algorithms are explored in order to exploit hyperspectral imaging for application to food quality evaluations. The breadth of different image processing approaches adopted over the years in attempting to implement hyperspectral imaging for food quality monitoring was surveyed. Firstly, the fundamental configurations and working principles of hyperspectral systems, as well as the basic concept and structure of hyperspectral data, were described and explained. The understanding of different approaches used during image acquisition, data collection and visualisation were examined. Strategies and essential image processing routines necessary for making the appropriate decision during detection, classification, identification, quantification and/or prediction processes are presented. Examples and figures were selected to reinforce the main approach of each analysis algorithm applied in different agro-food products to answer the question “What does the user want to see in the target food samples?” The theoretical background for each algorithm was beyond the scope of this article thus only essential equations were addressed. The literature presented clearly revealed that hyperspectral imaging systems have gained a rapid interest from researchers to display the chemical structure and related physical properties of numerous types of food stuffs and hyperspectral imaging systems are expected to gain more considerably more potential and application in food processing and engineering plants.

* *Corresponding author*. Department of Computer Science and Engineering, Toyohashi University of Technology, 1-1 Hibarigaoka Tenpaku, Toyohashi 441-8580, Japan. Tel.: +81 532 81 5122.

E-mail address: g.elmasry@vpac.cs.tut.ac.jp (G. M. ElMasry).

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Nomenclature

Abbreviation

ACM	Active contour model
ANN	Artificial neural network
DA	Discriminant analysis
DT	Distance transform
EDM	Euclidean distance measure
EMCCD	Electron-multiplying charged coupled device
FCM	Fuzzy C-means
FDR	Fisher discriminant ratio
FT	Fourier transform
GLCM	Grey level co-occurrence matrix
GML	Gaussian maximum likelihood
IR	Infrared
LDA	Linear discriminant analysis
LS-SVM	Least-squares support vector machine
MLC	Maximum likelihood classification
MLR	Multi-linear regression
MSC	Multiplicative scatter correction
NG	Neural Gas
NIR	Near-infrared
OSC	Orthogonal signal correction
PC	Principle component
PCA	Principle component analysis
PLS	Partial least square
PLS-DA	Partial least square discriminant analysis
QDA	Quadratic discriminant analysis
RGB	Red, green and blue
ROI	Region of interest
S/N-ratio	Signal-to-noise ratio
SAM	Spectral angle mapper
SCM	Spectral correlation measure
SNV	Standard normal variate
SVM	Support vector machine
UV	Ultraviolet
VIS	Visible range
WT	Wavelet transform
WTA	Wavelet texture analysis
X-matrix	Spectral data
Y-matrix	Real reference values of quality traits
i	Class number
ω_i	Spectral data matrix of each pixel belonging to class i
$p(\omega_i)$	Probability of class having ω_i
$\lvert\Sigma_i\rvert$	Determinant of the covariance matrix in class ω_i
Σ_i^{-1}	Inverse of the covariance matrix of class ω_i
m_i	Mean vector of the spectral data for all pixels belonging to class i.
$R(x)$	Calibrated image
β	Threshold chosen for tuning the detection rate
r_m	Matching position between sample and reference spectra
λ_t	Sample spectrum
λ_r	Reference spectrum

Symbol

$I(x, y)$	Two-dimensional sub-image
$I(x, y, \lambda)$	A hyperspectral image '*hypercube*'
λ	Spectral dimension, wavelength
$I(\lambda)$	Spectrum at one point in the image
P_{ij}	Pixel value at position (i,j)
D_{ij}	Pixel value in the dark reference image
W_{ij}	Pixel value in the white reference image
P_λ	Spectral value at wavelength (λ)
n	Number of wavelengths, number of objects
$\rho(\lambda)$	Reflectance of the sample at wavelength λ
α_D	Factor that relates the percentage of direct and diffuse light arriving at the sample
$\cos(\varphi)$	Factor modulates the amount of direct light reflected at each point
$E(C, c_1, c_2)$	Energy function
$E(V, W)$	Energy function
d	Euclidean distance
$h_\gamma(r,V,W_c)$	Degree of neighbourhood cooperation
$k_r(V,W_c)$	Number of prototypes
γ	Neighbourhood range
$J(U,V)$	Weighted within group sum of squared error objective function
x_k	kth p-dimensional data vector
v_i	Prototype of the centre of cluster i
u_{ik}	Degree of membership of x_k in cluster i
m	Fuzzy weighting exponent
$d(x_k, v_i)$	Distance measure between object x_k and cluster centre v_i
c	Number of clusters
θ	Direction angle (0°, 45°, 90°, or 135°)
μ_x	Mean of rows in the GLCM
μ_y	Mean of columns in the GLCM
σ_x	Standard deviation of rows in GLCM
σ_y	Standard deviation of columns in GLCM
$\underline{m}$	Number of rows in the image
$\underline{n}$	Number of columns in the image
ΔE	Total colour change
L^*	Lightness
a^*	Redness
b^*	Yellowness
$S(\lambda_n)$	Reflectance image at the centre wavelength λ_n
$S''(\lambda_n, g)$	The second difference image at the wavelength λ_n with a gap (g)

1. Introduction

Interests in food quality are driven from the essential need to supply consumers with consistent products at an affordable price. The ideal way to enhance food supplies and consider food safety issues is to regularly monitor food products during all stages of handling chain to detect the onset of potential issues and to take timely action once a problem has been identified. Effective monitoring systems and an intelligent