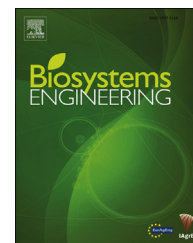


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Research Paper

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

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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.

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Nomenclature		β	Threshold chosen for tuning the detection rate
Abbreviation		r_m	Matching position between sample and reference spectra
ACM	Active contour model	λ_t	Sample spectrum
ANN	Artificial neural network	λ_r	Reference spectrum
DA	Discriminant analysis	Symbol	
DT	Distance transform	$I(x, y)$	Two-dimensional sub-image
EDM	Euclidean distance measure	$I(x, y, \lambda)$	A hyperspectral image ‘hypercube’
EMCCD	Electron-multiplying charged coupled device	λ	Spectral dimension, wavelength
FCM	Fuzzy C-means	$I(\lambda)$	Spectrum at one point in the image
FDR	Fisher discriminant ratio	P_{ij}	Pixel value at position (i,j)
FT	Fourier transform	D_{ij}	Pixel value in the dark reference image
GLCM	Grey level co-occurrence matrix	W_{ij}	Pixel value in the white reference image
GML	Gaussian maximum likelihood	P_λ	Spectral value at wavelength (λ)
IR	Infrared	n	Number of wavelengths, number of objects
LDA	Linear discriminant analysis	$\rho(\lambda)$	Reflectance of the sample at wavelength λ
LS-SVM	Least-squares support vector machine	α_D	Factor that relates the percentage of direct and diffuse light arriving at the sample
MLC	Maximum likelihood classification	$\cos(\varphi)$	Factor modulates the amount of direct light reflected at each point
MLR	Multi-linear regression	$E(C, c_1, c_2)$	Energy function
MSC	Multiplicative scatter correction	$E(V, W)$	Energy function
NG	Neural Gas	d	Euclidean distance
NIR	Near-infrared	$h_\gamma(r, V, W_c)$	Degree of neighbourhood cooperation
OSC	Orthogonal signal correction	$k_r(V, W_c)$	Number of prototypes
PC	Principle component	γ	Neighbourhood range
PCA	Principle component analysis	$J(U, V)$	Weighted within group sum of squared error objective function
PLS	Partial least square	x_k	kth p-dimensional data vector
PLS-DA	Partial least square discriminant analysis	v_i	Prototype of the centre of cluster i
QDA	Quadratic discriminant analysis	u_{ik}	Degree of membership of x_k in cluster i
RGB	Red, green and blue	m	Fuzzy weighting exponent
ROI	Region of interest	$d(x_k, v_i)$	Distance measure between object x_k and cluster centre v_i
S/N-ratio	Signal-to-noise ratio	c	Number of clusters
SAM	Spectral angle mapper	θ	Direction angle (0°, 45°, 90°, or 135°)
SCM	Spectral correlation measure	μ_x	Mean of rows in the GLCM
SNV	Standard normal variate	μ_y	Mean of columns in the GLCM
SVM	Support vector machine	σ_x	Standard deviation of rows in GLCM
UV	Ultraviolet	σ_y	Standard deviation of columns in GLCM
VIS	Visible range	$\underline{m}$	Number of rows in the image
WT	Wavelet transform	$\underline{n}$	Number of columns in the image
WTA	Wavelet texture analysis	ΔE	Total colour change
X-matrix	Spectral data	L^*	Lightness
Y-matrix	Real reference values of quality traits	a^*	Redness
i	Class number	b^*	Yellowness
ω_i	Spectral data matrix of each pixel belonging to class i	$S(\lambda_n)$	Reflectance image at the centre wavelength λ_n
$p(\omega_i)$	Probability of class having ω_i	$S''(\lambda_n, g)$	The second difference image at the wavelength λ_n with a gap (g)
$ \Sigma_i $	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		

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

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