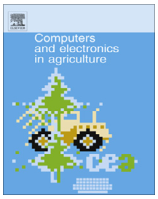
Computers and Electronics in Agriculture 99 (2013) 41–53

Contents lists available at ScienceDirect

Computers and Electronics in Agriculture

journal homepage: www.elsevier.com/locate/compag



Visualizing quantitatively the freshness of intact fresh pork using acousto-optical tunable filter-based visible/near-infrared spectral imagery ☆

Xiwei Wang [a], Maocheng Zhao [a,*], Ronghua Ju [b], Qinghua Song [a], Dongqing Hua [a], Cheng Wang [a], Tingting Chen [a]

[a] Mechanical and Electronic Engineering School, Nanjing Forestry University, Nanjing 210037, China
[b] Nanjing Institute of Food Packaging Machinery, Nanjing 210029, China

ARTICLE INFO

Article history:
Received 23 March 2013
Received in revised form 27 August 2013
Accepted 30 August 2013

Keywords:
Pork
Electrically tunable filter (ETF) based spectral imagery
Acousto-optical tunable filter (AOTF)
Nondestructive testing
Total volatile basic nitrogen (TVB-N) content
Visible/near-infrared hyperspectral imaging

ABSTRACT

Although pork freshness is one of the top concerns to consumers, no systems are currently available to the pork industry that could quantitatively predict its spatial distribution in a rapid and nondestructive way. The main objective of this study was to investigate the feasibility of acousto-optical tunable filter (AOTF) based spectral imagery in the visible/near-infrared region for the non-destructive prediction and visualization of the spoilage-indicating chemicals over the surface of intact fresh pork. We developed an AOTF-based spectral imaging system (wavelength range: 550–1000 nm) to visualize pork freshness by mapping the predicted total volatile basic nitrogen (TVB-N) content over the surface. Reflectance hyperspectral images of pork loins in packages ($n = 43$) were acquired from day 3 to day 13 post-mortem, and the corresponding TVB-N references were recorded using conventional chemical procedures. The eligible muscle region of interest (EMROI) on a sample surface was auto-segmented, from which the signature spectrum was extracted. After standard normal variate (SNV) filtering, the signature spectra together with their chemical references were fed into a partial least squares regression (PLSR) to create a prediction model on a consecutive spectral range (575–940 nm). An analysis of the regression coefficients identified 9 important predictive wavelengths (575, 600, 615, 705, 765, 825, 885, 915, and 935 nm). The prediction model was subsequently refined to use the feature wavelengths only. A leave-one-out (LOO) cross-validation showed that the prediction of the TVB-N contents using the refined model was good and had a root mean square error ($\mathrm{RMSE_{CV}}$) of 1.94 mg/100 g and a coefficient of determination (R^2_{cv}) of 0.89. Finally, the freshness distribution over an entire pork surface was visualized by mapping the pixel-wise TVB-N predictions in pseudo-colors based on the refined model. The spatial prediction was also verified in terms of mean and range. The mean values coincided well with their chemical references (with a R^2 of 0.81 and a RMSE of 2.58 mg/100 g), and the range is within reasonable limits (with 95% pixels within 0-50.0 mg/100 g). The results indicated that the AOTF-based spectral imagery system could be a promising method to predict pork freshness in an *in situ* test with unprecedented details of the spatial distribution of freshness.

Industrial relevance: An AOTF-based VIS/NIR spectral imagery system has the potential for acceptance sampling in meat production plants or for hygienic supervision in the marketplace to predict the freshness of intact chill-stored pork.

1. Introduction

Conventional inspection methods that are still heavily depended on in current meat industry are mainly based on human sensory tests or instrumental physic-chemical tests. The former is operator-dependent and the latter is often destructive and time consuming. Rapid and nondestructive testing methods have been explored for decades to predict the quality and safety of meat. But conventional instrumental tests and many of the newly evolved prediction methods are still based either on a sample as a whole, e.g., an electronic nose (Huang et al., 2011; Papadopoulou

---

Abbreviations: AOTF, acousto-optic tunable filter; LCTF, liquid crystal tunable filter; LOO, leave one out; ETF, electronically tunable filter; TVB-N, total volatile basic nitrogen; VIS, visible; NIR, near infrared; RF, radio frequency; PE, polyethylene; PLS, partial least squares; PLSR, partial least squares regression; $\mathrm{RMSE_C}$, root mean square error of calibration; $\mathrm{RMSE_{CV}}$, root mean square error of cross validation; RMSE, root mean square error (used in this paper for to refer generally to both $\mathrm{RMSE_C}$ and $\mathrm{RMSE_{CV}}$); EMROI, eligible muscle region of interest; R^2, coefficient of determination; Mb, myoglobin; DeoMb, deoxymyoglobin; OxyMb, oxymyoglobin; MetMb, metmyoglobin; NDT, non-destructive testing; PSE, pale, soft, and exudative; DFD, dark, firm, and dry; CIE, International Commission on Illumination.

☆ This work is in partial fulfillment of a Ph.D. study.

* Corresponding author. Tel.: +86 25 85428005.
E-mail address: mczhao@njfu.edu.cn (M. Zhao).

0168-1699/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.compag.2013.08.025

et al., 2013; Umuhumuza and Sun, 2011), or on a manually selected local region for a "point" test (thus susceptible to the subjectivity of operator), e.g., an electronic tongue (Gil et al., 2011; Kaneki et al., 2004; Umuhumuza and Sun, 2011) and a spectroscopy (Argyri et al., 2013; Cai et al., 2009; Chen et al., 1996; Hu et al., 2008; Liu et al., 2003; Xu et al., 2009). However, pork as a food from a natural source is highly heterogeneous (except when minced), and there are cases in which the spatial distribution of quality parameters is needed (ElMasry and Sun, 2010) This need could be better addressed by hyperspectral imaging, a technique originally intended for remote sensing that offers the spatial distribution of spectral information (Goetz et al., 1985). However, it was not until the past decade that this technology was introduced to the meat industry due to its increasing accessibility and decreasing cost. From the early detection applications of foreign materials (Heitschmidt et al., 1999; Park et al., 2002; Windham et al., 2002) and the discrimination of similar structures of the same material (Chao et al., 2002, 2000; Hogan, 2004; Kim et al., 2004; Nakariyakul and Casasent, 2004; Sivertsen et al., 2009) to later applications for the prediction of minor chemical variations of the same material (Li et al., 2011; Naganathan et al., 2008; Qiao et al., 2007a, 2007b; Sone et al., 2012; Tao et al., 2012; Wang et al., 2010a,b; Wu et al., 2012; Xia et al., 2007; Zhang et al., 2012), hyperspectral imaging is finally capable of visually predicting the spatial distribution of quality attributes in terms of minor variations of the chemical composition in the same material (ElMasry et al., 2011, 2012; Kamruzzaman et al., 2011, 2012). The visualization genre of applications examines the available spectral and spatial information to a great extent, and its mapping characteristic makes it truly unique compared with other newly evolved predictive methods.

The spoilage of pork inevitably occurs immediately after slaughter with decreasing nutritional value and increasing risk from pathogenic microorganisms. The transition is accompanied by sensory, physical-chemical, and biological changes. Color plays a great role in sensory evaluation and indicates the storage environment and time. Major pigments in fresh meat are the redox forms of Mb while interacting with oxygen or sulfur, which leaves clues in the VIS region from their spectral fingerprints (Mancini and Hunt, 2005). From the chemical point of view, large molecular proteins in muscle break down to a spectrum of smaller molecules of total volatile basic-nitrogen (TVB-N) compounds containing mainly ammonia, trimethylamine (TMA) and dimethylamine (DMA) under the influence of enzymes and microorganisms during storage (Umuhumuza and Sun, 2011). The TVB-N content was adopted as an important freshness indicating index of pork and fish in previous research (Cai et al., 2011, 2009; Hou et al., 2006) and regulation (Hygiene and Committee, 2005). The C–H overtones and C–H combination bands of these small compounds fall in the NIR region (ElMasry et al., 2012).

The objective of this study was to develop and test an AOTF-based spectral imagery system working in the VIS/NIR region to map the predicted TVB-N content over the surface of intact fresh pork for acceptance sampling at meat production plants and/or for hygienic supervision in the marketplace.

2. Materials and methods

2.1. The AOTF-based spectral imagery system

2.1.1. Components and architecture of the system

We developed an AOTF-based spectral imaging system, which consists of an acousto-optic tunable filter (AOTF Camera Video Adapter CVA-200, BRIMROSE, USA) with an extra-low dispersion lens (AF 28–80 mm F/3.5–5.6, Tamron, Japan) at the front and a monochrome camera (TM-1327GE, JAI PULNiX, Canada) at the back, an illumination unit composed of three tungsten-halogen lamps of 500 W each (PENGYANG, China), a data acquisition system developed by the authors, an uninterruptible power supply (UPS) (C3K, SANTAKUPS, China), and a computer (Yangtian A4600t, Lenovo, China) with a gigabit Ethernet network adapter (Intel Pro1000, Intel, USA). The spectral imager includes an AOTF with an anti-chromatic lens in the front and a VIS-NIR camera attached in the back. A RF controller modulates the band pass wavelength and the amplitude of the AOTF (Fig. 1). The bandwidth of each waveband is approximately 20 nm (Brimrose, 2008).

The spectral imaging system collected spectral images at full resolution of 1392 × 1040 in the range of 550–1000 nm with an increment of 5 nm, producing a spectral cube with a total of 91 bands for each scan. The sample and the spectral imaging system were relatively stationary during data acquisition while the AOTF swept through the target spectral range.

The AOTF-based spectral imaging system was designed in 5 relatively independent logical tiers (Fig. 2.) based on the modular architecture in Wang et al. (2012b) while considering the scalability, the reusability, and the reduction of the complexity. The hardware was composed of a computer with interfaces (tier 2) and a basic tier (tier 1) including a spectral imager and an illuminator unit. The RF controller of the spectral imager interfaced with a computer via an on-board RS-232 serial port while the VIS-NIR camera interfaced with the computer via a gigabit Ethernet network adapter. The software had the following 3 tiers: (1) an infrastructure tier including component drives, Halcon™ toolkits (MVTec™, Germany) for multi-channel image related operations, and Microsoft™ Windows Foundation Class (MFC); (2) a control tier incorporating workflow control and supportive functional modules; and (3) a presentation tier to render a graphical user interface.

2.1.2. Calibration

A temporal test over 3 days showed that the spectral read-out of a reflectance standard (SRT-99-100, Labsphere, USA) stabilized within the first 8 min after the system startup, and thus the system

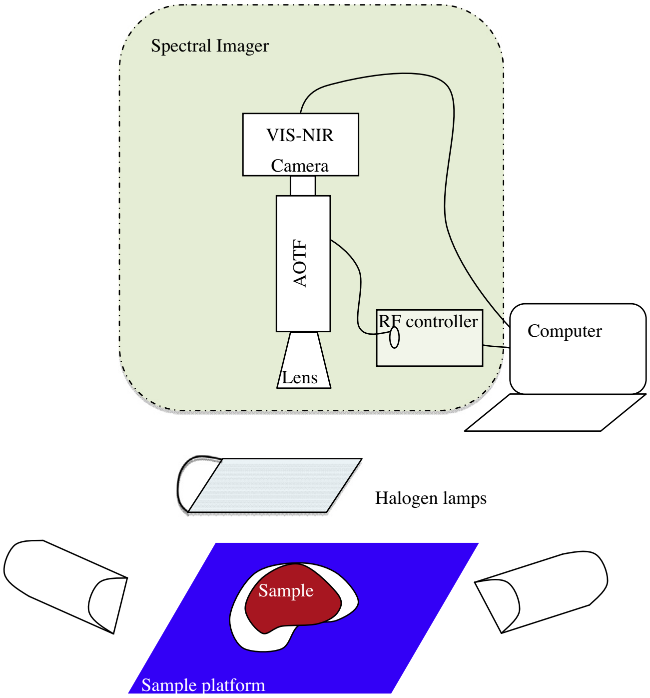


Fig. 1. The AOTF-based spectral imaging system.