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Multispectral laser imaging for advanced food analysis

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HIGHLIGHTS

- Infrared laser radiation in trough-transmission configuration for defects detection.
- Four different laser wavelength used simultaneously to build multispectral images.
- The system is able to detect degradation of food products, such as moulds (fungus).
- A renewed Lock-In recovery signal technique is successfully used.
- Interesting procedures of multispectral image formation are proposed.

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ABSTRACT

A hardware–software apparatus for food inspection capable of realizing multispectral NIR laser imaging at four different wavelengths is herein discussed. The system was designed to operate in a through-transmission configuration to detect the presence of unwanted foreign bodies inside samples, whether packed or unpacked. A modified Lock-In technique was employed to counterbalance the significant signal intensity attenuation due to transmission across the sample and to extract the multispectral information more efficiently. The NIR laser wavelengths used to acquire the multispectral images can be varied to deal with different materials and to focus on specific aspects. In the present work the wavelengths were selected after a preliminary analysis to enhance the image contrast between foreign bodies and food in the sample, thus identifying the location and nature of the defects. Experimental results obtained from several specimens, with and without packaging, are presented and the multispectral image processing as well as the achievable spatial resolution of the system are discussed.

1. Introduction

Non-Destructive Evaluation (*NDE*) is an applied field of engineering science that comprises many different techniques and approaches. Over the past few decades there have been tremendous advances in *NDE* technology, allowing researchers and engineers to tackle problems in many scientific and industrial fields. In the food industry, various *NDE* techniques have been applied [6,18,23], including those based on the use of Infra-red (*IR*) radiation, which give excellent results [11,15,27,24]. There are several *NDE* techniques that rely on the use of the *IR* radiation, ranging from thermography to multi-spectral analysis, to the so called vibrational spectroscopy. In particular, by allowing the characterization of the vibrational molecular states within the *IR* spectrum, some of these techniques permit the classification of the different components and materials [1,3,26,17]. For instance the fundamental vibration modes of the molecules fall within the Middle Infra-red range (*MIR* 2500–25000 nm), while the overtones of the fundamental MIR resonances (NIR 2500–750 nm) belong to the Near Infra-red (NIR) range. The sample being tested can be characterized in terms of its optical absorption spectra, as all the organic molecules vibrate and absorb photons at specific wavelengths. Since it is possible to estimate and measure many parameters of fundamental importance in nutritional characterization, soil analysis, etc. [25,7,9,3], NIR Spectroscopy has revolutionized the food characterization process.

Several techniques have been continuously developed displaying ever greater ability in detecting pollutants, foreign bodies, or harmful chemicals in food products by exploiting the properties of NIR radiation. Of these techniques NIR thermography and hyper-spectral imaging have improved greatly in the past few years.

These techniques have been proven suitable for food analysis, as shown in many studies concerning bruises, grain quality, foreign body detection, water content and meat properties [12], and have

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also become more easily accessible. Until few decades ago, the very heavy, non-portable, and expensive sensors limited their application mainly to lab research [4] (the first portable thermal cameras were introduced into the market in the late 1970s).

As soon as, in recent years, these limiting factors were removed, hyper-spectral imaging techniques have become of great interest in food & feed inspection: finding application in quality assessment, sorting, detection of foreign material and the identification of food additives. The main difference between a hyper-spectral image and other NIR imaging techniques is that the former provides spectral information for each pixel. An NIR hyper-spectral imaging camera can be easily fitted in an online inspection of food in a processing plant, and can be implemented for a wide variety of analyses [5,22,29,2]. However, there are still some limitations. The long computational time and the enormous computational power required to process the hyper-spectral data hinder the widespread diffusion of such techniques, but the main issue is represented by the low penetrating power of the radiation that in most cases limits the analysis to surface and sub-surface characteristics [21]. For this reason, techniques enabling fast, contact-less, non-invasive, and high-resolution NIR imaging of volume in through transmission configuration are still uncommon [6,18,24,23] and the Multi-spectral NIR Laser Imaging system presented here tries to fill this gap.

The basic idea underlying the device is the following: a number N_λ of NIR lasers ($N_\lambda = 4$ in the present case) are combined in a single fiber optic cable and then conveyed onto the sample to take transmission measurements on a regular grid of points (Fig. 1). The resulting attenuated transmitted beam is then collected onto a photodiode and, from the measurements of the amplitude of its components, a multi-spectral image of the sample is produced (Figs. 1 and 2). With respect to the standard hyper-spectral methods, the spectral analysis is here reduced to a few *IR* wavelengths but operates in through-transmission to ensure the inspection of the entire volume of the sample. Furthermore this measurement method is suitable for on-line implementation and can detect very small foreign bodies, on the order of millimeters in unpacked, and even in packed food exploiting imaging procedures and image processing.

Since the absorption spectra of various materials are well known, or can easily be obtained through preliminary spectroscopic analysis to calibrate the system to the desired focus (quality analysis, defect identification, etc.), the N_λ wavelengths can be carefully chosen to optimize the sensitivity of the procedure with respect to the desired target: e.g. the detection of moulds (fungus) or of pieces of plastic, glass, metal, wood, etc.

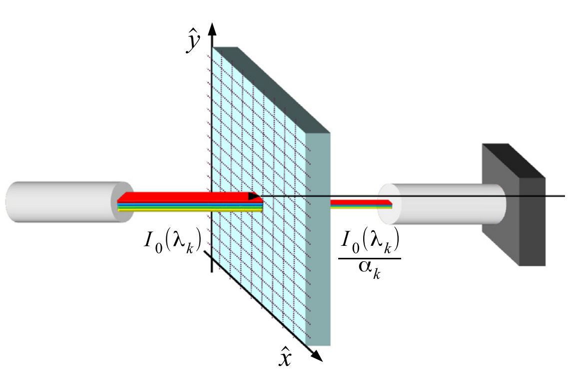

Fig. 1. Base scheme of the measurement setup. Four different wavelength laser signals ($\lambda_1 - \lambda_4$) are generated and modulated at four different Lock-In frequencies ($\chi_1 - \chi_4$) then convoyed in a unique fiberglass cable to the collimator and to the sample. Noisy NIR signals are detected on the other side of the sample by a second collimator and brought to the photodiode in a single fiberglass cable, and finally through the NI schedule to the PC where they are demodulated in order to extract the four desired signals.

From an experimental point of view, two major problems present themselves: (1) how to cope with the very low intensity of the transmitted beam; (2) how to extract the information regarding the N_λ wavelengths from a single measurement. The following Sections describe how these two problems have been solved by developing a Multi-Frequency Lock-In (*MF-LI*) detection scheme.

The paper is organized as follows: Section 2 and its Subsections, illustrates the hardware set-up of the multi-spectral imaging apparatus, the basic principle of the image formation procedure and the *MF-LI* technique, including a preliminary analysis of the spatial resolution of the device. In Section 3 the results of the measurements on a number of samples are reported: three kind of cheese, fruits (cherries, prunes, olives), Italian Mortadella, Italian Lasagne Pasta, with different foreign bodies – plastic, glass, iron, stone, wood – and packagings (mostly plastic) so as to determine the system's detection capabilities, and discussions are presented. In Section 4 some general conclusions and prospects for further improvements are drawn.

2. Multi-spectral imaging apparatus (materials and methods)

In this Section the image formation procedure is detailed by first explaining the theory underlying it, subsequently by describing the hardware utilized and finally by introducing the image processing algorithms applied to the reconstructed images. More precisely, Section 2.1 illustrates the basic principle of the apparatus by introducing the Lock-In -*LI*- procedure and by explaining how this is modified to deal with multi-spectral analysis; Section 2.2 gives a comprehensive description of the hardware set-up and of the spatial resolution attained; Section 2.3 elaborates on the image processing algorithms developed to improve the quality of the images in terms of contrast, spatial resolution and foreign body detection.

2.1. Multi-frequency Lock-In and image formation

The basic principle of the image formation procedure is illustrated in Fig. 1: a multi-spectral beam, obtained by superimposing N_λ lasers having wavelengths $\{\lambda_k,\ k \in [1, N_\lambda]\}$ exits from an optic fiber cable and impinges on the sample under test. The intensity of the beam exiting the sample is strongly reduced, with an attenuation $\alpha(\lambda)$ that varies depending on both the wavelength and the incidence point in the material. By moving the sample with the help of a *XY* translation stage, a set of attenuation measurements on a regular grid of $x - y$ points is collected and then, for each kth wavelength, a $N_x \times N_y$ pixels image is constructed that visualizes the attenuation $\alpha(x_i, y_j, \lambda_k)$, with $i \in [1, N_x],\ j \in [1, N_y]$. If the pixel dimension is smaller than the laser spot, the whole sample surface can be inspected and covered almost uniformly. At the end of the procedure, to each sample a multi-spectral image $IM_\alpha(x_i, y_j, \lambda_k)$ is associated, derived from the attenuation measurements. Depending on the particular application, various choices are available to visualize the images [14,16,23]. In this paper, the sample images show the reciprocal of the attenuation in dB scale: $IM_\alpha(x_i, y_j, \lambda_k) \propto -log_{10}[\alpha(x_i, y_j, \lambda_k)]$.

As mentioned above, two main problems arise in measuring the $\alpha(x_i, y_j, \lambda_k)$ values: (I) how to cope with an attenuation that for some materials and thickness could be very high leading to a very low value in Signal to Noise Ratio (*SNR*); (II) how to extract information related to the N_λ different wavelengths λ_k and in general for an arbitrary number of wavelengths.

A well-known way to measure the intensity of signals embedded in noise is represented by the Lock-In (*LI*) technique, which dates back the 30s and 40s [8,19]. The technique was used for decades in various laser applications and has recently been applied in