Photonics Enhanced Sensors for Food Monitoring: Part 2

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Food quality and food safety are gaining more and more importance in recent decades. In particular, applications have included domains such as the identification of foreign bodies in solid food streams, the quality screening of vegetables and fruits, the recognition of food products inducing a health risk and the monitoring of the quality and authentication of liquids. Solid food sensing methods are often insufficient in the sense that they are error-sensitive and time-consuming due to the manual or chemical, sample-based screening of the products. For most liquids a decent monitoring method is missing. In view of this, the authors of these papers started exploring the potential of photonics to answer the question if food screening methods could be photonics-based. This paper gives an overview of our research of the past eighteen years.

In the first part [1], we described the theoretical aspects of the various physical phenomena that can occur during food screening, together with their related measurement set-ups, data-processing steps and the concerned sensing platforms. This paper demonstrates the usefulness of optical screening methods to identify foreign bodies in solid food streams and defines concrete applications together with the corresponding optical measures.

Application 1: Use of Selective Absorption

Foreign body identification requires the use of absorption, fluorescence, or elastic scattering as the sensing principle, depending on the application. In the first application, we present an example of selective absorption used to identify foreign objects with different colors in food products.

All kinds of foreign material can enter the food stream both during harvest and during post-processing steps. These unwanted pieces can be classified into two groups:

- pieces with a natural origin, e.g., insects, parts of small animals such as mice and frogs, remains from the plant tissue (roots, stems, leaves, clots of earth, ropes, stones, small parts of wood or metals); and
- a group of man-made foreign materials consisting of all kinds of colored and non-colored pieces of plastic, cardboard, paper, and alloys.

Pigments define the color of a specific vegetable or fruit product. Since specific absorption bands characterize each pigment, the target is to tune the illumination wavelengths to those spectral regions where the difference in absorption between the wanted and unwanted species is the largest.

Since green vegetables are an important market from a commercial point of view, we consider the application of a case study where the goal is to identify differently colored foreign bodies in a stream of green vegetables by using commercially available illumination wavelengths.

Materials and Methods

The studied group of green vegetables consisted of broccoli (both the flower and stem parts), garden beans, green beans, lettuce (both light and dark colored leaves), spinach, peas, and sprouts. Foreign bodies cover the full color spectrum; blue PVC plastic, blue-grey stone, green glass, brown cardboard, brown glass, brown stone, and dark brown wood. We measured the reflectance spectra in the visible part of the electromagnetic spectrum with the set-up shown in [1, Fig. 2a]. For each vegetable type, between 10 and 30 spectra are recorded. For the foreign materials, only five spectra are taken for each sample type because of more limited availability.

Starting from the measured reflectance spectra, the absorption spectra are calculated following the Lambert-Beer law. Analysis of the second derivative spectra gives us knowledge about the most distinct absorption bands.

Next, we need to define the optical sensing parameter(s), which allow us to separate green vegetables and foreign objects. In view of the practical implementation, the concept consists of defining an object's color density using only three

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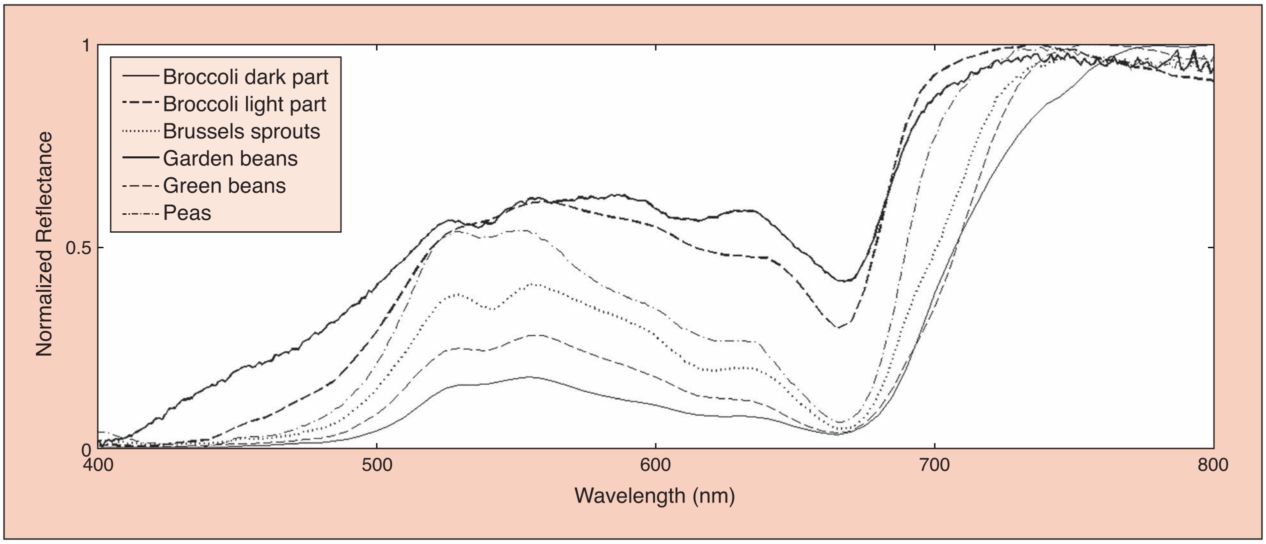

Fig. 1. The presence of chlorophyll molecules in green vegetables is confirmed by the increased absorption between 425-440 nm and 665-675 nm.

laser lines spread over the visible wavelength region, which are one wavelength selected in the blue, the green, and the red part of the spectrum. We worked with the 488 nm and 514 nm argon laser lines and a 660 nm wavelength emitted by an InGaAlP semiconductor laser. The color density is obtained by replacing the color matching functions used for the traditional CIE1931 color calculation by three δ-functions centered around the three selected wavelengths and with a width equal to the 1/e beam diameter of the concerned laser. This leads to the three reflectance values *R*, *G* and *B*. Normalization is conducted by measuring the reflectance spectrum of a white and a black reflectance tile with nominal reflectance values of respectively 2% and 99% (SRT-02 and SRT-99 - Labsphere) and by calculation of the six corresponding reflectance values R_{white}, G_{white}, B_{white}, R_{black}, G_{black}, and B_{black}. From this, the three optical measures that represent the sample's color can be easily obtained by applying the following formulas:

$$r_t = \frac{R - R_{black}}{R_{white} - R_{black}}; \qquad g_t = \frac{G - G_{black}}{G_{white} - G_{black}}; \qquad b_t = \frac{B - B_{black}}{B_{white} - B_{black}} \quad (1)$$

$$r = \frac{r_t}{r_t + g_t + b_t}; \qquad g = \frac{g_t}{r_t + g_t + b_t}; \qquad b = \frac{b_t}{r_t + g_t + b_t} \quad (2)$$

Analysis of the *r*, *g*, *b* values for the different green vegetables and foreign objects allows the identification of the optical parameter resulting in the largest contrast. Once the illumination wavelengths are selected, final tests are conducted on a scanning-based detection platform.

Measurement Results

For all green vegetables, the dominating pigment is chlorophyll. Two types of chlorophyll are present: chlorophyll-a and chlorophyll-b, with theoretical absorption peak values located at 430 nm and 662 nm (type a) and 453 nm and 642 nm (type b) [2]. Their presence is confirmed by the increased absorption between 425-440 nm and 665-675 nm (Fig. 1). For both spectral regions the spectral position of the absorption peak depends on the vegetable type. The absorption peaks shift towards longer wavelengths for darker green vegetables. Typically, the darker the vegetable, the higher its chlorophyll concentration. The observed wavelength shift is explained by a difference in molecular structure. The higher the chlorophyll content, the higher the chance of polymerization of the chlorophyll a molecules due to appearing molecular aggregations between chlorophyll-chlorophyll or chlorophyll-albumen molecules. As such, the higher the chlorophyll concentration, the larger the variety in molecular structure. Since each chemical arrangement is characterized by a specific location of the absorption maxima, the cumulative spectrum will have a less profound and broader absorption peak. The relationship between a vegetable's CIE1931 color values and the spectral position of the absorption bands in the 665-675 nm region is illustrated in Fig. 2 for the dark and light parts of broccoli.

Fig. 3 compares the normalized (averaged) reflectance spectra of a green vegetable (green beans) together with a bluish (blue PVC plastic) and a brownish (brown stone) foreign object. We also plot the spectral positions of the three selected laser lines (488 nm, 514 nm and 660 nm). The largest contrast between the vegetable and the blue plastic is close to the 488 nm line; identification of the brown stone requires illumination with the 660 nm laser line. A more generalized view is given in Fig. 4, which shows the *r*, *b* scatter plot of all measured green vegetables and foreign bodies. We conclude that for the identification of bluish objects and brownish objects, we need to use the two color density parameters *r* and *b*. Green objects can obviously not be detected with this phenomenon.

Implementation in Scanning Engine

Finally, we implement the two selected laser lines in the static proof-of-concept scanning-based optical platform. The intensity of the reflected light for both wavelengths is recorded for one scanning line containing bluish, greenish and brownish

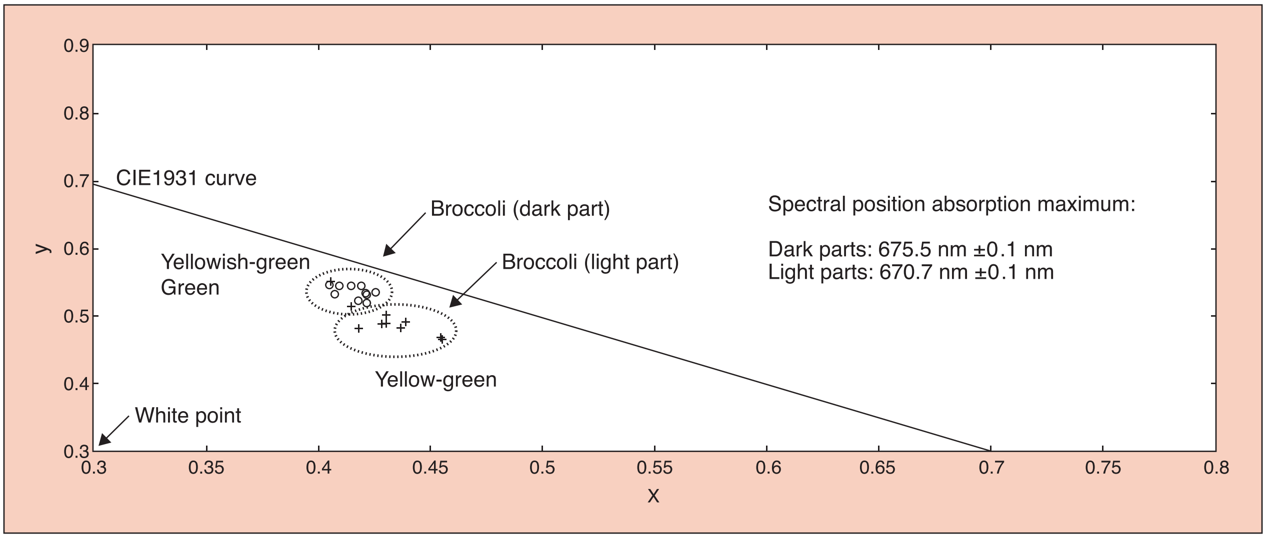

Fig. 2. The spectral position of the chlorophyll absorption shifts to longer wavelengths for darker green vegetables.

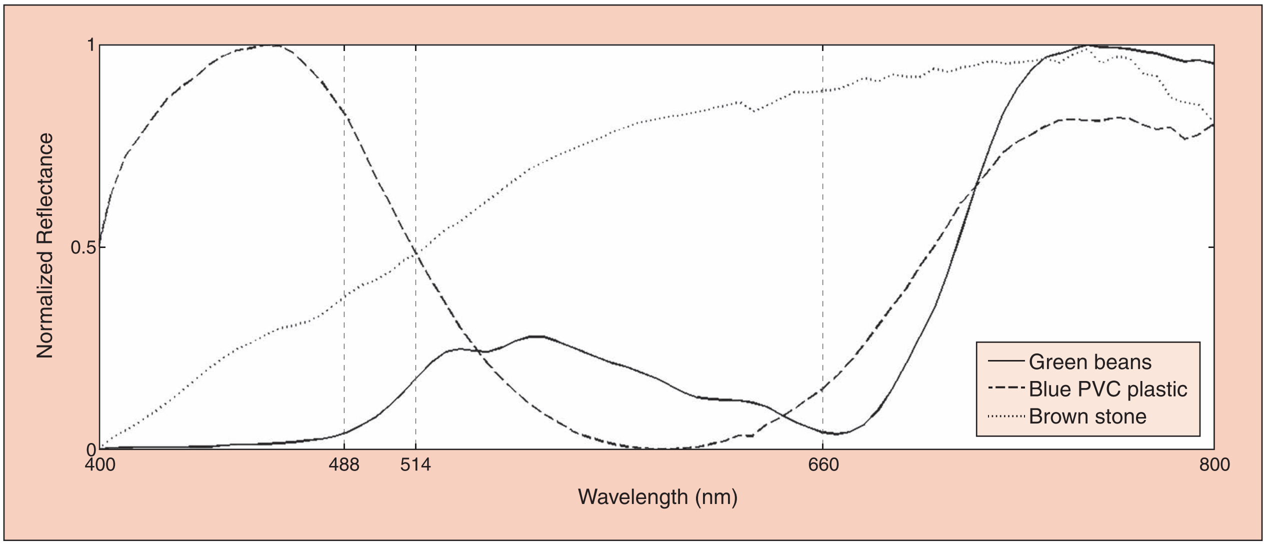

Fig. 3. The largest contrast between a green vegetable and the blue plastic is close to the 488 nm line; identification of the brown stone requires illumination with the 660 nm laser line.

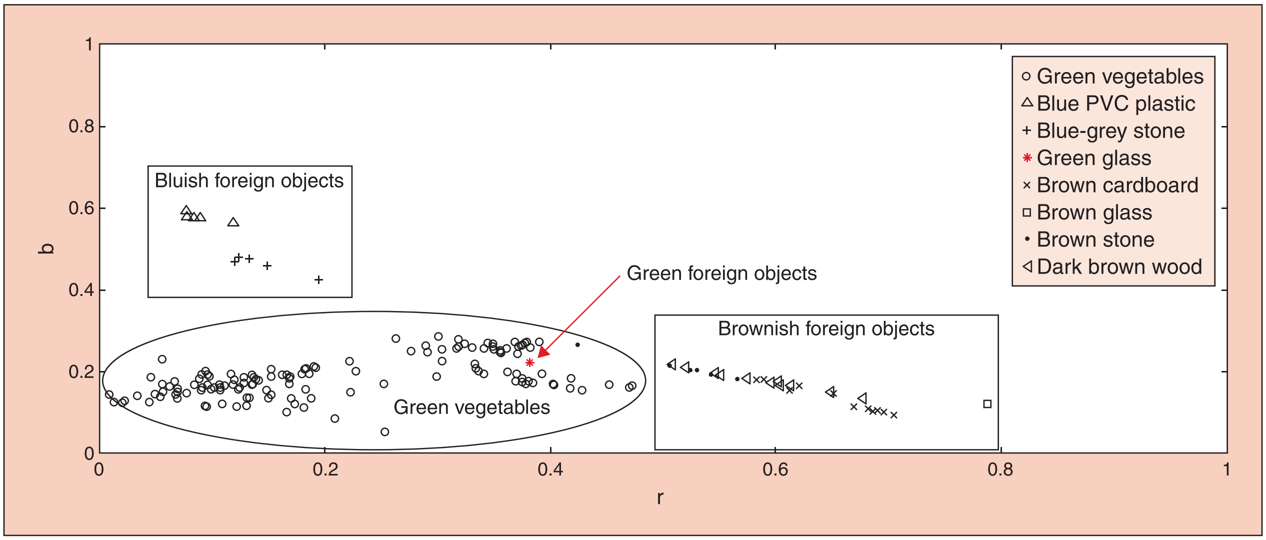

Fig. 4. Identification of bluish objects and brownish objects requires the use the two-color density parameters *r* and *b*.

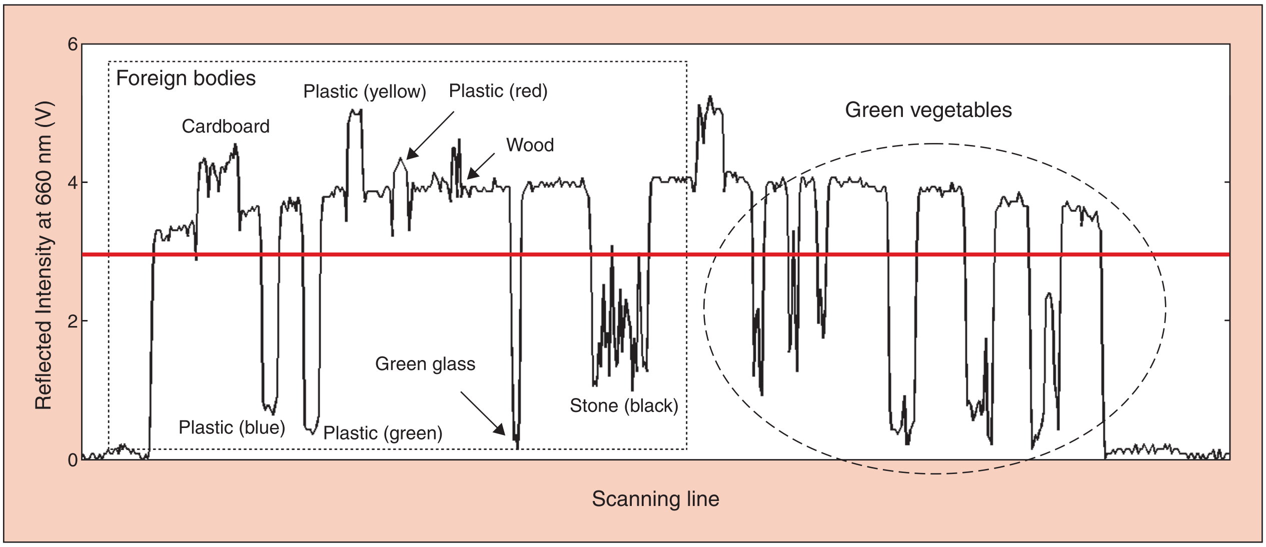

Fig. 5. Scan plot demonstrating the use of the reflected intensity at 660 nm as optical measure to separate non-green colored foreign bodies from green vegetables.

defects together with six green vegetables. The test measurements confirmed the outcome of the spectroscopic research as illustrated in Fig. 5. The plot clearly shows it is possible to identify brownish objects in a stream of green vegetables using the reflected intensity after illumination with a 660 nm laser. The threshold level is close to 3 V.

Conclusion

Whenever there is a color difference between the vegetables/fruits and the foreign objects, the identification process can be based on selective absorption.

Application 2: Use of Fluorescence in Products with Equal Color

The second application presents the use of fluorescence to separate foreign objects and food products with an equal color. If the foreign bodies and the vegetables are equally colored, the use of an optical identification parameter based on selective absorption is inefficient. Frequent examples of these are the appearance of green glass shards, pieces of plastic, or even frogs.

Plants grow by utilizing the energy generated during the photosynthesis process, which is initiated by the absorption of (sun) light. Light that is not used for this process might be dissipated from the chlorophyll centers via the emission of fluorescence light. The typical chlorophyll fluorescence spectrum is between 650-800 nm and is characterized by two maxima close to 685 nm and 730 nm.

The aim of this research is to investigate if the presence or absence of chlorophyll fluorescence can be used to identify green colored fragments in green vegetables.

Materials and Methods

The studied group of products include different types of green vegetables and green colored foreign bodies.

The first step is the selection of the optimum excitation wavelength and power. Therefore, we measured the fluorescence spectra of one test product (peas) after excitation with five different excitation wavelengths covering the ultraviolet and visible region of the electromagnetic spectrum (UV: 351.1 nm + 363.8 nm; blue: 405 nm, 457.9 nm, 488 nm; red: 660 nm) and used increasing excitation power. We carried out the measurements using the set-up described in [1]. An additional step variable metallic neutral density filter was positioned between the laser and the sample to vary the excitation power, which varied between a few microwatts and 20 mW for the 405 nm and 660 nm laser. For the 457.9 nm laser we could vary the emission power up to 150 mW. The targeted optical sorting parameter is the total emitted fluorescence intensity. Therefore, we integrate the measured fluorescence signal in the spectral region 650-800 nm.

Second, we studied the fluorescence intensities of three arbitrarily chosen green vegetables (Brussels sprouts, garden beans, and peas) to evaluate if the traditional weak fluorescence signals were strong enough to be measured by a photomultiplier tube, which is a detector type often used in scanning-based sorting platforms. Finally, we implemented the selected sorting parameter in a sorting platform.

Measurement Results

The intensity of the emitted fluorescence light depends on the wavelength and on the power of the excitation laser [2]. We observed that blue and red excitation wavelengths cause the highest fluorescence intensity. These observations can be explained considering the energy levels of a chlorophyll molecule. The first excitation state S1 is reached after the absorption of red light; the second state S2 is after the absorption of blue light [2]. Fluorescence will only take place after the decay from level S1. Via internal conversion, electrons can travel from S2 to S1. If the products are excited with red light, the electrons are immediately in the optimal energy level, leading to a maximum fluorescence efficiency.

Evaluating the total fluorescence intensity as a function of the excitation power for the three investigated excitation wavelengths, the fluorescence intensity increases linearly with an increasing excitation power within the lower power range (the correlation coefficient R^2 equals 0.99). After this, a saturation level is reached. For the 457.9 nm line, the threshold value is situated around 90 mW. For the other two wavelengths, we could not reach the threshold value. We only know that for these wavelengths, the saturation level will correspond to a lower excitation power since the slope of the curve strongly depends on the excitation wavelength. The higher the chance of absorption, the faster the saturation level is reached. Regarding fluorescence efficiency, we also concluded that for chlorophyll, the use of a red excitation wavelength is preferable [3].

Analyzing the averaged fluorescence intensities of peas in three different conditions (frozen, dried, and fresh) illustrates the high level of emission values, which are above the detection limits of standard optical detectors. These measurement results are confirmed for the other two test products not shown here. The total fluorescence intensity depends on the condition of the product; frozen and dry products have higher emission values. This is caused by the influence of the freezing and drying process on the internal structure. The bonds between the chlorophyll molecules are broken, preventing the transportation of electrons needed for photosynthesis but provoking fluorescence.

Implementation in Scanning Engine

In the final step, we implemented a red excitation laser in the static proof-of-concept scanning-based optical platform. The total fluorescence emission was recorded for one scanning line containing both fluorescing and non-fluorescing substances. The test measurements confirmed the use of the fluorescence intensity as an optical measure to separate different types of colored foreign objects (e.g., cardboard, glass, plastics, stones, or wood), and green colored pieces from the green vegetables. The large contrast between the non-fluorescing foreign objects and the fluorescing green objects was manifest.

Conclusion

Green foreign bodies can easily be identified in streams of green vegetables using the emitted fluorescence intensity as an optical measure after excitation with a red laser source.

Application 3: Use of Internal Scattering

The third application presents the use of internal scattering to separate products with a difference in porosity. The use of selective absorption or fluorescence gives poor results in those cases where a mixture of vegetables is present or when a non-fluorescing food product must be separated from an equally colored foreign object (e.g., brown stone – potato). Since both product groups are characterized by an apparent difference in porosity, the question arises if a related optical measure can be identified.

Materials and Methods

We analyzed the scatter patterns for different vegetables and foreign bodies with configurations described in [1]. For an angle of incidence of -45° we measured the cosine corrected Bi-directional Scattering Distribution Function (ccBSDF) for three different illumination wavelengths (488/514 nm, 660 nm and 830 nm). Images of the scattered light beams were recorded after illumination with 660 nm and 830 nm, respectively.

Measurement Results

The ccBSDF of most of the foreign bodies were concentrated around the specular reflection component at +45° due to their dense internal structure [2]. For vegetables, the ccBSDF values expressed a much broader profile due to their more porous internal structure. As a case-study, we compared the ccBSDF of peas and potatoes [3]. The ccBSDF was maximal for the specular component (at +45°) and decreased from that point. The decrease rate depends on the illumination wavelength. For the peas, the strongest decrease was observed for the red wavelength (660 nm). This is within expectations since the chlorophyll containing product strongly absorbs this wavelength, meaning that the detected scattered light will mainly arrive from the surface. We conclude that this application requires the use of a near-infrared wavelength. For non-green vegetables, like potatoes, the red wavelength will only be partly absorbed. The largest scatter contribution originates from inside the product, and as a consequence, the range of angles over which the light is scattered is extensive. The ccBSDF values for the red (660 nm) and for the infrared (830 nm) wavelength were comparable. For this application, a red as well as a near-infrared wavelength can be selected.

The scatter plots captured with the CCD camera strengthen these findings. In Fig. 6, the scatter plots are shown in (a) for a green glass part and in (b) for a potato illuminated by a 660 nm laser line.

Implementation in Scanning Engine

To implement light scattering as an optical measure in a scanning engine, we need to separate the light captured at the center of the detector's active surface from the light falling on the outer parts. This can be done by using commercially available ring sensor detectors. Fig. 6a and 6b simulates the use of such a device to differentiate stones from potatoes, in Fig. 6c and 6d, respectively.

Conclusion

The conclusion that we reached is that the classification of food products based on differences in internal cell structure is possible. Porous products such as vegetables can be distinguished from more dense foreign bodies by analyzing the emission angles of the scattered light. The more porous the product, the broader the angle over which the light is scattered. The optimum wavelength for irradiation depends primarily on the pigment types and then on the application.

Application 4: Use of Vibrational Absorption

The last application presents the use of vibrational absorption to classify products based on differences in water or oil

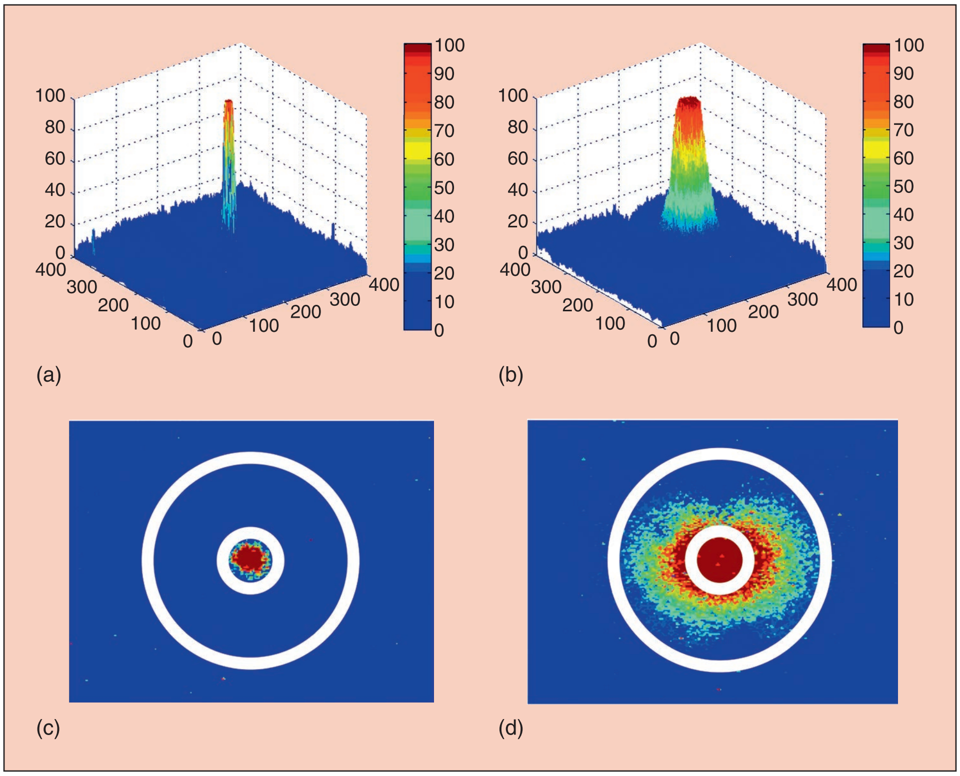

Fig. 6. Differences in scatter properties are distinct due to dissimilarities in porosity between (a) a piece of glass and (b) a potato. Simulation of the use of a ring sensor to separate light scattered in (c) the inner and (d) the outer parts of the scattered light beam.

concentration. Since the absorption spectrum in the near-infrared region provides a product's basic components, or fingerprint, the objective was to verify that it is possible to identify foreign bodies based on the optical sensing of the presence or absence of water or oil.

Materials and Methods

The idea consists of measuring the ratio of the reflected light for two well selected wavelengths. The first wavelength tunes with an absorption wavelength of the considered component (see Table 1 in [1]). The difference in reflectance between a vegetable and a foreign body is maximal for this wavelength. To eliminate the effect of environmental factors such as differences in internal scattering between products with an equal concentration, we measured the reflected intensity for a reference wavelength, which did not coincide with an absorption wavelength.

We performed the study on two test groups. The first group targeted the definition of an optical measure to classify products based on differences in water concentration. We compared vegetables and wet foreign objects. Possible absorption wavelengths were selected at 980 nm, 1190 nm and 1480 nm. As reference wavelengths, we studied the use of 780 nm and 1300 nm. Following a similar strategy, we conducted a study to select the optical measure able to separate foreign objects from oil containing products. We considered three different types of nuts: hazelnuts, macadamia nuts, and peanuts. Referring to the near-infrared absorption bands of oil, we selected 1392 nm and 1440 nm as potential absorption wavelength and again choose the 780 nm as the reference wavelength.

Measurement Results

For the first case, both reference wavelengths were a good choice, though the 1300 nm line gives a larger contrast (~a factor of 2) compared to 780 nm [2]. As an absorption wavelength, we must work with the 1480 nm line. Only then are we able to identify foreign bodies in a stream of vegetables based on the presence of water [3]. In addition, the defined optical measure to recognize oil containing food products gives satisfactory results. For this case, the optical measure defined to separate products with low and high oil concentrations is based on the ratio of the light reflectance at 780 nm and 1440 nm [2].

Since all studied wavelengths are available as commercial laser wavelengths, implementation in an optical scanning engine is straightforward.

Conclusion

Foreign bodies can be identified based on the optical sensing of the presence or absence of water or oil.

General Conclusion

This paper shows that photonics-based food sensors can definitely contribute to the enhancement and safety of solid food products. With the help of four concrete case-studies covering the main application domains of foreign body identification, we demonstrated the usefulness of optical screening methods in general and defined for each application, in particular, the corresponding optical measures. In Part 3 of this series, we will discuss two additional main application domains: the quality screening of solid food products and the quality monitoring and authentication of liquids.

References

[1] W. Meulebroeck, H. Thienpont, and H. Ottevaere, "Photonics-enhanced sensors for food monitoring: part 1," *IEEE Instrum. Meas. Mag.*, vol. 19, no. 6, Dec. 2016.

[2] W. Meulebroeck, "Optical detection techniques for lasersorting machines: productidentification and quality control (Dutch version only)." Ph.D. thesis, Applied Sciences, Vrije Universiteit, Brussel, 2004.

[3] W. Meulebroeck and H. Thienpont, "Optical detection techniques for laser sorting machines," *Optical Sensing II*, 2006, vol. 6189, p. 61891F–61891F–12.

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