A Microwave Imaging Device for Detecting Contaminants in Water-based Food Products

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***Abstract*—Food and beverage industries are paying an increasing attention to the development of new technologies for non-invasive assessment of food products. In particular, there is a need of deploying tools to detect low-density plastic, rubber, wood and glass that are unlikely to be detected by X-Rays, currently used in the most powerful commercial systems. To this end, we propose a microwave-based device, exploiting the dielectric contrast between potential intrusions (e.g., plastic fragments) and the surrounding medium, represented by the food/beverage product. In particular, this work aims to numerically assess this principle of detection to water-based products that are, due to the medium losses, a challenging category at microwaves. An antennas array surrounds the object moving along the production line, to monitor the electromagnetic signal variations with respect to a reference case. The working frequency is chosen by selecting a proper trade-off between penetration depth and image resolution. Then, a procedure, based on the application of the distorted-Born approximation is applied to reconstruct a 3-D image of the contaminant position. Finally, the successful detection of a millimetric-sized plastic sphere is presented in the case of a common commercial bottle filled with water.**

***Index Terms*—microwave imaging, non-invasive diagnostics, food inspection, food security, food safety**

I. Introduction

The increasing customers attention for quality in food and beverage purchases, as well as the increase in physical contamination found in packaged food [1], calls for a novel technology development to face these issues. The limitations in employed quality monitoring devices are intrinsic due to their detection principles: metal detectors (MD) can only see conductive materials inside products, while the penetration capabilities of X-rays (XRI) are limited if contaminants density is low, and may fail in detecting some classes of materials, such as wood, glass or low-density plastics. In particular, plastic and rubber are two of the most widely employed materials in food production facilities, but also possibly two of the trickiest contaminants to find with existing devices [2]. Moreover, XRI systems employ ionizing radiations which can be unsafe if not handled properly.

The potential issues due to undetected contaminated products are multiple. Primarily, there is a health risk: fragments of glass or plastic can severely damage the digestive system, and children and seniors may be particularly affected. Then, customers reactions may lead to loss of trust in a brand identity, or worse to legal consequences for industries.

In recent years, an interest for the development of new technologies arouse, motivated by an industrial push to complement existing techniques. Microwave imaging (MWI) attracted increasing attention for the purpose [3]. The MWI detection principle does not rely on materials densities but rather on the dielectric contrast between the contaminant and the sample to inspect. In [4], J. A. Tobón Vasquez and co-authors introduced a first implementation of MWI device, tested at industrial facilities, to prove the feasibility of this novel detection principle. Due to an insufficient amount of data to reconstruct a tomography of the target, the system was renovated by increasing the number of sensors in [5], [6].

Given the successful implementation with a certain class of oily-based food items, in this paper, an extension of the working principle for a more challenging class of food products, mainly composed by water is proposed. Such products include a large variety of articles, from most beverages, to several dairy food, or also marmalade and many others. The dielectric features of the main component of such items (i.e., water) requires a significant adaptation of the proposed methodology: the high losses, caused by water at microwave frequencies, needs a proper selection of the working frequency in order to sufficiently penetrate the medium and reveal possible intrusions, keeping at the same time enough imaging resolution. As a consequence, a new printed circuit board (PCB) antenna, based on [7], has been designed, also considering the possibility to employ a unique sensor for different test cases: indeed, an ultra-wide band (UWB) monopole antenna is developed for the purpose. Further, the architecture has to be designed considering the physical constraints of the product to inspect: in this assessment, we used a common commercial bottle, with height of 30 cm and cylindrical base of approximately 7.5 cm, moving along a conveyor belt.

II. MWI System Description

The MWI device architecture is developed with respect to the constraints imposed by considered final application: the motion of the item flowing along the production line must not be interrupted, and the relative position of the antennas array with respect to the product to inspect must be optimized in order to maximize the illumination of the target. The shape of the product to analyze is a further input for the antennas positioning. For these reasons, we designed a sort of "portal"

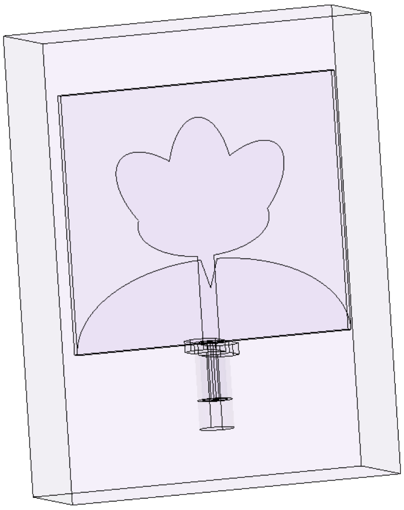

Fig. 1. UWB antenna design, whose dimensions are 45 mm and 50 mm respectively

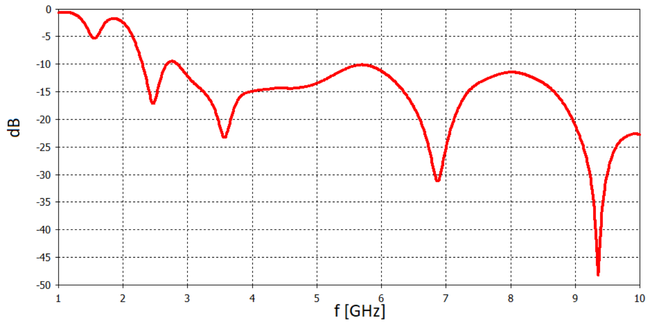

Fig. 2. Antenna shown in Fig. 1 reflection coefficient in [1-10] GHz frequency band

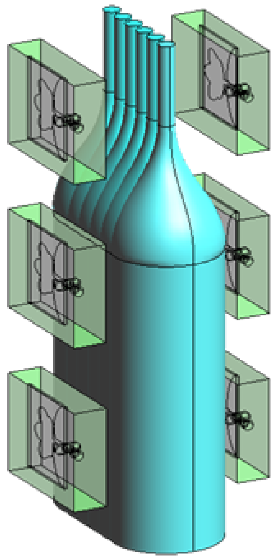

Fig. 3. Antennas array architecture with respect to the bottle moving along an industrial conveyor belt. Inter-distances are computed considering a 100 cm/s motion speed and a commercial VNA acquisition time

configuration, with three antennas arranged on each side of the production line, in order to let the object pass through it, and obtain useful information in the whole volume to analyze. The number of antennas was set in order to obtain a sufficient amount of data to reconstruct a 3-D image, but while allowing enough spacing between the antennas so to avoid redundant information and mutual coupling [8].

The proposed novel antenna design has a double purpose: first, to extend the prototype operation to another frequency range, compared to previously assessed tests for oil-based products; second, to provide a unique solution, being able to work at different frequency ranges, so to have a single sensor for different applications. The selection of the operating frequency derives from the dielectric features of the inspected medium: considering the high relative permittivity of water and its electric conductivity, as well as the antennas features, a frequency of 2.5 GHz allows to have sufficient penetration depth (i.e., around 4 cm inside water) and a good antenna matching. The UWB designed antenna, shown in Fig. 1, is here proposed as a suitable solution: as shown in Fig. 2, its reflection coefficient is below -10 dB from around 2.3 GHz, showing a wide band behaviour.

Assuming the motion of the bottle at industrial speed (i.e., 100 cm/s), and in addition the acquisition time of a commercial vector network analyzer (VNA) [9], we set six different evaluation positions of the bottle along the conveyor belt (see Fig. 3), supposing the possibility to receive in parallel all the transmitted signals (that is possible with a 6-port signal acquisition device).

III. Numerical Assessment and 3-D Image Reconstructions

The exploited principle to perform 3-D image reconstructions is based on the MWI system described in [6]. All items passing by the conveyor belt are supposed to be equal, so that it is possible to consider a reference case, as an uncontaminated sample. The data measured for the sample under test are subtracted from those obtained from the reference. By doing so, the resulting differential scattering matrix is only due to the presence of the potential contamination, if the signal level overcomes the noise one. The distorted-Born approximation can be then exploited since the potential intrusions are supposed to be small. This allows to linearize the MWI problem in order to have a linear dependence between the differential scattering matrix and the dielectric contrast. The linearized problem can be then solved via the truncated singular value decomposition (TSVD) using the discretized version of the scattering operator, computed through a finite element solver (FEM) solver [10], [11].

The projection of the differential scattering matrix on the TSVD decomposed and truncated operator allows to obtain the image reconstruction in real-time. A threshold is applied in order to highlight the peaks corresponding to the contaminant

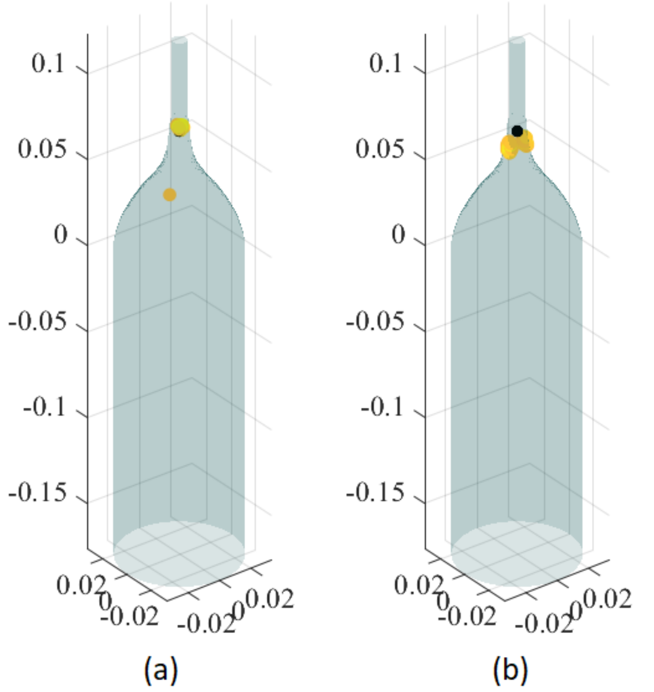

Fig. 4. 3-D image reconstruction, the intrusion original position depicted as a black sphere, while reconstruction values are yellow circles. (a) shows the ideal case reconstruction, (b) is affected by AWGN (SNR=80 dB)

position. Moreover, given the non-uniformity of the radiated fields by the antennas array, considering the unsymmetrical shape of the tested object, i.e. the bottle, an algorithm to balance the illumination on the target is then applied, to enhance the reconstruction by considering a more balanced coverage on the whole volume under test.

As a proof of concept, the operation of the designed device has been simulated for a class of contaminant which is invisible from other detection devices. In particular, a low-density plastic spherical intrusion is considered, whose radius is equal to 2.5 mm. Since a small piece of low-density plastic is supposed to float in an item mainly composed by water, the selected position is the interface between water and air. Two different reconstructions are shown in Fig. 4: the bottle is represented in transparent light green, the intrusion original position as a black sphere (at the interface within the bottle between water and air), and the reconstruction values as yellow-orange circles. Figure 4-a shows the image reconstruction: the contaminant is correctly detected, as it can be easily noticed, given that the black sphere is basically covered by reconstruction values. While Fig. 4-b represents a reconstruction after the application of additive white Gaussian noise (AWGN) with SNR=80 dB on the differential scattering matrix, in order to present a more realistic scenario: in this case, again the target is detected almost exactly, with a slight misplacement due to noise effect.

IV. Conclusion and Perspectives

In this paper, a microwave-based device designed for contamination monitoring of water-based food products has been presented. The performed numerical analysis supports future work with the development of a device able to work in-line, while the products flow along a production line and without stopping the processes or even reducing the speed. It consists in the validation of this approach with actual measurements, and in parallel with further tests on different food and beverage products, as well as more classes of contaminants and relative positions in the item volume. Moreover, the use of machine learning techniques, as in [12], will be investigated.

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