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AI-Assisted Design and Experimental Testing of a Compact UWB Antenna for the Inspection of Food and Beverage Products

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***Abstract*—Detecting physical contamination caused by low-density foreign bodies is an ongoing challenge faced by the food and beverage industries. To overcome the limitations of existing devices, a novel detection principle based on microwave imaging (MWI) has been assessed. MWI enables safe and non-invasive analysis of the sample under test through a 3-D reconstruction obtained from the alteration that the electromagnetic scattered waves undergo due to the presence of a foreign body. To make the application of this technology more appealing in real-world scenarios, we propose an antenna that can cover a broad set of food types, permitting the adaptability of the system's operating frequency depending on the products' dielectric properties and the containers' type or shape. The proposed antenna is designed with the help of artificial intelligence (AI). Thanks to its low cost and small dimensions, we can increase the quantity of acquired information by increasing the number of antennas placed around the product. A complete functioning system using the designed antenna is presented, assessing the image reconstruction in a case with realistic products and contaminants.**

***Index Terms*—antennas, microwave antennas, microwave imaging, microwave inspection**

I. Introduction

As the demand for non-invasive real-time monitoring along industrial production lines grows, traditional inspection devices show limitations. Companies in the food and beverage, cosmetic, and pharmaceutical industries are looking into new technologies [1]–[4] to improve detection accuracy for certain types of foreign bodies and materials, including polymers, bacteria, and fungi, that are difficult to detect with current techniques. The rise in food recalls [5] only highlights the need for a paradigm shift in inspection techniques. Microwave imaging (MWI)-based inspection of food and beverages is a promising solution, overcoming the limitations of current methods. MWI can detect non-conductive materials, including glass, plastic, and wood, which metal detectors or X-ray imaging devices can miss. Recent studies [6] have demonstrated the practicality of MWI, making it a viable option for real-time monitoring in industrial settings.

When it comes to microwave inspection, it is important to have antennas that can efficiently analyze the object being inspected by collecting relevant information [6]. These antennas must receive signals above the noise level while being compact, lightweight, low profile, and easy to maintain with a simple feeding structure. A similar antenna array meeting these requirements has already been developed in [7], [8]. That system uses a machine-learning approach to classify clean and contaminated food samples and has been validated for a single class of products. However, there is still work to generalize this approach and apply it to a broader range of products while trying to accurately reconstruct the 3-D map of the product's dielectric features. This generalization will require optimizing the antenna's radiating elements and tailoring the working frequency based on the product's dielectric features and physical constraints.

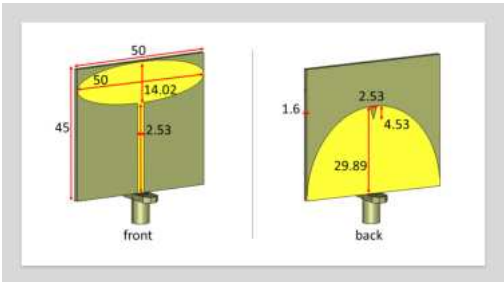
In this work, we have focused on enhancing the antenna's frequency responses in terms of impedance bandwidth, gain, and total radiation efficiency over the ultra-wideband (UWB) frequency spectrum while accounting for the presence of a bottle. To achieve this goal, we have employed the use of artificial intelligence (AI), specifically machine learning. We utilized a state-of-the-art machine learning-assisted global optimization method called parallel surrogate model-assisted hybrid differential evolution for antenna optimization (PSADEA) [9], [10].

II. Optimization and Antenna Design

PSADEA is the third installment in the SADEA series of [9]–[12], and utilizes the surrogate model-aware evolutionary search (SMAS) framework [13] in its optimization kernel, which allows it to use fewer expensive full-wave EM simulations in the optimization process. This is achieved by ensuring a harmonious working balance between evolutionary computation and supervised learning. PSADEA uses differential evolution (DE) to drive the global search of the antenna design space and Gaussian process (GP) for predicting the antenna's performance based on candidate design parameters.

PSADEA is efficient for tackling difficult antenna design problems. It provides a good quality of design solutions and is several times, to up to 20 times, faster compared to standard numerical optimization methods. PSADEA does not require an initial design or any other ad-hoc processes, making it fit for optimizing challenging antenna designs that other optimization methods can not address [11], [12].

Fig. 1. A commercial glass bottle surrounded by six fabricated prototypes of the PSADEA-optimized antenna to acquire a 6×6 scattering matrix and perform the microwave image reconstruction.



(a) PSADEA-optimized simulation model. All dimension in millimeters.

(b) Physical implementation.

Fig. 2. The PSADEA-optimized antenna.

In this work, the PSADEA-driven optimization is applied to design an antenna for microwave inspection of food and beverages products to be used in an array configuration as shown in Fig. 1. The design goal is to maximize the bandwidth in the UWB frequency spectrum of 2 GHz to 11 GHz, with a maximum in-band return loss lower than -10 dB, while considering the presence of the bottle in front of the antenna. Moreover, a constraint added in the optimization process is the reduced size of the optimized antenna, allowing the increase of the number of antennas placed around the product under test.

The PSADEA-guided topological evolution generated the antenna shown in Fig. 2. The reflection coefficients are depicted in Fig. 3, comparing simulations and measurements. The discrepancies can be attributed to the manual welding of the SMA coaxial connector antenna.

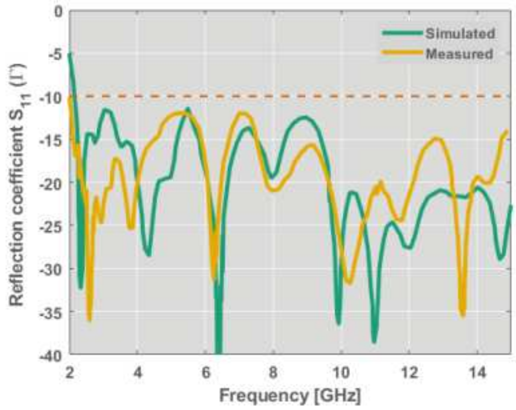


Fig. 3. Simulated and measured amplitude of the reflection coefficient (dB unit) for the PSADEA-optimized designed antenna.

III. Microwave Imaging System

The optimized antenna is then used in the microwave imaging system (Fig. 1) designed to inspect a commercial bottle, looking for foreign bodies that are challenging to the assessed devices, as plastic, glass, and wood. Six antennas are placed to properly illuminate the whole volume of the bottle, with their positions being numerically evaluated to maximize the quantity of non-redundant information necessary for the 3-D inversion problem [14].

Microwave imaging is performed through the truncated singular value decomposition (TSVD) of the linearized discretized scattering operator, where the differential measured scattering matrix is projected on the inverse of the linear operator [15].

To show the adaptability of the system to different products, and to highlight the importance of an UWB antenna, we tested 2 different cases: the water-based case and oil-based product. In both cases we use the same commercial bottle as container and, as foreign body, a glass fragment of approximately 1 cm × 2 cm × 0.2 cm. Fig. 4 shows the two different products surrounded by the antennas, and the foreign bodies used in the experimental testing. The selection of the frequencies in each case seeks the balance between penetration and image resolution. In the water-based case, we work at 2 GHz and 4 GHz, while the oil-based product the working frequency is at 10 GHz. In Fig. 5, we can see the reconstructed images for both cases. The quantity depicted is the normalized reconstructed values, thresholding at the equivalence of -3 dB from the maximum, represents the physical contaminant. For both, water and oil-based products, the foreign body expected position and size are correctly identified.

IV. Conclusion and Perspectives

We have successfully employed a PSADEA-optimized antenna design to develop a prototype for MWI. Our goal was to accurately identify low-density contaminants in different classes of food products, each with unique dielectric features in terms of permittivity, conductivity, and container size and

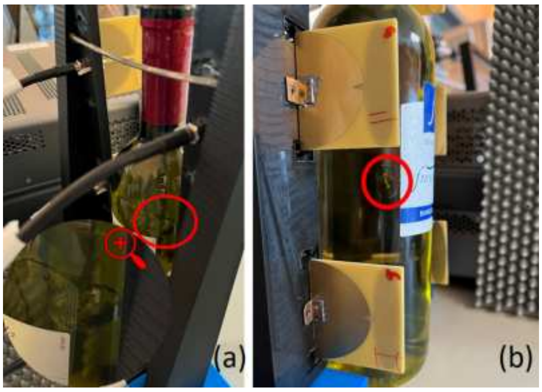


Fig. 4. A glass splinter in the target bottles, measured by the microwave sensing system. (a) shows Water-based item case, the contaminant is highlighted and zoomed in the bottom left. (b) shows the bottle filled with corn oil, the contaminant position is highlighted by a red circle.

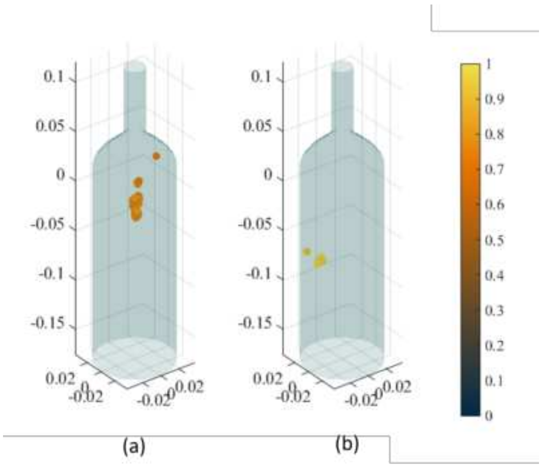


Fig. 5. The normalized image reconstruction of the two considered scenario: the bottle is sketched through transparent green surfaces, while the reconstruction values are yellow-orange circles. (a) shows the reconstruction with water-based medium, (b) with the bottle filled with corn oil. All dimensions in m.

shape. The wide-band capabilities in our antenna design allowed us to seamlessly switch to the desired frequency, ensuring that we could penetrate the medium being studied with the highest possible resolution. We are pleased to report that the imaging procedure yielded good recognition results, and this work can serve as the foundation for a device that can monitor several different classes of food products, whether they are water-based or oil-based.

The next step of this work is to apply the designed antenna and system to products moving along an industrial conveyor belt.

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