Experimental Investigation of Microwave Imaging as Means to Assess Fruit Quality

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***Abstract*—The continuous increase in global food consumption brings forward the need for constant development of technologies to enhance the existing quality assessment methods. Such enhancement can both increase the safety of the consumers and decrease the product wastage. In recent decades, microwave imaging has emerged as a promising non-invasive and non-ionizing technology for a range of applications. In this paper, the applicability of a newly developed microwave radar algorithm for fruit imaging is proposed. The measurements have been performed using purpose built hardware and the image reconstruction has been performed through a Huygens principle based algorithm. The variation in the dielectric properties of the fruits' internal body allows the algorithm to detect and capture the contrast when reconstructing their internal field. Experimental results on lemons and grapefruits indicate the capability of the algorithm to both detect seeds inside the fruits and distinguish between seeded and seedless samples.**

***Index Terms*—Microwave imaging, Food quality, Non-invasive.**

I. INTRODUCTION

The world has experienced a remarkable rise in the volume of agricultural products in recent years. As such, an increasing demand for high quality fruits and vegetables requires rapid advancement in post-harvesting technologies. The food testing market makes up 22% of the world's testing industry market, while the worldwide food safety testing market is predicted to hit 17.7 billion dollars in 2021, rising at a compound annual growth rate of 7.2% from 2017 to 2021 [1]. This strong growth is linked to several factors such as the advancements in food safety technology testing, firm regulations, rising outbreak of food-borne illness, and the globalization of food supply. At present, consumption reduction of post harvest fruit is a key concern for world agricultural trade. According to [2], post harvest fruit consumption accounts for 15 to 20 % of the total consumption amount in developed countries.

Due to the lower added value present in the agricultural sector in comparison with most other industries, the interest in development of cutting edge technologies and machinery for non-destructive quality control has only witnessed a rise in recent decades. Manual sorting of fruits is not only costly and time consuming, but also very subjective and inconsistent. In addition, visual inspection would not be able to identify any abnormality inside the products. At present, characterization techniques are separated into two groups, destructive and non-destructive techniques. In potatoes alone, destructive tests account for an estimated 0.5% of the post-harvest wastage volume, amounting to more than 10 million pounds [3]. In order to decrease this kind of wastage, non-destructive testing technologies have gained more attention in recent decades [4]. Various non-destructive techniques such as ultrasound, X-rays, optics, magnetic resonance imaging (MRI) and near infrared have been tested for automated fruit grading and sorting and in some cases have reached industrial implementation stage. These technologies have their drawbacks, such as safety issues in X-rays [5], or operational limitations in ultrasound [6].

Non destructive testing for detection of the black heart cavities inside potatoes using microwaves has been performed in [3]. A recent research on using synthetic aperture microwave radar for detecting grape bunch in vineyards has been reported in [7]. Several other studies on fruits' electrical properties and the related experimental results on a variety of fruits and vegetables have also been reported [8-14]. The originality of this work is the capability of the algorithm to both detect seeds inside the fruits and distinguish between seeded and seedless samples. To the best of authors' knowledge, this paper presents the first use of back-propagation through microwave radar imaging for the purpose of internal fruit imaging for seed detection and localization.

The microwave imaging algorithm presented in this paper makes use of the variation in dielectric properties between the seeds and the rest of the fruit to detect and localize the seeds inside them. This is based on the close relation of dielectric constant to the water content of fruit tissues. The algorithm used for reconstructing the fruit images was first introduced in [15], and has previously shown promising results in detecting cancerous tumors through simulations and phantom measurements [16], [17]. The technique makes use of the large amount of collected data to detect and locate the mismatch (target) inside an object or medium. The algorithm measures the external surface field of the object and back-propagates numerically this field into the imaging domain, thus reconstructing the internal field. This paper is structured as follows. Section II reviews the radar based imaging algorithm while the experimental set up and system is described in section III. Section IV then presents and discusses the reconstruction results, and lastly section V concludes the work.

II. IMAGING ALGORITHM

To provide an overview of the algorithm, let us consider a cylindrical object in free space, which is illuminated by a transmitter tx_m, with $m = 1,...,M$ operating at a range of frequencies f_l, with $l = 1,...,L$. We have N receivers, with receiver n at location ρ_n measuring field $E_{nm}(f_l)$ from receiver m at frequency f_l. The objective is to find and localize the discontinuities within the object from the fields measured at the receivers, $E_{nm}(f_l)$.

To reconstruct a uniform field at location ρ within the object, the field received from transmitter m at each receiver n re-radiates (virtually) back isotropically within the cylinder. Thus the inside field of the object is calculated through superposition of these fields re-radiated by the N receiving antennas, resulting in the reconstructed 2D field E_{HP} (subscript HP indicates the Huygens Principle method employed).

$$E_{\text{HP}}(\rho, m, f_l) = \sum_{n=1}^{N} E_{nm}(f_l) G(k_l |\rho_n - \rho|) \tag{1}$$

where $G(k_l|\rho_n - \rho|)$ represents the Green's function as defined in [15]:

$$G(k_l|\rho_n - \rho|) = \frac{1}{4\pi} e^{-jk_l|\rho_n - \rho|} \tag{2}$$

In above, k_l is the medium's wave number at frequency f_l. It should be pointed out that k_l is complex, to model both phase delay and attenuation.

Inserting Green's function into (1) we have:

$$E_{\text{HP}}(\rho, m, f_l) = \frac{1}{4\pi} \sum_{n=1}^{N} E_{nm}(f_l) e^{-jk_l|\rho_n - \rho|} \tag{3}$$

In order to resolve the two common problems of transmitter image and object's skin appearing as artefacts and masking the area of interest, two solutions may be used. Firstly, for more regularly shaped objects such as the fruits of interest in this paper the "averaging" method may be used. This is the method that has been employed for producing the images in this paper. In this way, the artefact image can be successfully removed by changing (1) such that:

$$E'_{\text{HP}}(\rho, m, f_l) = \sum_{n=1}^{N} (E_{nm} - \text{avg}_M\{E_{nm}\}) G(k_l|\rho_n - \rho|) \tag{4}$$

where $\text{avg}_M\{E_{nm}\}$ indicates the average of signals attained from the M separate transmitter positions.

For objects in general and irregularly shaped fruits and vegetables such as grapes and potatoes, the "nearby transmitter subtraction" solution may also be used. When using this method, we perform a subtraction between S21 measurements of two transmitting antennas placed 5 to 10 degrees away from each other. In this way (1) is modified to:

$$E'_{\text{HP}}(\rho, m, f_l) = \sum_{n=1}^{N} (E_{nm} - E_{nm'}) G(k_l|\rho_n - \rho|) \tag{5}$$

with m and m' being the nearby transmitters.

Finally, the total intensity is calculated through incoherent summation of all the frequencies and transmitting positions.

$$I_{\text{HP}}(\rho) = \sum_{m=1}^{M} \left[\sum_{l=1}^{L} E'_{\text{HP}}(\rho, m, f_l) \right]^2 \tag{6}$$

III. Experimental configuration

The microwave apparatus used in this research has been initially presented in [18], and can be seen in Fig. 1. It has been custom-designed for an 8-antenna tomography system for multilayered phantom measurements but has been modified slightly here to meet the needs of the radar measurement configuration. The setup here consists of a cylindrical tank with a diameter of 300 mm. The transmitter and receiver antenna are placed in a circular ring inside the acrylic tank. Horizontal and vertical mounts permit us to control the antenna positions with accurate precision. The antennas are connected to a 2-port Vector Network Analyzer.

Two custom-made inverted triangular patch antennas were used as the transmitting and receiving antennas. The geometrical configuration of the antenna is shown in Fig. 2. The antennas have been designed on a 12 mm by 15 mm FR-4 to enhance their operational bandwidth when immersed inside matching liquids. Although the antennas have been specifically designed to be used inside a matching liquid in the range of 1-3 GHz, they behave well at higher frequencies of up to 10 GHz in free space, allowing them to be used in all measurements presented in this paper.

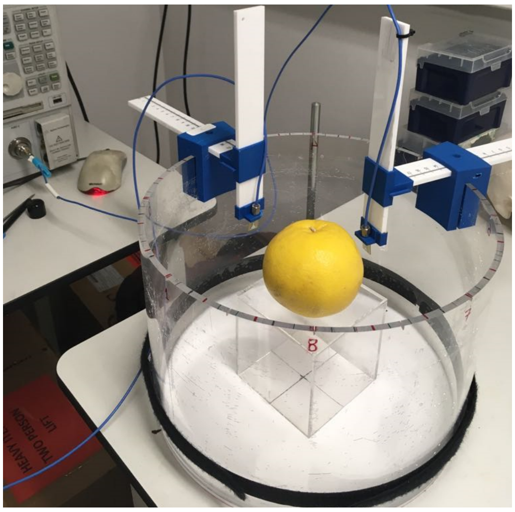


Fig. 1. Fruit imaging measurement setup.

The data acquisition process used in this paper was motivated from successful imaging experiments with this algorithm in previous work [16]. For each set of measurements, the position of transmitting antenna was kept constant at 3 cm distance from the fruit's skin at its largest diameter. The receiving antenna was positioned nearer to the fruit at roughly 1 cm away from the fruit's external skin. The antennas were placed in such a way as to have their center of transmission aligned with the fruit's vertical center, thus acquiring a 2D imaging plane covering the seeds. Frequency band of 1 to 10

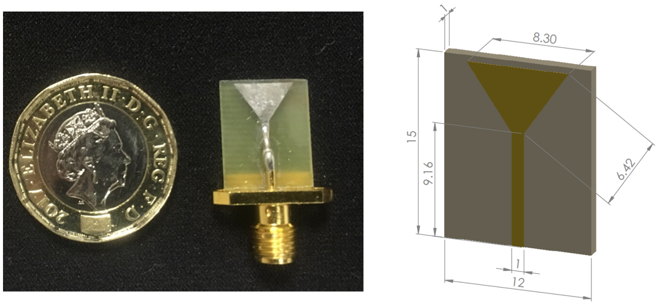


Fig. 2. Design views of the used inverted triangular patch antenna [18]. Values are in mm.

GHz using a frequency step of 5.6 MHz was used and the measurements were performed in free space. For each transmitting position, the receiver was manually rotated radially with a step of 15 degrees in order to measure the external field of the fruits at 24 receiving positions. Four sets of measured data were acquired, each time rotating the transmitter antenna position by 90 degrees. As the last step, the average of the four data sets was calculated and the Huygens method was applied after subtracting the average field from the measured field as shown in (4). It should be noted that since the measurements were done manually, each set of measurement took approximately 10 minutes to complete. The measurement time will be noticeably reduced through an automated system in the future.

IV. Results and Discussion

The experimental results of imaging four fruits are presented in this paper. Simulation results validating the experimental results have been performed and will be presented during the conference presentation. An 8 cm diameter grapefruit having 5 seeds, a seedless lemon with a diameter of 4.7 cm, and two seeded lemons with diameters of 6 and 10 cm respectively were used for testing. After the corresponding measurement of each fruit was completed, it was cut open to check its number of seeds and their locations.

Referring to the grapefruit measurement, Fig. 3 shows the S21 magnitude (dB) for the frequency range of 1-10 GHz when the antennas are at their nearest distance, midway distance (90 degrees apart) and farthest distance, respectively. This plot confirms that the signals are above the noise level of -80 dB in all distances and within the whole frequency range of 1-10 GHz. Due to this good signal propagation the whole frequency range was used for reconstruction.

Figs. 4(a) and 4(b) depict the normalized intensity images of the grapefruit obtained through (6), before and after image adjusting, respectively. Image adjustment is performed through converting intensity values lower than 0.6 to 0, and ranging values greater than 0.6 from 0 to 1.

After finishing the measurements, the grapefruit was cut open and 5 seeds were found concentrated in the center of the fruit. Comparing the images to the opened fruit, it was observed that the seeds were detected and localized in approximately the same position and with a similar size.

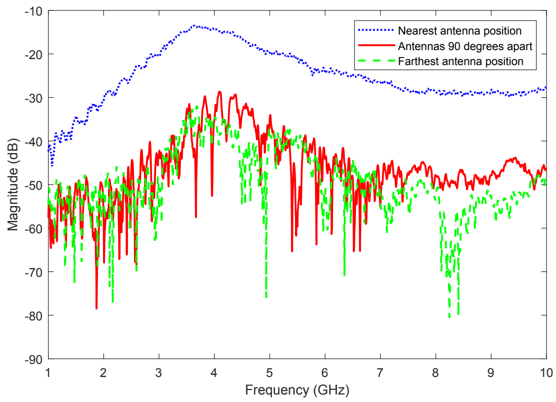
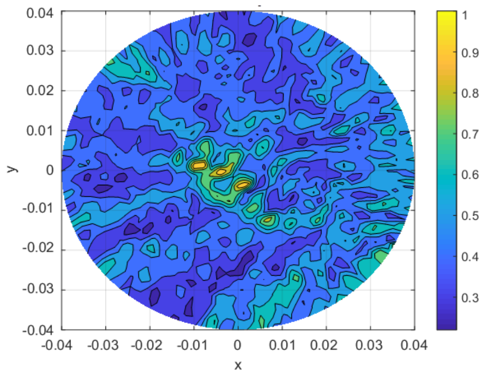
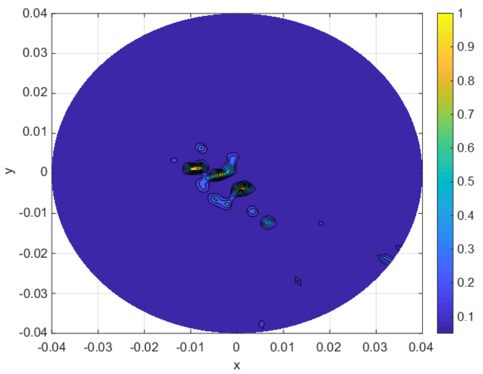


Fig. 3. S21 magnitude (dB) plot for different antenna distances in the range of 1-10 GHz.

Figs. 5 and 6 show the final intensity image of the lemon with 2 and 4 seeds, respectively. Once again, a good correlation between the location and size of the seeds in the image and within the fruit has been observed. Fig. 7 shows the resulting image of the seedless lemon. A clear visual difference can be seen between this image and those of the fruits containing seeds.



(a)



(b)

Fig. 4. Normalized intensity image of the grapefruit (a) before and (b) after image adjusting; x and y axes are in meters.

We note that we have performed measurements and reconstructions only across one axial slice, and hence any seed not present in the 2D view of the antennas may have been missed or detected with a lower contrast and intensity. In future the measurements can be extended to 3D either through z-axis rotation of the fruits or through combination of several 2D views to cover their whole vertical height.

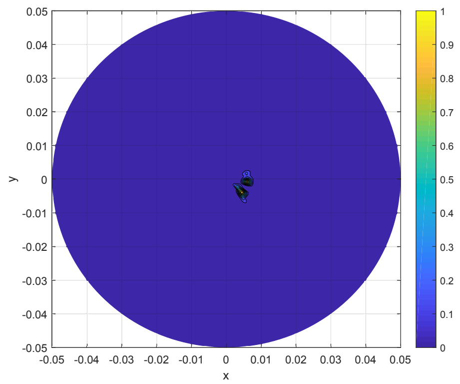


Fig. 5. Normalized intensity image corresponding to lemon with 2 seeds; x and y axes are in meters.

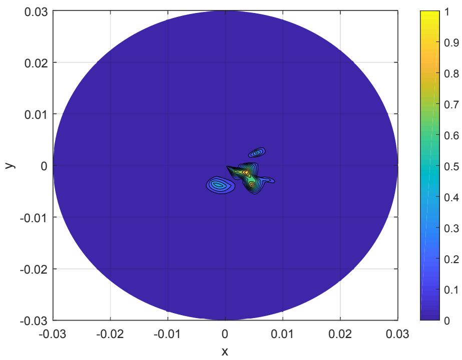


Fig. 6. Normalized intensity image corresponding to lemon with 4 seeds; x and y axes are in meters.

V. Conclusions

Assessing fruit quality through microwaves has many advantages which include being non-invasive and non-destructive, high accuracy, fast detection speed, and its low cost compared to traditional and modern detection techniques. In this paper, the applicability of a radar based microwave imaging algorithm to image the interior of fruits has been presented. This Huygens principle based method uses the difference in the dielectric properties between the fruit and its seeds (dielectric variation) to capture the contrast, detect internal seeds and distinguish between seeded and seedless products.

Future work will focus on developing a system that can be useful for real life industrial applications. To this end, we are working towards making the system more compact, quicker and more efficient. Furthermore, a wider analysis and investigation on the optimum bandwidth, minimum number of antenna positions required, and the optimum antenna distance from the object will be performed. Moreover, in order to reduce unwanted measurement errors and enhance the resolution and stability of the images, wideband designed antennas and rigid cables will be employed in the hardware set up. Solutions towards a continuous monitoring system are under investigation to tackle the need of monitoring vast amounts of fruits using non-destructive testing.

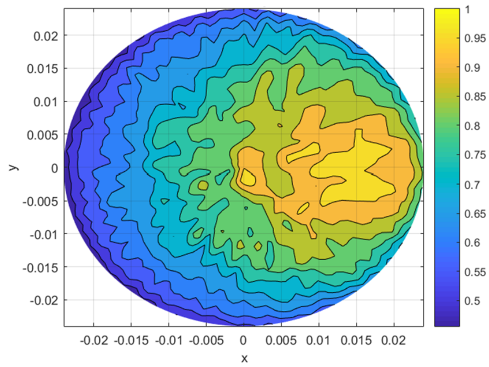


Fig. 7. Normalized intensity image corresponding to the seedless lemon; x and y axes are in meters.

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