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The simulation of sugar content estimation of sugarcane based on dielectric properties for microwave imaging technique.

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Abstract

The simulation of sugar content estimation of sugarcane based on dielectric properties for microwave imaging technique is proposed in this research. The specific dielectric constant contained in each pixel in the image is applied to indicate the type and position of objects in the area under test (AUT) such as sugarcane sample. The number of antenna around the AUT is defined by the angle of each antenna ($\Delta\theta$) that directly affects to the resolution of reconstructed image. The major challenge of this project is a trade-off between image resolution and number of antenna. Increasing the numbers of antennas provide higher image resolution, however it also makes the imaging system more complex. The determination of suitable $\Delta\theta$ value is operated in the first process. It is found that the 5° of $\Delta\theta$ value provides the good agreement between image resolution and number of antenna for estimating sugar content. The simulation error of sugar content estimation in the reconstructed image is between 1.97-7.24% of given sweetness range (9-21 °Brix). The error is computed by using the average of obtained dielectric constant in pixel near the core of cane sample area.

Keywords

sugar content estimation; microwave imaging; sugarcane; dielectric constant; non-invasive measurement

1. Introduction

Smart farming is a rapidly growing trend in agriculture that leverages advanced technologies and data-driven approaches to optimize various aspects of farming operations. Farmers can exactly know ripeness periods of fruit and obtain the best price when they sell to customer or factory. The one of major agricultural product of Thailand economy is sugarcane. Sugarcane is the main material for sugar industries because it provides high sugar content. By implementing technologies that accurately measurement and monitoring the ripeness of sugarcane, Thai farmers are able to obtain the product with the highest sugar content. This, in turn, leads to higher profits for the farmers, ultimately improving their quality of life.

Noninvasive measurement with imaging technique is widely studied to inspect the quality of agricultural product such as banana [1], apple [2], pear [3], and pomegranate [4]. The technique is categorized in non-destructive method and has multiple advantages that is suitable for real-time measurement. This method is nondestructive, contactless, sensitive, time-saving, and labor-saving [5]. Noninvasive technique using microwave imaging has received extensive attention to inspect and estimate quality of agricultural products [6,7]. This approach aims to map microwave energy interactions with dielectric objects into images by means of interrogating electromagnetic waves. According to inverse scattering relations, scattered electric field depends on the dielectric properties of the material under test.

The major component of sugarcane consists of water and sugar content, which these compositions make sugarcane behave like dielectric material in electric field [8]. Thus, the sugar content estimation of sugarcane compared to variation of dielectric properties by using microwave imaging technique is interested in this research. The objective of this article is to simulate the sugar content estimation of sugarcane using imaging technique. The dielectric constant related to variation of sugar content in sugarcane is implemented to indicate the position of sugarcane sample in the image.

2. Method

This section describes the entire processes of simulation of imaging technique for sugar content estimation based on dielectric constant as following the flowchart in Fig. 1. Image reconstruction by using fanbeam projections technique is employed in this article, which consist of Radon Transform and filtered back projection (FBP). The main processes consist of configuration of simulated area under test, determination of number of antenna, image reconstruction, and image validation. The simulation process is operated by using MATLAB program.

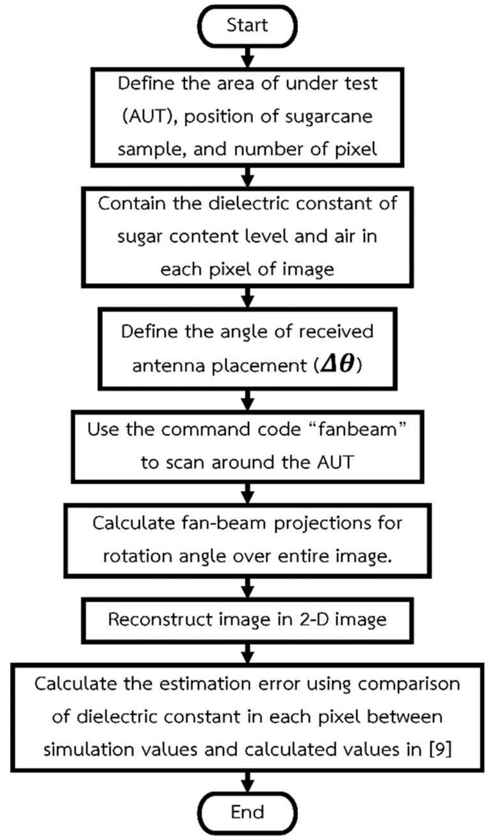

Fig.1 The flowchart of the simulation of sugar content estimation for sugarcane using imaging technique.

2.1 Configuration of area under test (AUT) and cane sample.

The area under test (AUT) is defined to a circular area with diameter of 40 cm, which is determined by near- field distance of 8 GHz related to average diameter of sugarcane (3.75 cm). There are five sugarcane samples each having a diameter of 5 cm at the center of the AUT as shown in Fig.2. The geometry of entire structures in circular AUT is depicted in Fig. 3a. To determine the resolution of the reconstructed image, the AUT is divided into numerous tiny square areas, illustrated in Fig. 3b. Each square area, referred to as a "1 pixel", contributes to the overall resolution. The image resolution is specifically set at 512x512 pixels, with each pixel representing dimension of 0.78x0.78 mm^2. The pixel in sugarcane sample area (indicated by the green color in Fig. 3) is contained dielectric constant of investigated sugar content, calculated using the Cole-Cole equation in [9]. Conversely, the remaining area outside the sugarcane sample contains the dielectric constant of air $(\varepsilon_{air} = 1)$.

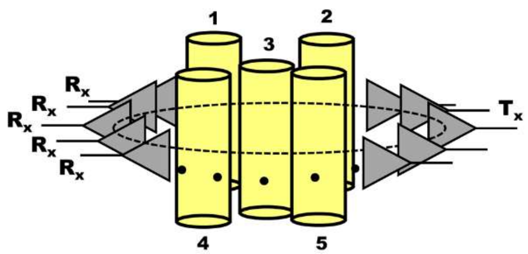

Fig. 2 The simulation setup of imaging technique.

2.2 Determination of number of antenna for image resolution.

The multiple antennas are located surrounding AUT for transmitting and receiving the signal. The number of antenna is defined using the angle of each receiver placement $(\Delta\theta)$ and can be calculated as following equation.

$$N_{antenna} = \frac{360}{\Delta\theta} \quad (1)$$

It means that the increase of $\Delta\theta$ value affects to decrease the number of antenna. The number of antenna placing surround AUT directly affects to the resolution of reconstructed image due to analysis of more signal path. However, the large number of antenna causes the complex of imaging system. The suitable $\Delta\theta$ value that provides good agreement for estimating sugar content is analyzed by comparing the resolution of each reconstructed image with the same dielectric constant of cane sample, which is constant as $\varepsilon' = 45$.

2.3 Image reconstruction processes

The transmitted signal with the beam width of 90° of the first transmitter moving through the cane sample area and then the scattered signal from the sample is gathered by receivers at opposite side as expressed in Fig.3c. After that, the second transmitter next to the first one generates the new signal and then the scattered signal from the sample is gathered by receivers at opposite side. Then, the processes are repeated until the last transmitter. The data of each signal path is computed and expressed as a sinogram that refers to a two-dimensional plot. It represents the data obtained from an imaging system. The data represents the measurements of the images obtained from different angles or directions. It is typically acquired by capturing the integrated intensity of the image along a set of parallel or fan-beam paths. The data of sinogram is implemented to reconstruct the image, which contains by the calculated dielectric constant in each pixel.

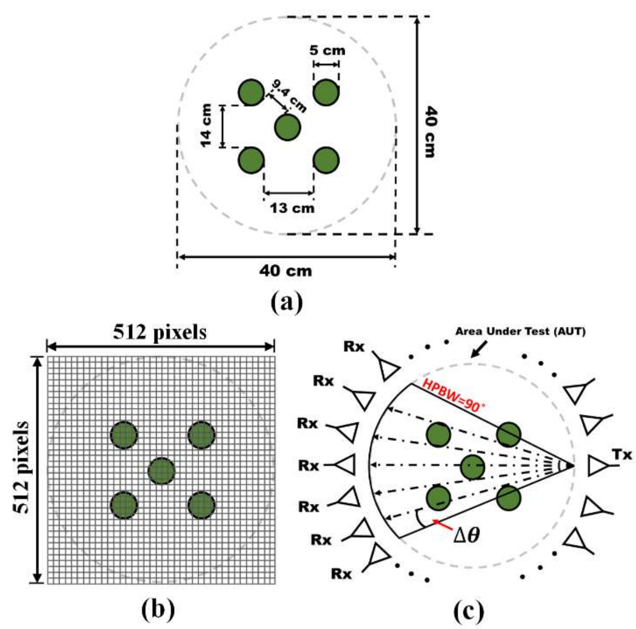

Fig.3 Top view of AUT; (a) geometry of AUT, (b) pixel separation, and (c) fan beam simulation.

2.4 Validation of reconstructed image

In order to validate the accuracy of sugar content estimation using the imaging technique, the percentage error of prediction is expressed as following equation.

$$\%error = \frac{\left|\varepsilon'_{actual} - \overline{\varepsilon}'_{image}\right|}{\varepsilon'_{actual}} \times 100 \quad (2)$$

where ε'_{actual} is actual dielectric constant of sugar content and $\overline{\varepsilon}'_{image}$ is the average of obtained dielectric constant in each pixel that is within cane sample area of reconstructed image. To improve the accuracy of sugar content estimation, the comparison of calculated $\overline{\varepsilon}'_{image}$ with two different investigated pixel areas consisting of the whole area and the core area of sample is also analyzed. The dielectric constants applied in this process are 50.77, 48.60, 46.47, 44.18, and 41.83 that are relate to sugar content of 9, 12, 15, 18, and 21°Brix in sugarcane, respectively. These sugar content are covered the actual sweetness range of sugarcane.

3. Results and discussions

3.1 The determination of suitable $\Delta\theta$ value.

To obtain the suitable antenna placement around the AUT defined by $\Delta\theta$ values, the $\Delta\theta$ values varied from 1° to 9° are analyzed and simulated. When all antennas fully transmit the signal to the AUT, the sinogram of nine different angles of $\Delta\theta$ are depicted in Fig. 4. The decreasing of $\Delta\theta$ value, which is the increase number of antenna, can gather more signal path noticed from the smoothness of image. The reconstructed images from sinogram are presented in Fig. 5. The resolution of image is increased when the $\Delta\theta$ value is decreased. It means that the use of more receiving antenna makes reconstructed image with high resolution. In variations of the $\Delta\theta$ value from 1° to 4° in Fig. 5(a)-(d), respectively, the position and obtained dielectric constant of cane sample are similar to the actual ones especially $\Delta\theta = 1°$. However, the large number of antenna with low $\Delta\theta$ value causes the complex design of microwave imaging system. In case of the $\Delta\theta$ value from 6° to 9° in Fig. 5(f)-(i), respectively, although these images can be clearly expressed the position of cane sample, the obtained dielectric constant in sample area is too fluctuated. Table 1 lists the calculated percentage errors of each sample position in reconstructed image with investigated $\Delta\theta$ value from 1° to 9°. The errors of $\Delta\theta$ values from 6° to 9° are larger than 30%. Considering the errors of $\Delta\theta$ values from 1° to 5°, decreasing $\Delta\theta$ value provides lower error but more number of used antenna. Hence, the $\Delta\theta$ value of 5° is a representative value to estimate sugar content in imaging technique.

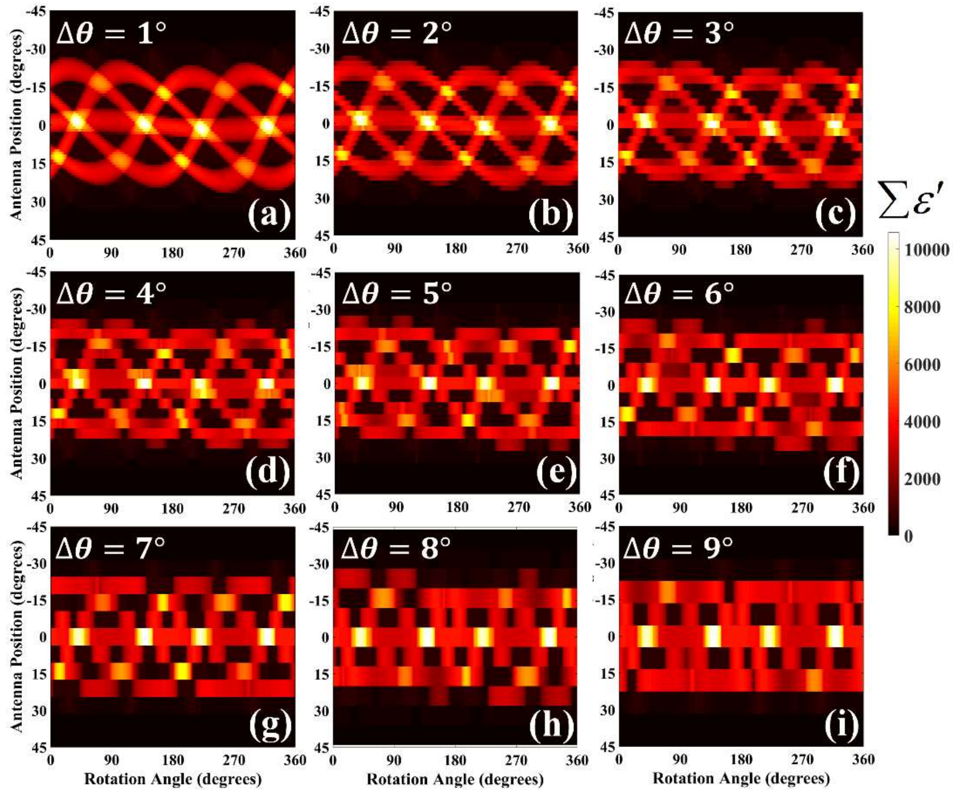

Fig.4 The sinogram results of different $\Delta\theta$ values.

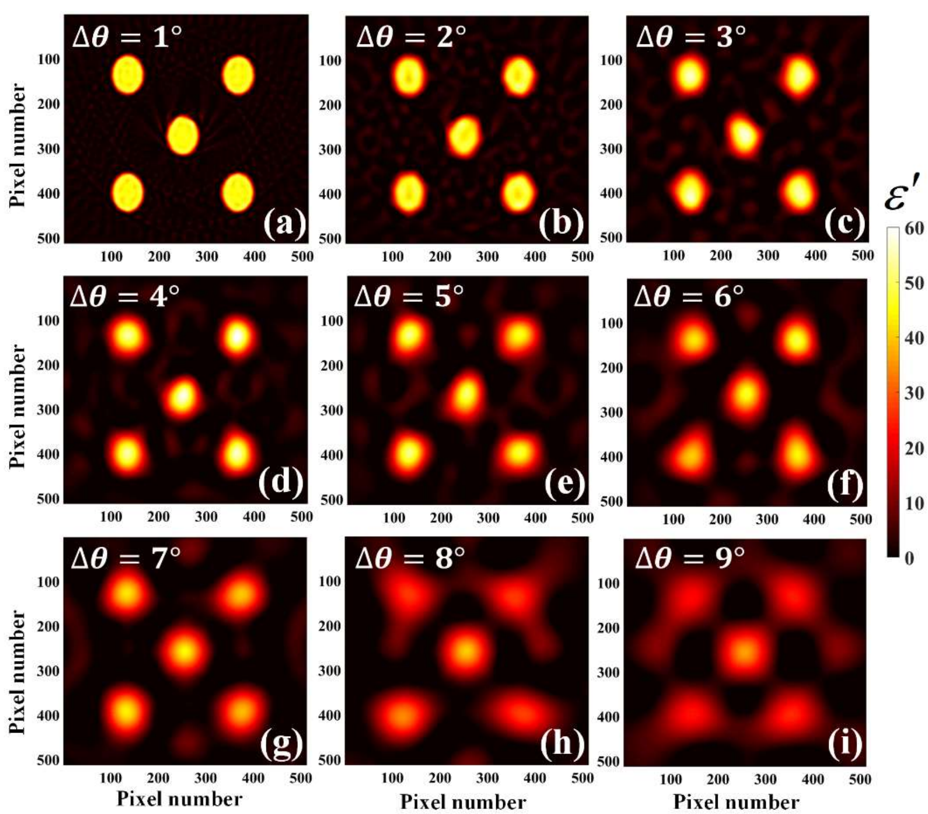

Fig.5 The reconstructed image results of different $\Delta\theta$ values.

Table 1 Calculated percentage errors of each sample position in reconstructed image with given $\Delta\theta$ values

Calculated percentage error (%)									
Position of sample	**Angle between antenna (degree)**								
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
1	9.3	13.9	20.0	22.2	25.5	36.0	32.5	51.1	59.0
2	9.4	13.3	17.3	20.5	30.5	27.8	36.7	52.2	56.7
3	9.2	14.1	19.5	20.9	25.9	30.2	33.4	36.8	41.7
4	9.4	14.3	18.1	22.3	23.8	35.3	29.2	43.1	57.7
5	9.3	12.8	17.5	21.1	29.5	28.9	39.6	52.4	54.8
All positions	**9.3**	**13.7**	**18.5**	**21.4**	**27.0**	**31.6**	**34.3**	**47.1**	**54.0**

3.2 Sugar content estimation from reconstructed image.

To validate the accuracy of the technique when the $\Delta\theta$ value is 5°, the five different sugar contents of samples consisting of 9, 12, 15, 18, and 21 °Brix are defined as shown in Fig. 6. The particular dielectric constant at each position represents each sugar concentration of sugarcane when it is under an electric field, which is calculated by equations in [9]. When the scanning is done, the result of reconstructed image clearly expresses the five positions of sugarcane sample as shown in Fig.7. The color bar in Fig.7 indicates the calculated dielectric constant contained in each pixel in the image, which is obtained from scanning processes. However, the edge of sample in each position is quite fade away (shown light red color), It results to the obtained dielectric constant extremely differ from the actual value. That is because the contrast of dielectric constant at the edge of medium between sugarcane sample and air is too large.

To validate the accuracy of the simulation, the two different methods for estimating the simulation errors of obtained images are presented in Figs. 7(a) and (b). The first error estimation is computed by using the average dielectric constant in each sample area compared to the actual value of each position. For the second case, the scope of error estimation is reduced closed to the core of sample area. The errors of two methods are calculated by using equation (2). The comparisons of two estimations are presented in Table 2. The simulation errors of first method are larger than 20% for every given sugar content (up to 27.66% for 12 °Brix). For the second method, the errors are clearly reduced for every investigated sugar content. The highest error of the second method is 7.24% for 18 °Brix. The error reduction of the second method is because the uncertain dielectric constant at the edge of sample area is eliminated.

The proposed technique utilizes the analysis properties of microwave imaging to estimate sugar content in sugarcane, which is one of challenging method for precise agriculture. Since the main strengths of the proposed technique, including depth of measurement, multiple sample test, and high sensitivity, is suitable to apply for sugarcane inspection. However, the design of microwave imaging system is complex and challenging. Comparing with the previous technique such as Near-field Infrared (NIR), although it provides high accuracy for sugar content measurement, the external light disruption is the major limitation that increase measurement error. For the future work, the proposed technique will be developed and applied to the microwave imaging system and test with real sugarcane.

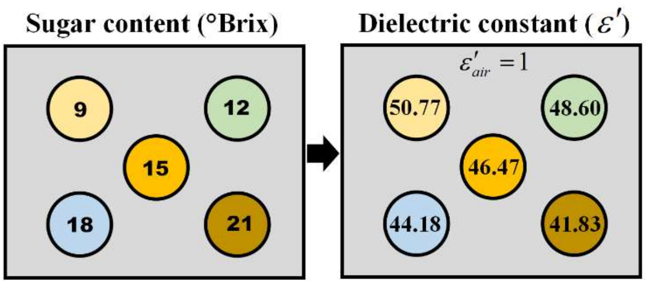

Fig.6 Configuration of dielectric constant correlated to given sugar content of sugarcane at 12 GHz in the AUT.

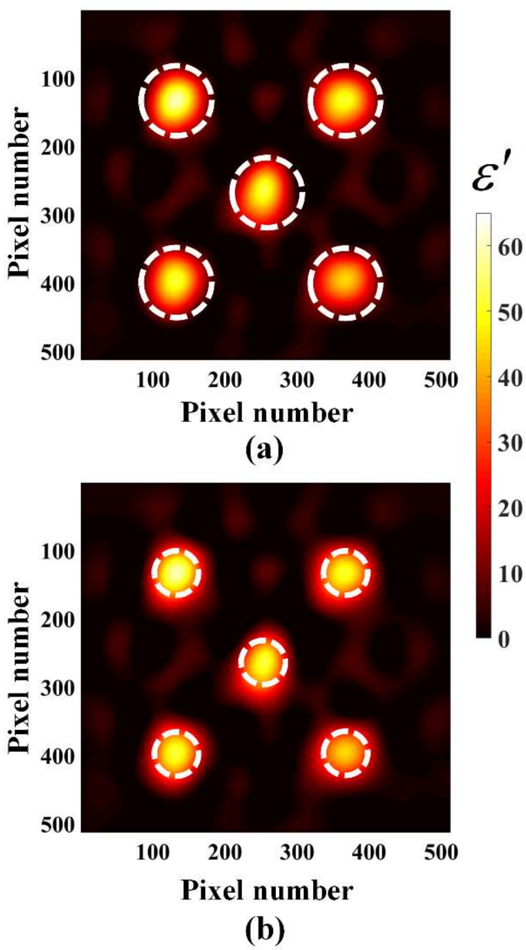

Fig.7 The reconstructed images with specific scope (white dash line) for error estimation; (a) entire sample area and (b) core of sample area.

Table 2 The estimation error for different investigated area of sample.

Sugar concentration (°Brix)	The simulation error (%)	
	Entire sample area	Core of sample area
9	23.07	6.38
12	27.66	3.67
15	22.93	2.11
18	21.23	7.24
21	27.14	1.97

4. Conclusion

The simulation of sugar content estimation of sugarcane based on dielectric properties for microwave imaging technique is proposed in this research. The suitable angle of each antenna placement is crucial to improve resolution and design the imaging system. The $\Delta\theta$ value of 5° is a representative for estimating sugar content in the simulation. The two methods with different the investigated area of cane sample in reconstructed image for estimating the simulation error are compared. It is found that the second method that is calculated using dielectric constant in the pixel near the core of cane sample area can improve the error. The method reduces the simulation error from 20% to 1.97-7.24% at given sugar content. In the future work, the proposed approach will be implemented within the context of a microwave imaging system, with subsequent testing conducted using actual sugarcane samples.

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