A 3-D Ray Tracing Model for Short-Range Radar Sensing of Hand Gestures

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Abstract—**In this paper, a three-dimensional (3-D) ray tracing model is presented for touchless sensing of hand gestures using a microwave or millimeter-wave radar. The model was built up based on radar range equation by analyzing the electromagnetic waves transmitted to the target hand and reflected from the numerous scattering points on the hand. The detailed mathematical approach for building up the 3-D ray tracing model was discussed, including both nonlinear phase modulation and linear phase demodulation of the gesture motions. Simulation results show that the proposed 3-D model can be used to accurately predict the complex motions of the action gestures.**

Keywords—hand gesture, ray tracing, radar, wireless sensing.

I. INTRODUCTION

The short-range radar system owns merits such as high-precision positioning and high-accuracy displacement sensing, which makes it a good option for noncontact sensing of hand gestures for human-computer interaction (HCI) [1]–[3]. Radar sensing of the hands' action gestures brings a lot of convenience and revolutionizes the way we humans interact with machines. For example, gestures together with speech may provide a more natural and intelligent way of HCI [4]–[5]. Moreover, due to the advancement of semiconductor technologies, nowadays it is possible to integrate the entire radar system on chip [6]. The working principle of radar sensing of hand gestures is that the hand will reflect part of the electromagnetic waves emitted from the radar. The motion information of the hand will be modulated in the reflected signal, which is essentially nonlinear phase modulation [2]. With linear phase demodulation techniques, the gesture motions can be reconstructed [2].

In short-range radar sensing of hand gestures, the subject hand is close to the radar sensor so that it cannot be modeled as a point scatter. Instead, it could be divided into hundreds of thousands of point scatters. Therefore, the hand model could be equivalent to the superposition of the numerous point scatters. Additionally, in radar gesture sensing, there are scenarios where only the finger is moving, while the rest of the hand is still. In this case, the radar will still simultaneously receive the electromagnetic (EM) reflections from both the moving and stationary parts of the hand.

Most of the existing demodulation algorithms for short-range radars are derived based on the assumption that the object is a point scatter [7] and the study on a 3D model for gesture sensing hasn't been discussed in details yet. In this paper, a 3-D ray tracing model for short-range microwave and millimeter-wave hand gesture sensing is introduced. The reflected EM waves from different parts of the 3-D hand model, which contains the motion information of the action gestures, are analyzed and simulated based on the working principle of the continuous wave Doppler radar. The proposed 3-D ray tracing model is beneficial for optimizing the radar system for gesture sensing by allowing prediction of the complex gesture motions and analyzing the system's specifications before it is actually fabricated. Simulations for sensing the palm and the fingers' movements were carried out based on the proposed 3-D ray tracing model and the results demonstrated the efficacy.

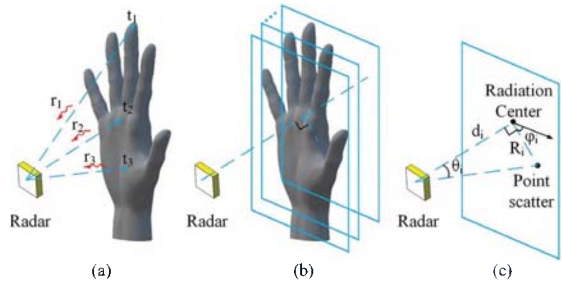

Fig. 1. (a) A radar sensor transmits a broad radiation beam that covers the entire hand. The radar received signal is the superposition of reflections from all the point scatters on the band, (b) the hand model can be divided into numerous planes, and (c) the equivalent polar coordinate system on one of the planes.

II. THREE-DIMENSIONAL HAND MODEL

The 3-D human model used in this paper can be regarded as a collection of numerous points. A human hand model built in 3d Max is imported into MATLAB and stored in the form of a three-dimensional matrix. The value "1" in the three-dimensional matrix represents the sampling points on the surface of the human hand, while the value "0" represents points behind the surface so that they do not reflect electromagnetic waves.

As shown in Fig. 1 (a), the hand model can be divided into numerous scattering centers and each scattering center can be modeled as a point scatter. The 5.8 GHz and 60 GHz patch antenna arrays spaced by half the wavelength were used in this paper. The EM waves illustrated as $t_1, t_2, t_3, \ldots, t_n$ hit the different point scatters on the hand, and get reflected (illustrated as $r_1, r_2, r_3, \ldots, r_n$) back to the receiving antenna.

Assuming that the hand model is in the boresight of the antenna so that it can be divided into different planes perpendicular to the maximum radiation direction of the antenna and each plane contains part of the points on the human model, as shown in Fig. 1 (b). Taking the antenna's radiation center on each plane as the pole, the polar coordinate system can be established for each plane perpendicular to the antenna's maximum radiation direction. For each point scatter, the polar diameter R_i and polar angle φ_i can be obtained, as shown in Fig. 1(c). The pattern of a planar antenna array can be equivalent to the product of the patterns of two orthogonal linear arrays [8]. Since the hand is illuminated by the broad radiation beam, the antenna gain G_i

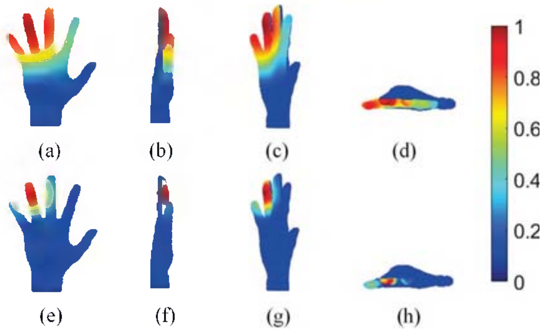

Fig. 2. The ray-tracing simulation for radar gesture sensing at a distance of 50 cm. The normalized intensity of the received EM radiation on the surface of the hand model using a 2 × 2 antennas array is shown in (a) front view, (b) side view, (c) side view, (d) top view; The normalized radiation intensity on the surface of the hand model using a 4 × 4 antennas array is shown in (e) front view, (f) side view, (g) side view, (h) top view.

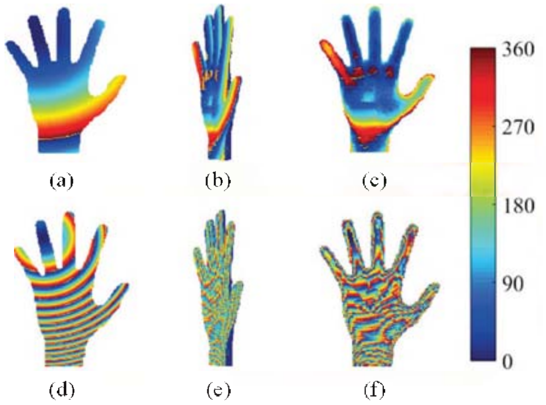

Fig. 3. The phase offset on the hand's surface when the working frequency is (a)/(b)/(c) 5.8 GHz or (d)/(e)/(f) 60 GHz. (a) and (d) are calculated on a flat surface, while the others are calculated with the 3-D hand model.

in the three-dimensional space can be obtained from the antenna array model [8]. Then the intensity of the received EM radiation I_i at the point scatter i can be obtained by (1):

$$I_i = \frac{G_i \cdot \cos(\theta_i)}{d_i^2 + R_i^2} \tag{1}$$

, where d_i is the distance from the plane where the point scatter resides to the antenna and θ_i is the angle between the normal of the plane and the direction from the antenna to the point target, which can by calculate by (2):

$$\theta_i = \arctan(R_i/d_i) \tag{2}.$$

It should be noted that the intensity of the received EM radiation on the point scatters blocked by the proceeding point scatters in the direction along the antenna toward the hand were set to zero. The normalized intensity of the received EM radiation on the surface of the hand model is shown in Fig. 2. As can be seen in Fig. 2 (a) and (e), the radiation coverage of a 4 × 4 antenna array is more focused around the radiation center on the ring finger than that of a 2 × 2 antenna array. Fig. 3 illustrates the phase offset on the hand's surface when the working frequency of the antenna array is 5.8 GHz or 60 GHz. The phase offset on the hand when the hand is a flat surface is also shown in Fig. 3 (a) and (d). It can be seen that as the operating frequency goes higher, the phase offset changes more drastically. Moreover, the uneven surface has introduced more complex phase changes.

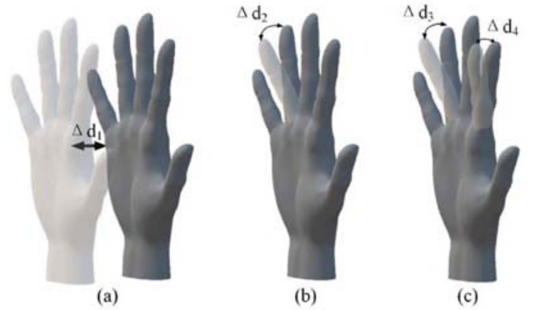

Fig. 4. (a) The entire palm performs a sinusoidal motion with a frequency of 1 Hz and an amplitude of 10 mm; (b) the ring finger performs a sinusoidal motion with a frequency of 1 Hz and an amplitude of 10 mm; (c) the ring finger performs a sinusoidal motion with a frequency of 1.2 Hz and an amplitude of 10 mm while the index finger performs a sinusoidal motion with a frequency of 0.6 Hz and an amplitude of 10 mm.

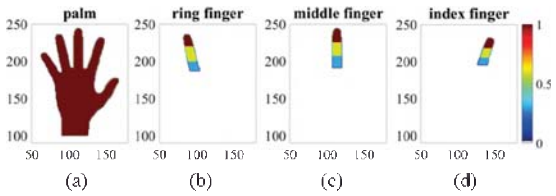

Fig. 5. The correlation coefficient matrix for (a) the palm movement, (b) the ring finger movement, (c) the middle finger movement, and (d) the index finger movement.

Based on the three-dimensional hand model, EM waves are reflected and captured from different parts of the hand. It can be assumed that the normalized intensity of the received EM radiation on the palm surface is the propagation loss of the signal. So, for every point scatter on the hand, the reflected signal can be calculated by (3) according to [7]:

$$Signal_i = I_i \cdot e^{mod(4\pi * x_i, \lambda)} \tag{3}$$

, where x_i is the distance from the point scatter to the antenna considering the motion m_i. Assuming that the direction of motion is aligned with the boresight of the antenna, x_i can be written as:

$$x_i = \sqrt{\left(d_i + m_i(t)\right)^2 + R_i^2} \tag{4}.$$

From the ray-tracing standpoint, the total signals received by the antenna are equal to the summation of the reflections from all the scattering points on the hand, as shown in (5):

$$Signal = \sum_{i=1}^{n} Signal_i \tag{5}.$$

In the simulation, the real and imaginary parts of $Signal$ are regarded as the quadrature signals I and Q, respectively. By leveraging the extended differentiate cross-multiply (DACM) algorithm, I/Q signals may be combined to reconstruct the phase evolution for the target gesture motions without causing any phase ambiguities [7].

III. Simulation Results

Three kinds of action gestures are simulated with the 3-D ray tracing model and each movement is in the radical direction of the antenna radiation. The antenna used in the simulation is a 2×2 patch antenna array at 5.8 GHz. As shown in Fig. 4, the first movement is the palm performing a sinusoidal motion with a frequency of 1 Hz and an amplitude of 10 mm. The second movement is the ring finger performing a sinusoidal motion with a frequency of 1 Hz and an amplitude of 10 mm. Considering that the movement of the ring finger will drive the movement of the middle finger, it can be assumed that the middle finger will simultaneously perform a sinusoidal motion with a frequency of 1 Hz and an amplitude of 5 mm. The third movement is a complex motion, in which the ring finger performing a sinusoidal motion with a frequency of 1.2 Hz and an amplitude of 10 mm while the index finger performing a sinusoidal motion with a frequency of 0.6 Hz and an amplitude of 10 mm.

Considering that the amplitude of the movement differs along the finger, four correlation coefficient matrices were introduced and the plane corresponding to the matrix is perpendicular to the boresight of the antenna, as shown in Fig. 5. The product of the matrix and the sinusoidal movement is the actual movement of the corresponding point scatter. As can be seen in Fig. 5 (b), (c) and (d), the closer to the fingertip, the greater the amplitude of the movement, which is the same as the practical case. The received signals were processed to reconstruct the trajectory of the gesture motions. Fig. 6 illustrates the normalized spectra of the simulation results including the reconstructed phase evolution representing the gesture motions.

A. *Palm's movement*

As shown in Fig. 6 (a), the reconstructed palm movement is almost exactly the same as the original motion, except for a little attenuation in amplitude, which is caused by the effect of multiple scattering points because the EM reflections from different point scatters were added up with different phases.

B. *Finger's movement*

As shown in Fig. 6 (a), the frequency of the reconstructed finger's movement is the same as the original movement, but the amplitude differs. This is because the reconstructed movement represents the weighted summation of the motions of all moving scattering points on the hand.

For two fingers' movement, as shown in Fig. 6 (b), the reconstructed gesture motion is the superposition of two movements with variations in the amplitude. In addition, it is obvious that the signal is peaked at 1.2 Hz and 0.6 Hz because the complex motion contains two frequency components.

IV. Conclusion

A 3-D ray tracing model for short-range microwave and millimeter-wave hand gesture sensing is introduced to simulate the backscattered EM waves from different parts of the 3-D hand model. The signal received at the radar is modeled as the superposition of the EM reflections from different parts of the hand. The simulation results verify the efficacy of the proposed 3-D ray tracing model, which would be beneficial for optimizing the radar system for gesture sensing.

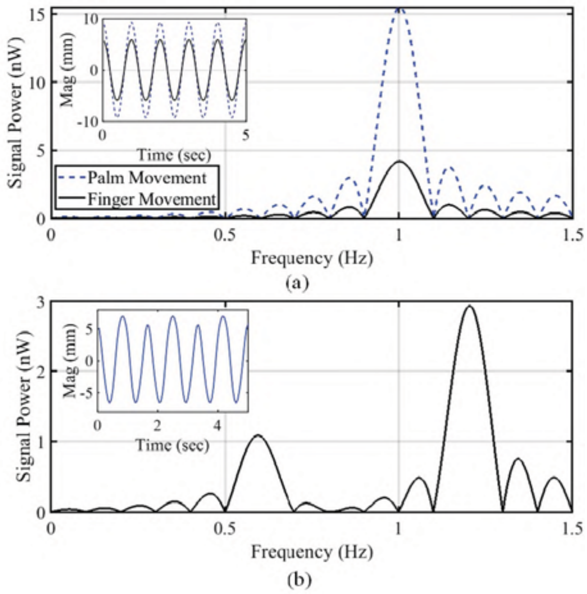

Fig. 6. The spectra of the received signal and the reconstructed movements: (a) the entire palm or the ring finger performs a sinusoidal motion with a frequency of 1 Hz and an amplitude of 10 mm, and (b) the ring finger performs a sinusoidal motion with a frequency of 1.2 Hz and an amplitude of 10 mm while the index finger simultaneously performs a sinusoidal motion with a frequency of 0.6 Hz and an amplitude of 10 mm.

Acknowledgment

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