Prediction and Simulation of FMCW Radar Hand Gesture Detection based on Captured 3D Motion Data

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***Abstract*—This paper presents a novel frequency modulated continuous wave (FMCW) radar response simulation method with a focus on human gesture detection. Through use of 3D motion captured by an infrared (IR) camera system and data processing, a realistic and computationally efficient simulation is produced. The gestures considered are a hand raise (up-down), right-left arm sweep, and push forward. The high efficiency in simulation is due to a simplified yet effective approach to radar cross section (RCS) calculation and radar-detected signal integration. This allows for the simulation to run smoothly while still resulting in realistic approximations of both range profile and doppler response of gestures. The simulated results are validated with experimental results detected by an Infineon 60-GHz radar.**

Keywords—frequency modulated continuous wave (FMCW) radar simulation, radar cross section (RCS), range profile, Doppler spectrogram, human gesture recognition

I. Introduction

Human gesture recognition has been a focus of human machine interfacing for years [1]. Several types of technology have been considered for the capturing of this data from optical cameras to VR handsets. Gesture recognition using radar tracking has many advantages that other forms of gesture capturing lack. Radars are less susceptible to light as well as on average being smaller to install. The implementation of gesture recognition into home and personal appliances (such as television, media centers, mobile devices, and wearables) would allow for a wider range of accessibility and ease of use for their users. The ability for unobstructed monitoring of motion allows for more natural recording of data for study in the medical and kinesiology field. Along with less privacy concerns for the subjects involved due to no physical contact. To this end, this paper explores a novel simulation method for prediction and study of human micro doppler responses from frequency modulated continuous wave (FMCW) radars.

The simulation uses 3D motion captured data to predict the returns. The data used for this simulation was captured using an IR camera setup from the Texas Tech University Mechanical Engineering department. The captured 3D motion data was used to both get accurate 3-dimensional (x, y, z) data as well as being able to create time averaged human motions from multiple distinct body types by averaging the data returned for certain points along the subject's arm to create generalized behavior for points along a human arm during the gestures. The averaged points generated are then used in conjunction with a different approach from previous works [2] to radar cross section (RCS) and radar-detected signal construction to create a computationally efficient and realistic output. The simulation output is then compared against experimental data obtained using the Infineon BGT 60 GHz radar sensor to check validity and accuracy of the proposed method.

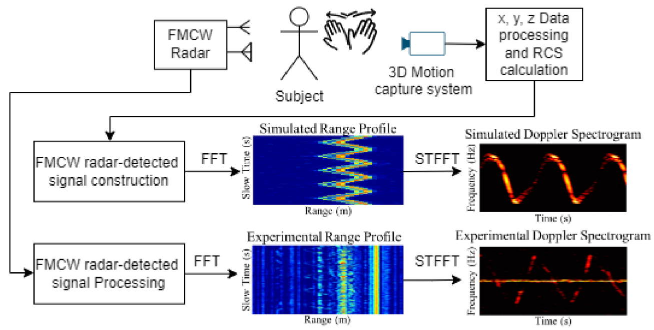

Fig 1. Setup for radar gesture recognition simulation and verification.

II. Theory and Simulation Setup

A. Setup for This Study

The movement of objects induce a change in frequency when observed with an FMCW radar. These changes in frequency allow for the finding of the range of objects to the radar (range profile). The velocity of those objects over time (Doppler spectrogram) can be further derived from this change in frequency. The scene under consideration for this study was of a subject sitting 90° in front of the radar at around 2.2 m performing the gestures, as shown in Fig. 1. In this position the subject performed three distinct gestures captured by the 3D motion capture system. The gestures captured were hand-raise, right-left arm sweep, and push forward. These gestures were tracked by reflective points placed along the arm. The radar readings for the gestures performed were taken in the 3D motion capture room, then again in front of the absorbent wall

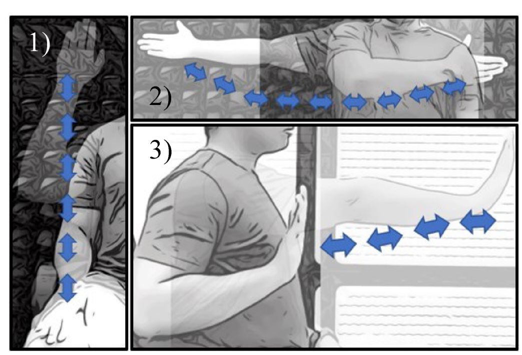

Fig. 2. Diagram of human gesture; 1) Hand-raise, 2) right-left sweep, and 3) push forward.

Table I. Subject arm dimensions.

Subject:	1	2	3
Height (feet, inches):	5' 8"	6' 2"	5' 8"
Hand length (m):	0.197	0.2	0.191
Hand Radius (m):	0.057	0.051	0.054
Forearm Length (m):	0.279	0.3	0.254
Forearm Radius* (m):	0.043	0.048	0.035
Bicep Length (m):	0.305	0.32	0.305
Bicep Radius* (m)	0.044	0.067	0.038
Total Arm Length (m):	0.781	0.82	0.75

a. The (*) on the table represent that the data shown in those rows is for the center of mass for the point in question. For other point along the body a different radius was found corresponding to it.

pictured in the background of Fig 2. The 3D captured data was then split into 3-dimensional data (x, y, z) as well as converted into the radial displacement to the radar (R) for each point. The data for each point along the arm were then averaged between the three volunteers during each captured time step to create an averaged representation of the three motions across different body types. The averaged gesture was then repeated and filtered to create a recreation of the performed motion. The radar configuration for the recordings used a center frequency of 61.25 GHz with a bandwidth of 2.5 GHz and a capture window of 10 seconds per gesture capture. The bandwidth of the chirps sent from the radar result in a range resolution of 6 cm. This range resolution makes it possible for the radar to differentiate between multiple body parts of the subject (i.e. hand, wrist, etc.). A depiction of the gestures performed as well as the some of the dimension of the people who performed them is shown in Fig. 2 and Table I respectively.

B. RCS Calculation

The averaged radial data and arm dimensions of the subjects were then used to calculate the target's RCS seen by the radar. For the RCS calculated in the simulation, a square plate approach proposed in [3] was implemented. For this approach the arm is split into *n* points with *t* number of time dependent positions. The initial points used came from the 3D motion capture system. To create a more realistic return, more points were then derived along the bones in the arm. All points were then put into the square plate RCS (σ) equation in simulation. The equation used is [3]:

$$\sigma_n(t) = \frac{4\pi a^4}{\lambda^2}\left[\frac{\sin(ka\sin\theta_n(t))}{ka\sin(\theta_n(t))}\right]. \quad (1)$$

The RCS found through this approach is a function of the time of observation (t) and θ the angle from the normal of the radar to the point of interest. The amplitude of the RCS is a function of the radius of the region (a) and the wavelength (λ). The "a" is considered constant for all times for a specific point relative to the radar. Some of the radius considered can be seen in table I. The angle used was calculated independently each time step using the law of cosines. This allows for the angle to be created accurately from the data simulated, and 3D motion captured. This found angle is responsible for controlling the envelope of the sine functions in the equation (1). The wavevector (k) is

$$k = \frac{2\pi}{\lambda}, \quad (2)$$

which is a frequency-dependent variable that represents the number of waves present in one unit length. The use of averaged data allows for a generalized RCS to be returned for each point. This approach to RCS calculation is less computationally intensive in comparison to previous works in this area [2], while offering comparable experimental authenticity. The reduced tax on computation is due to the RCS being calculated with a 1st degree approximate equation. This approach also allows for simplistic solving for unknown variables in this circumstance.

C. Radar-Detected Signal Construction

The derived RCS is then used in conjunction with a modified radar-detected signal ($S_b(t)$) based on a combination of [4] and [5] to create an approximation of the received beat signal from the FMCW radar. From these two equations the superposition principle was then applied to consider the returns from multiple points along the target. The resulting equation is:

$$S_b(t) = \sum_n \sum_m \sigma_n * exp\left(2\pi i\left(\left(\frac{2\gamma R(n,m)}{c} + \frac{2f_c v(n,m)}{c}\right)t + \frac{2f_c R(n,m)}{c}\right)\right). \quad (3)$$

This equation is an application of two summations. The first being for the superpostion of multiple targets (n). While the second summation is for the total chirps in the transmitted signal (m). The RCS calculated in section II.B is integrated as the magnitude of the returned signal. The exponential in the equation represents a complex signal created from both the transmitted and recieved FMCW signals mixed. The frequency component of the signal is formed though a combination of the range and velocity dependant parts. The range section is a function of the slope of the chirps(γ) and the recorded range of the target (R). The chirp slope is found using the bandwidth of the signal and the time elasped during the chirp. The

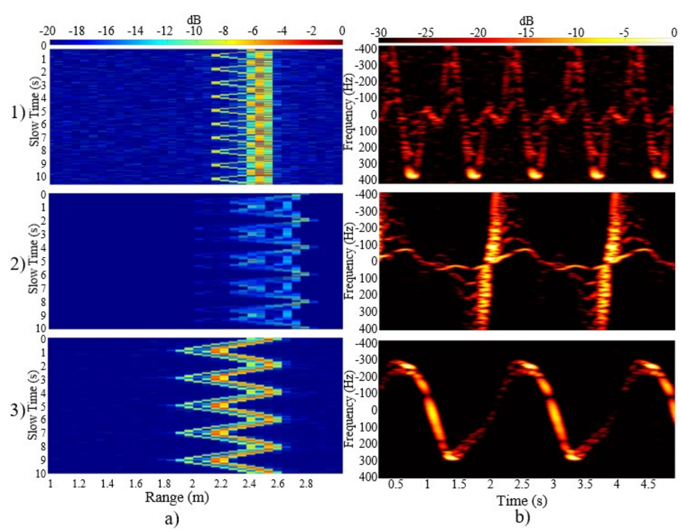

Fig 3. Simualted FMCW reponse of: 1) hand-raise, 2) right-left sweep, 3) push forward with a) range profiles and b) Doppler spectrograms.

characteristics used for the chirp mirrored the ones used in the setup of the experimental test described in section II.A. The construction of the received radar-dected signal allows for the processing and treatment of simulated data like experimental data received from a conventional FMCW radar. Specifically, this allows for the use of conventional data processing techniques. The realism of the returned simulation is due to the RCS found as well as addition of a level of envirmental noise to the signal. This creates a more accurate retun of power from the arm. The constructed radar-detected signal is then ran through conventional processes to create the resultant range profile and Doppler spectrogram of each gesture. The created plots are shown in Fig. 3 for each motion.

III. Validation with Experimental Results

The experimental results mentioned in section II.C were captured using the Infineon 60 GHz radar mentioned in section II.A. The gestures were all ran with a 60 Hz metronome to provide consistency from performance to performance. The frequency response of the measured gestures were then compared to the simulations. The experimental range profile and Doppler spectrogram are shown in Fig. 4. When compared against the simulated returns for the same gestures the behavior of the simulation closely follows that of real radar readings. Specifically in power behavior and strongest reflector. The range profiles of the simulation (Fig. 3, column a) are clearer than the experimental results (Fig. 4, column a) would be without filtering the data due to environmental noise and clutter. The Doppler spectrum shown however does relate clearly to the gesture simulated. The push forward motion is the clearest example of this with the predicted parts of the arm being the hand to mid-forearm region in conjunction with the bicep of the arm in the range profile. The spectrogram derived from the range bin corroborate this behavior with the strongest returns in doppler being from that region of the arm.

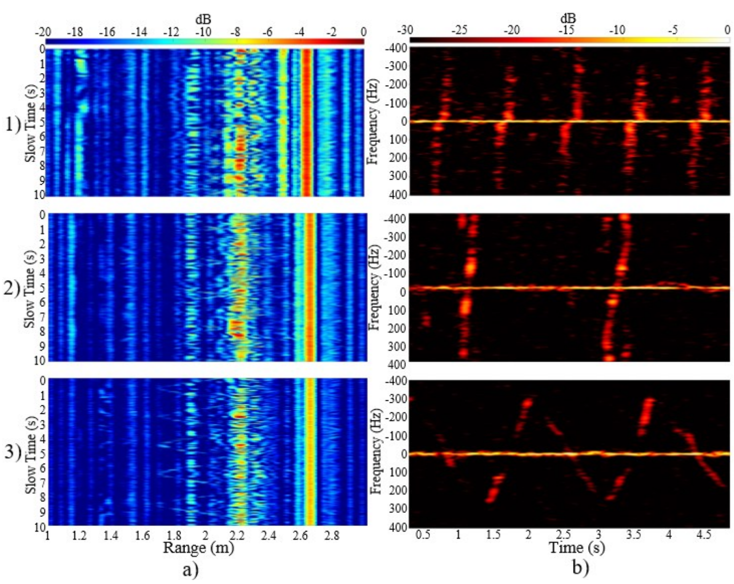

Fig 4. Experimental FMCW range profile and Doppler spectrogram from tested hand gestures: 1) hand-raise, 2) right to left, 3) push forward with a) range profile and b) Doppler spectrogram.

Another example is the simulation of the hand raise (Fig. 3. 1). It has the same shape of doppler response as the experimental result (Fig. 4.1). For the hand-raise the strongest returns are from the hand to mid forearm region of the subject's arm. This relationship between strongest reflector from simulation to experimental holds true for all tested gestures. The differences in the range profile and Doppler spectrogram are a function of clutter during the experiment as well as other environmental factors mention earlier. These differences are due to the simulation being an ideal environment in terms of targets, environmental clutter, and radar characteristics.

IV. Conclusion

In this paper a novel and efficient simulation method for FMCW radars is proposed. Using 3D motion captured data in combination with experimental environmental noise readings, a realistic simulation of radar returns for human gestures is produced. Due to a simplified approach to RCS calculation in conjunction with a modified radar-detected signal construction, the simulation runs relatively fast while returning appropriate approximations for the reflectors during gesture readings. The simulated returns from the tested gestures could allow for in-depth study into unique properties of the strongest reflectors during hand gestures. This could allow for the extraction of more specific and unique properties of gestures for classification. The approach proposed for radar-detected signal construction and RCS calculation allows for the relative rapid simulation of multiple inputs. The simulated responses of the gestures show clearly which part of the human body is responsible for the strongest returns for each gesture. To improve the accuracy of simulation, further development on noise and clutter representation could be the next step of this work.

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