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Automatic Tracking of Human Body Using Millimeter-Wave Adaptive Array Radar for Noncontact Heart Rate Measurement

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***Abstract*—Radar-based noncontact heart rate measurement is attracting increasing attention. However, the measurement accuracy is dependent on the position and posture of the target body. In this work, we generate radar echo waveforms using a physical optics approximation and a numerical human body model that was obtained using a depth camera. Millimeter-wave array radar is used to form an optimal antenna pattern directed towards the most dominant scattering center on the human body. We demonstrate that the proposed method can track a moving human body automatically and accurately, even when the body is in motion, thus enabling noncontact heartbeat measurement.**

***Index Terms*—adaptive arrays, array signal processing, biomedical applications of electromagnetic radiation, biomedical monitoring, millimeter wave radar, physical optics, radar tracking**

I. Introduction

Recently, remote heartbeat estimation technology based on ultra-wideband radar has been attracting increasing attention [1]. For example, researchers have reported that that the heart rate can be measured from human feet [2]. However, other reports have indicated that the accuracy of these measurements can be significantly compromised by its dependence on the posture and orientation of the target body during the measurement process. To analyze the mechanism that leads to this problem, it is necessary to specify the required echo reflection position on the human body surface.

In this study, we recorded a three-dimensional video of a moving human body using a depth video camera and performed electromagnetic scattering analysis using a physical optics (PO) approximation. In particular, based on the assumption that the measurements are intended to be performed when the subject is asleep, each participant was instructed to lie down and turn over on the floor during the measurement procedure.

In addition, we propose an adaptive array processing method that improves heart rate estimation accuracy and demonstrate that the proposed approach allows the array beam to follow the actual scattering center position automatically using a 16-channel 4×4 multiple-input multiple-output (MIMO) array radar system. The performance of the proposed method was evaluated using numerical experiments based on an actual three-dimensional depth video of a moving human body.

II. Numerical Experiments on Electromagnetic Wave Scattering

A. Electromagnetic Scattering Analysis using PO

In our measurements, a human body was recorded using a depth camera that acquires a group of points to represent the body's surface. We applied a PO approximation to this group of points to simulate realistic radar data [3]. In our simulations, the antennas were modeled as infinitesimal dipoles with lengths of $\mathrm{d}l$ and a vertical polarization that was located at the origin. In the transmitting antenna dipole, a sinusoidal electric current denoted by $Ie^{\mathrm{j}\omega t}$ is assumed, where I is the complex-valued amplitude of the current, t is time, and ω is the angular frequency. The target human body is modeled using a shape recorded in a depth video and the material of the body is assumed to be a perfect electric conductor.

The current density $\boldsymbol{i}$ induced on the body surface by the incident magnetic field $\boldsymbol{H}$ that is radiated by the transmitting antenna is approximated as

$$\boldsymbol{i} = 2\boldsymbol{n} \times \boldsymbol{H}, \tag{1}$$

based on the normal vector $\boldsymbol{n}$ on the human body surface [4].

Next, we derive the electric field radiated by the body surface current, which is approximated using Eq. (1). Because the receiving elements are assumed to be vertically polarized, the received voltage signal is modeled using the z-components of the electric field E_z at the receiving element positions. The received signal E_{R} can then be calculated using

$$E_{\mathrm{R}} = \iint_{S_0} E_z(\boldsymbol{r}_{\mathrm{R}}, \boldsymbol{r})\mathrm{d}S, \tag{2}$$

where S_0 represents the entire surface of the human body and $E_z(\boldsymbol{r}_{\mathrm{R}}, \boldsymbol{r})$ is the electric field due to the current at receiver $\boldsymbol{r}$ on the body. Therefore, the received signal is the vertical component of the electric field detected by the receiving elements $\boldsymbol{r}_{\mathrm{R}}$.

B. Estimation of Scattering Center on Human Body

The scattering center position is estimated using the technique proposed by Shijo et al. [4], which was based

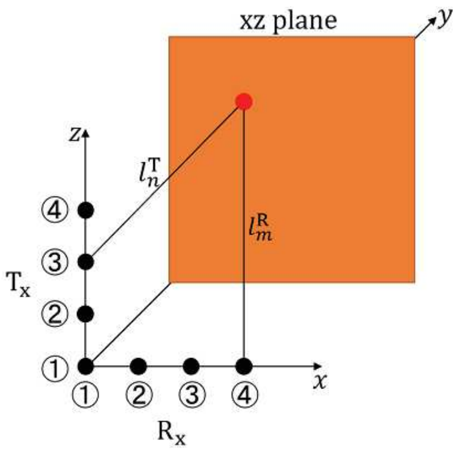

Fig. 1. Model of MIMO array radar and adaptive array signal processing system.

on the PO approximation. Shijo et al. used the weight function $w(\boldsymbol{r}_0,\boldsymbol{r})$ given by

$$w(\boldsymbol{r}_0,\boldsymbol{r})=\begin{cases}\frac{1}{2}(\cos(\pi|\boldsymbol{r}-\boldsymbol{r}_0|/a_0)+1) & (|\boldsymbol{r}-\boldsymbol{r}_0|\leq a_0)\\ 0 & (|\boldsymbol{r}-\boldsymbol{r}_0|>a_0).\end{cases} \tag{3}$$

By integrating the vertical component of the scattered electric field caused by the current at receiver $\boldsymbol{r}_0$ on the human body surface over the entire body surface S_0 using the form

$$E_z(\boldsymbol{r}_0)=\iint_{S_0} w(\boldsymbol{r}_0,\boldsymbol{r})E_z(\boldsymbol{r}_{\mathrm{R}},\boldsymbol{r})\mathrm{d}S, \tag{4}$$

we can obtain the received signal $E_z(\boldsymbol{r}_0)$ that arrives from a specific position on the target body surface. Using this technique, we can accurately locate the body part that is the most dominant contributor to the radar signal.

C. Adaptive Beamforming using Array Antenna

Next, we apply adaptive array signal processing techniques to the radar echo signals that were received using the 16-channel MIMO array radar system and investigate the performance of the proposed technique in adaptive formation of a beam focused on the actual scattering center on the human body. The system model is shown in Fig. 1. Four transmitting elements are located on the z axis and four receiving elements are located on the x axis with spacing equivalent to half the radar wavelength λ. The beam $G(x,y,z)$ that is formed on the x-z plane can then be calculated as follows:

$$G(x,y,z)=\sum_{n,m} w_{n,m}e^{\mathrm{j}k(l_n^{\mathrm{T}}+l_m^{\mathrm{R}})}\quad (n,m=1,\cdots,4), \tag{5}$$

where l_n^{T} and l_m^{R} are the distances between a position (x,y,z) and the transmitting and receiving elements, respectively, $w_{n,m}$ is a weight function, and the wavenumber $k=2\pi/\lambda$.

TABLE I
SPECIFICATIONS OF DEPTH CAMERA.

Resolution	512×424
Frame rate	30 fps
Measured distance range	0.5-8.0 m
Measurement accuracy	±3 mm
Horizontally measurable angle	± 35°
Vertically measurable angle	± 30°

We use the maximum eigenvalue method from [5] to determine the weight $w_{n,m}$ required in Eq. (5) to ensure that the beam is focused at the dominant scattering center position. First, we define the signal vector

$$\boldsymbol{x}(t)=\left(x_1(t)\ \ x_2(t)\ \ \ldots\ \ x_M(t)\right)^T, \tag{6}$$

where $M=4\times 4=16$, corresponding to all the MIMO channels. We then expand the covariance matrix $R_{xx}=\boldsymbol{x}(t)\boldsymbol{x}^H(t)$ to yield the eigenvalues in the form

$$R_{xx}=\left(\boldsymbol{v}_1\ \cdots\ \boldsymbol{v}_M\right)\begin{pmatrix}\sigma_1 & 0 & 0\\ 0 & \ddots & 0\\ 0 & 0 & \sigma_M\end{pmatrix}\begin{pmatrix}\boldsymbol{v}_1^H\\ \vdots\\ \boldsymbol{v}_M^H.\end{pmatrix} \tag{7}$$

Therefore, we obtain M eigenvalues, where $\sigma_1\geq\sigma_2\geq\ldots\geq\sigma_M$, and M normalized eigenvectors $\boldsymbol{v}_i$ $(i=1,2,\ldots,M)$. We then calculate the optimal beam pattern using $y(t)=\boldsymbol{v}_1^H\boldsymbol{x}(t)$, where eigenvector $\boldsymbol{v}_1$ corresponds to the largest eigenvalue σ_1. We assume ideal conditions under which each echo is incoherent with the other echoes for simplicity. The validity of this condition will be discussed as part of our future studies.

III. PERFORMANCE EVALUATION OF THE PROPOSED METHOD

A. Depth Video and Scattering Center on Human Body

A depth camera (Kinect for Windows v2, Microsoft Corporation, Redmond, WA, USA) is used to obtain a depth video of a human lying approximately 1.5 m away along the y axis. Table I lists the sensor specifications and Fig. 2 shows the actual measurement environment. When the three-dimensional video was recorded, the target person was wearing a skin-tight garment that covered their entire body to reduce the effects of wrinkles in their clothing. Fig. 3 shows a human body surface representation formed using a group of points. The resulting data were then resampled at intervals of 1.0 mm and smoothed using a Gaussian filter.

Next, using the method described in the previous section, we estimate the positions of the scattering centers on the human body surface. The transmission frequency was set at 60.0 GHz. The value of a_0 in the weight function $w(\boldsymbol{r}_0,\boldsymbol{r})$ of Eq. (4) was set at 9 mm. Fig. 4 shows the radiation power distribution obtained for the human body using the PO approximation. The figure shows that the largest echoes mainly return from the torso, head, and left arm.

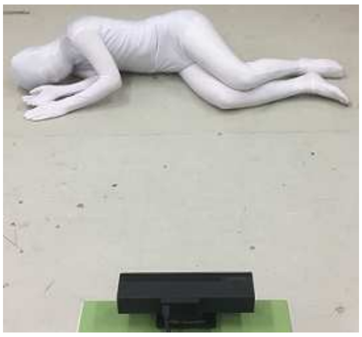

Fig. 2. Measurement setup with depth camera and participant lying on the floor.

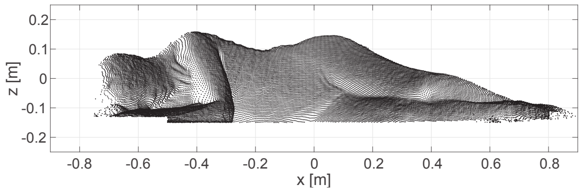

Fig. 3. Human body representation using a group of points.

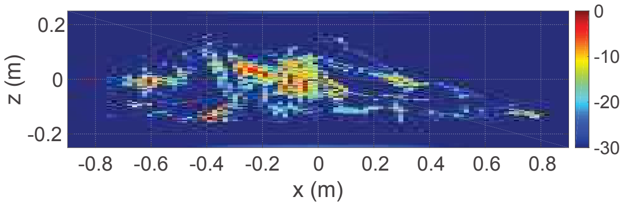

Fig. 4. Reflection position estimation using PO approximation (dB).

B. Application of Proposed Method to a Moving Human

To assess the feasibility of heart rate measurement during sleep, a test subject was instructed to lie on the floor and turn over from their right-hand side to their left-hand side. The recording took approximately 2.0 s. Fig. 5 compares the actual human body position with the direction of the maximum of the adaptive array beam. The root mean square (RMS) error was 1.47×10^{-2} m, which is sufficiently accurate for many applications and demonstrates the effectiveness of the proposed approach.

IV. Conclusion

In this study, an accurate human body model was generated by recording a three-dimensional video of a target human using a depth camera. First, we located the body parts that radiated the strongest echoes, which is important for improved heart rate measurement accuracy. Next, electromagnetic wave scattering analysis was performed using the PO approximation, and the locations of the radar scattering centers on the body were successfully identified. In addition, the maximum eigenvalue method was used to form an adaptive radar beam that can follow the position of the actual human body during motion. We

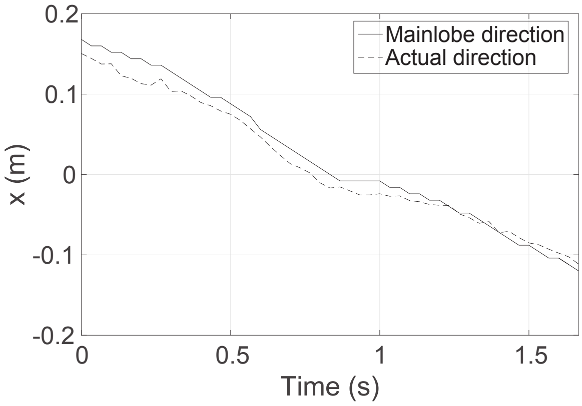

Fig. 5. Comparison of target human body position with adaptive array beam direction. The array beam tracks the actual target position successfully.

showed that the proposed approach can achieve remarkably accurate tracking with an RMS error in the human's lateral direction of less than 15.0 mm. The ranging accuracy required for measuring the heart rate is related to the error in the depth direction, which has nothing to do with the error in the lateral direction discussed above. The proposed technique will play an important role in enhancing the accuracy of noncontact heart rate measurement technology.

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