Radar-based Measurement of Pulse Wave using Fast Physiological Component Analysis

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***Abstract*—This study proposes a fast blind signal separation technique for human arterial pulse wave propagation measurement. One of the authors previously developed a blind signal separation method called physiological component analysis that uses mathematical modeling of the measured physiological signals, including the pulse wave propagation, and this method improves the signal separation accuracy when applied to array signal processing. Physiological component analysis, however, is known to require long computation times because it is based on high-dimensional global optimization. In this paper, we propose a method to reduce the dimensionality of the decision variables for the optimization process that uses the Schelkunoff polynomial method. Using this dimension reduction technique, we propose a new algorithm, called fast physiological component analysis, and the performance of this algorithm is evaluated using numerical simulations.**

***Index Terms*—array radar, Schelkunoff polynomial, pulse wave, physiological component analysis**

I. Introduction

To prevent cardiovascular diseases such as hypertension and atherosclerosis, constant monitoring and detection of the early signs of these diseases are essential. Therefore, it is important to establish a system for long-term monitoring of blood pressure and the condition of their blood vessels. An elastic wave called the pulse wave, which is synchronized with the heartbeat, propagates from the heart to the periphery. The pulse wave velocity (PWV) is known to be an important index for both arterial stiffness and blood pressure [1]–[7]. To enable PWV estimation, pulse wave signals are often measured simultaneously at multiple positions on the human body; the PWV can then be calculated from the time delay between two positions.

Contact-type sensors have commonly been used to measure the PWV [8]–[13], including photoplethysmography (PPG) sensors [14], microelectromechanical system-type sensors [15], smart glasses with three PPG sensors [16], and a combination of PPG, ballistocardiography, electrocardiography (ECG), and impedance cardiography (ICG) sensors [17]–[19]. Radar-based noncontact measurements have also been reported using a combination of 1 GHz microwave radar, ECG, ICG, and phonocardiogram sensors [20], [21], a combination of 900 MHz continuous wave radar, ECG, and PPG sensors [22], and a combination of a 2.4 GHz radar system and piezoelectric sensors [23]. Each of these studies used contact-type sensors in combination with a radar system; these approaches thus cannot be regarded as noncontact measurement methods.

To measure the PWV remotely without use of contact-type sensors, Lu et al. [24] used two 6 GHz radar systems, while Michler et al. [25] used a 24 GHz array radar system. One of the authors of the present study [26], [27] used an array radar system in combination with a novel blind signal separation algorithm that does not require prior information about the target body's position and size to measure the PWV. In the study by Oyamada et al. [27], the displacements caused by the pulse wave at the back and the calf of the subject were measured, and a conventional beamformer method was then applied to separate the signals, whereas Sakamoto [26] developed a blind signal separation algorithm that uses a mathematical model of the typical physiological signals of the human body. The latter method is called physiological component analysis (PHCA), and PHCA requires optimization of an objective function that comprises the small displacement approximation and a simplified impulse response for the pulse wave propagation.

The purpose of this study is to extend this PHCA to provide faster processing by reducing the dimensionality of the decision variables used for the optimization in the PHCA. The proposed method uses the Schelkunoff polynomial method to express the unmixing matrix required using only a few parameters that correspond to the directions of arrival of the radar echoes from the human body. By combining a low-dimensional representation of the unmixing matrix with the objective function proposed for use in the original PHCA, we demonstrate accurate and simultaneous measurement of human body displacements at multiple positions using an array radar system.

II. System Model and Physiological Component Analysis

We assume that multiple body positions contribute radar echoes that are received by an antenna array. Each of these

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body positions exhibits a specific displacement; the displacement for the n-th body position is $d_n(t)$ $(n = 1, \cdots, N)$, and the vector $\boldsymbol{d}(t) = [d_1(t), d_2(t), \cdots, d_N(t)]^{\mathrm{T}}$ is defined. The n-th radar echo can be expressed as $s_n(t) \propto \mathrm{e}^{\mathrm{j}2kd_n(t)}$, where $k = 2\pi/\lambda$ is the wave number, and the vector $\boldsymbol{s}(t) = [s_1(t), s_2(t), \cdots, s_N(t)]^{\mathrm{T}} = \exp(\mathrm{j}2k\boldsymbol{d}(t))$ is then defined. The received signal vector $\boldsymbol{x}(t) = [x_1(t), x_2(t), \cdots, x_M(t)]^{\mathrm{T}}$ is defined using the m-th element signal $x_m(t)$, where it is assumed that $N \le M$. The received signal vector $\boldsymbol{x}(t)$ is expressed as $\boldsymbol{x}(t) = A\boldsymbol{s}(t) + \boldsymbol{n}(t)$, where A is an $M \times N$ mixing matrix and $\boldsymbol{n}(t)$ is an additive noise vector. If an unmixing matrix W is given, the signals can then be separated as $\hat{\boldsymbol{s}}(t) = W\boldsymbol{x}(t)$, and the displacement $\hat{\boldsymbol{d}}(t) = (1/2k)\angle\hat{\boldsymbol{s}}(t)$ is thus restored.

In PHCA, the signal separation procedure is formulated as an optimization problem using the product of three different functions (i.e., $F(W) = F_1(W)F_2(W)F_3(W)$) as the objective function [26]. Signal separation is then achieved using the form of the optimization problem $\max_W F(W)$ to determine the $N \times M$ matrix $W = [\boldsymbol{w}_1\boldsymbol{w}_2 \cdots \boldsymbol{w}_M]^{\mathrm{T}}$. The functions $F_1(W)$, $F_2(W)$, and $F_3(W)$ are defined as

$$F_1(W) = \min_{1\le i\le N} \lambda(i)^2, \tag{1}$$

$$F_2(W) = \prod_{1\le i<j\le N} \frac{\int_{-\infty}^{\infty} |g_{i,j}(\tau)|^4 \,\mathrm{d}\tau}{\left(\int_{-\infty}^{\infty} |g_{i,j}(\tau)|^2 \,\mathrm{d}\tau\right)^2}, \tag{2}$$

$$F_3(W) = \prod_{1\le i<j\le N} \frac{\max_{\tau>0} |g_{i,j}(\tau)|^2}{\max_{\tau<0} |g_{i,j}(\tau)|^2}, \tag{3}$$

where

$$\lambda(i)^2 = \left|\int \Re[\hat{s}_i]^2 - \Im[\hat{s}_i]^2 \mathrm{d}t\right|^2 + 4\left|\int \Re[\hat{s}_i]\Im[\hat{s}_i]\mathrm{d}t\right|^2, \tag{4}$$

$$g_{i,j}(\tau) = \int_{-\infty}^{\infty} \frac{\int_{-\infty}^{\infty} d_j(t')\mathrm{e}^{-\mathrm{j}\omega t'}\mathrm{d}t'}{\int_{-\infty}^{\infty} d_i(t')\mathrm{e}^{-\mathrm{j}\omega t'}\mathrm{d}t'} \mathrm{e}^{\mathrm{j}\omega\tau}\mathrm{d}\omega. \tag{5}$$

In PHCA, all the complex elements in W must be determined via optimization of the function $F(W)$, which would require unacceptably high computational costs. In the next section, we extend the PHCA to reduce the dimensionality of the decision variables and thus express W using only a few parameters.

III. Proposed Fast Physiological Component Analysis and Performance Evaluation

For the array factor $P_w(\theta) = \sum_{m=0}^{M-1} w_m \mathrm{e}^{-\mathrm{j}\pi m \sin\theta}$ of a half-wavelength-spaced M-element linear array, introduction of the complex variable $z = \mathrm{e}^{-\mathrm{j}\pi\sin\theta}$ allows $P_w(\theta)$ to be expressed as $P(z) = \sum_{m=0}^{M-1} w_m z^m$, which is a polynomial of z. If the null is located in the direction θ', we then have $(z - z_{\theta'})$ as a factor of $P(z)$, where $z_{\theta'} = \mathrm{e}^{-\mathrm{j}kd\sin\theta'}$; this is called the Schelkunoff polynomial method. In the proposed fast PHCA method, instead of optimizing all elements of W, the null angles are optimized. As a result, the number of dimensions for the optimization problem can be reduced from $N \times M$ to N by setting each row vector of W analytically to maximize the response in the n-th direction while nulling other directions of arrival for all echoes other than the n-th echo using the Schelkunoff polynomial method.

The performance of the proposed method is evaluated via a simulation in which it is assumed that two reflection positions ($N = 2$) on the human body are used, and that a radar system with a center frequency of 79 GHz and a six-element antenna array ($M = 6$) is installed above the target subject (Fig. 1). The distance from the array radar system to the human body is assumed to be 1.2 m, the reflection positions are located at $x = 0$ and -0.3 m, the skin displacement waveform due to the pulse waves is assumed to be a triangular wave with an amplitude of ± 50 μm, and the delay between the two positions is assumed to be 0.1 s. A quasi-Newton method was used to optimize the objective function of the fast PHCA. The optimized directivity patterns are shown in Fig. 2, and the body displacement waveforms are shown in Fig. 3. Processing times of 71.4 s and 12.0 s were realized using conventional PHCA and the proposed fast PHCA method, respectively, corresponding to an approximate processing speed improvement of 6.0 times in the latter case.

In addition, we formed a radar image profile using the unmixing matrix that was optimized in the fast PHCA in a manner similar to a previous HCA-based imaging technique [28] using the expression

$$P(\theta) = \frac{\exp(\beta(P_1(\theta) - P_0))}{P_2(\theta) + \alpha} + \frac{\exp(\beta(P_2(\theta) - P_0))}{P_1(\theta) + \alpha}, \tag{6}$$

where $P_1(\theta)$ and $P_2(\theta)$ are array factors that were obtained using the first and second row vectors, respectively, of the unmixing matrix that was optimized using fast PHCA. We set $P_0 = -3$ dB, $\beta = 10$ dB, and $\alpha = -100$ dB empirically. Fig. 4 shows the radar image profiles that were obtained using the conventional beamformer method (black line) and fast PHCA (red line), along with the actual reflection positions (blue dashed lines). In the figure, we see that fast PHCA can achieve a higher resolution than the conventional beamformer method. We are currently working on expansion of this technique to two-dimensional array radar to generate high-resolution radar images of the human body and the pulse wave propagation.

IV. Conclusion

In this paper, we have proposed a novel algorithm, called fast PHCA, which is an extended version of the earlier PHCA. The proposed fast PHCA allows us to express the unmixing matrix using only a few parameters, thus reducing the number of dimensions of the optimization problem that arose in PHCA. A systematic matrix representation was combined with the objective function used in the original PHCA to realize both high-speed computation and accurate blind signal separation. In addition, we also applied the PHCA-based radar imaging technique in combination with fast PHCA, and demonstrated the super-resolution property of the proposed fast PHCA approach. Our next step will be to extend fast PHCA to a two-dimensional array radar system to generate

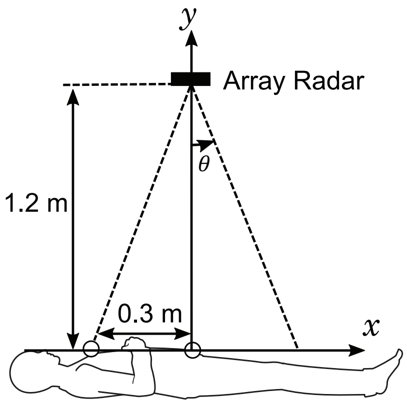

Fig. 1. System model assumed in this study for the simulations.

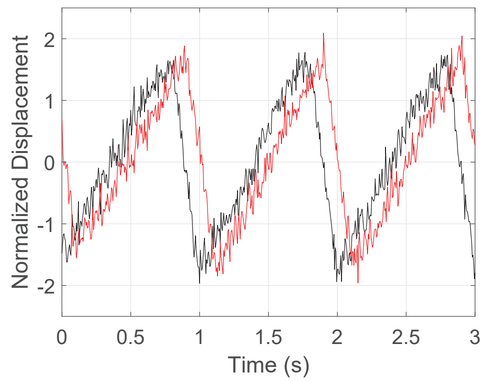

Fig. 3. Skin displacement waveforms (black and red lines) obtained using PHCA (average error: 5.3 μm).

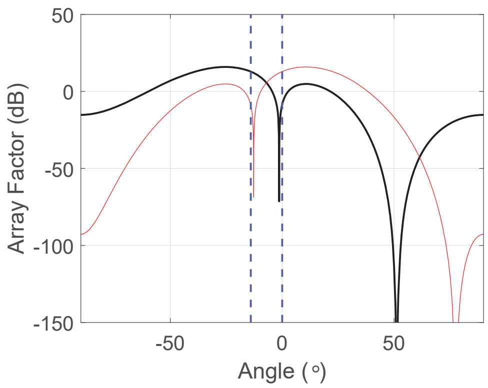

Fig. 2. Directivity patterns of PHCA (black and red solid lines) and the actual directions of arrival (blue broken lines).

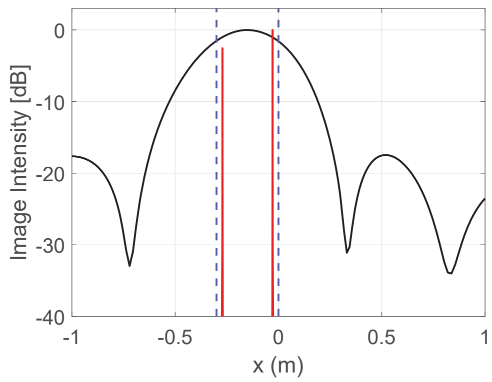

Fig. 4. Radar image profiles obtained using a conventional beamformer (black line) and PHCA (red lines), along with the actual target positions (blue dashed lines).

high resolution radar images of the human body and of arterial pulse wave propagation.

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