A Multi-Arc Method for Improving Doppler Radar Motion Measurement Accuracy

Songjie Bi[1], Xiaomeng Gao[1,3], Victor M. Lubecke[2], Olga Boric-Lubecke[2], Dennis Matthews[3], Xiaoguang "Leo" Liu[1]
[1]Department of Electrical and Computer Engineering
University of California, Davis
[2]Department of Electrical Engineering
University of Hawaii at Manoa
[3]Cardiac Motion LLC

***Abstract*—In this paper a phase shifter based multi-arc circle fitting method was proposed to improve accuracy of Doppler radar remote motion sensing. Experiments were conducted to validate the approach by measuring displacement of 3 mm using 2.4 GHz quadrature continuous wave (CW) Doppler radar. It was demonstrated that mean error drops from 4.529% to 1.073% when multiple shifting arcs are utilized to enhance detection accuracy. A greater improvement in accuracy is observed when more arcs are applied.**

Keywords*—*Doppler radar, phase shifter, multi-arc, accuracy improvement.

I. INTRODUCTION

Doppler radar has been studied extensively in non-invasive physiological monitoring, for wireless detection of respiration rate and heart rate, arterial pulse wave, respiratory tidal volume and sleep apnea [1]–[4]. Phase tuning of baseband signal can enhance Doppler radar vital sign detection performance, in terms of optimum detection and dc offset cancellation. Null point elimination was achieved in [5] by injecting a voltage-controlled tunable phase shifter after receiving antenna, making sure the detection is always tuned to optimum point even with a single mixer architecture. A simplified solution based on transdirectional coupler was implemented in direct conversion radar system in [6], which swiftly switch between two isolated phase-shifting states with $\pi/2$ apart. Furthermore, Girbau *et al.* investigated topologies to create phase shifts between two receiving channels of a quadrature receiver [7]. Optimum detection was realized by either implementing a $\lambda/8$ transmission line, or physically displacing two receiving antennas by $\lambda/8$. A dual phase shifters based architecture was proposed for fine tuning in [8]. By carefully selecting phase pairs, both optimum demodulation point and dc offset attenuation were achieved.

When it comes to motion detection, problems such as dc offset and limited motion amplitude become dominant. The I/Q components of the quadrature receiver form a trajectory that follows an arc, whose total length is linearly proportional to motion amplitude. The absolute motion amplitude can be arctangent-demodulated when the arc center is at the origin. However, clutter reflection and cross talk caused dc offset displaces the arc center by a vector, which should be accurately relocated before arctangent demodulation. In addition, since the cardiac motions are on the order of millimeters or fractions of millimeters, large error may be caused as associated phase changes are only a few degrees. This issue becomes severe as signal-to-noise ratio (SNR) value drops when motion amplitude decreases [9]. With DC offset being present, it is difficult to increase SNR simply with front-end amplifier as it may saturate the gain. To cope with the short arc length problem, it is applicable to increase radar detection frequency. But it also increases the overall hardware cost. Furthermore, the high carrier frequency shortens detection range due to high free space loss, yet makes it impossible for through-tissue cardiac motion pattern detection [10].

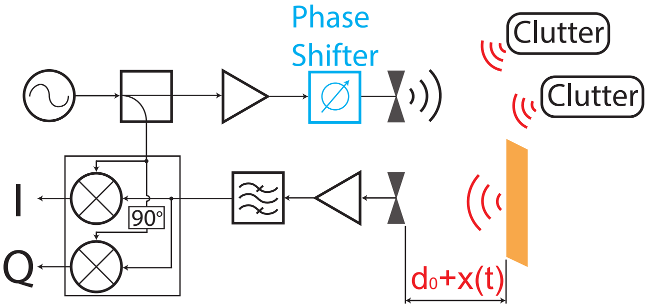

Fig. 1. Architecture of phase shifter based multi-arc Doppler. radar system

Considering the challenges of the hardware approach, the demodulation can then be modeled as a center finding or circle fitting problem. The most pressing issue is that limited arc length may induce large fitting errors. Some of the popular circle fitting methods discussed in [9], [11], [12] suffer from accuracy loss when fitting a circle to a short arc [13], [14]. It is demonstrated in [15] that an arc shifting method can enhance the performance of DC offset cancellation with small motion amplitude. By adjusting physical separation between radar receiver and target, phase shifts are manually introduced in received signal, creating additional data points for improved circle fitting. However, having the target move its relative position may not be practical, especially from a users perspective.

This paper presents an alternative approach for arc shifting. Instead of having the physical distance varied, a digitally controlled phase shifter is inserted in the radar transceiver. Therefore, multiple arcs originated from the same motion can be obtained. It not only eliminates the workload of having to precisely adjust the stand-off distance, but also improves motion demodulation accuracy.

II. MULTI-ARC PHASE-SHIFTING METHOD

Fig. 1 presents the concept of phase shifter based multi-arc vital sign detection. The VCO generates a signal

$$T(t) = A\cos(2\pi f t)\,. \tag{1}$$

Part of this signal is sent to the LO port of the IQ demodulator, while the other part forms the radar transmitted signal after power amplification and phase shifting. The signal radiated by the transmitting antenna becomes

$$T'(t) = A'\cos(2\pi f t + \theta_{ps} + \theta'_0)\,, \tag{2}$$

where θ_{ps} is the phase shift added by the programmable phase shifter, and θ'_o is the intrinsic phase delay between the oscillator and the phase shifter. Then the received echoes fed to the IQ demodulator chip is represented as

$$\begin{aligned} R(t) = {} & B_0\cdot\cos\left(2\pi f t - \frac{4\pi d_0}{\lambda} - \frac{4\pi x(t)}{\lambda} + \theta_{ps} + \theta_0\right) + \\ & \sum_{i=1}^{m} B_i\cdot\cos\left(2\pi f t - \frac{4\pi d_i}{\lambda} + \theta_{ps} + \theta_0\right) + \\ & \sum_{j=m+1}^{n} B_j\cdot\cos(2\pi f t + \theta_j)\,, \end{aligned} \tag{3}$$

where B_0, B_i and B_j are amplitudes, d_0 is the nominal distance between antenna and moving target, $x(t)$ is motion of the target, θ_0 is residual phase delay of the circuit, θ_j is the residual phase delay of the j-th circuit imperfection factor such as leakage. The equation above is categorized as 3 parts. The first part corresponds to the reflection from the moving target. The second part is caused by reflections from m clutter objects. Finally the third part represents circuit imperfection such as signal leakage from radar transmitter. Note this part doesn't have θ_{ps} in the cosine brackets because its signal path doesn't include the phase shifter.

After IQ-demodulation, there are two outputs given by

$$\begin{aligned} I(t) = {} & C_0\cdot\cos\left(\frac{4\pi x(t)}{\lambda} + \frac{4\pi d_0}{\lambda} - \theta_{ps} - \theta_0\right) + \\ & \sum_{i=1}^{m} C_i\cdot\cos\left(\frac{4\pi d_i}{\lambda} - \theta_{ps} - \theta_0\right) + \\ & \sum_{j=m+1}^{n} B_j\cdot\cos(\theta_j)\,, \end{aligned} \tag{4}$$

$$\begin{aligned} Q(t) = {} & C_0\cdot\sin\left(\frac{4\pi x(t)}{\lambda} + \frac{4\pi d_0}{\lambda} - \theta_{ps} - \theta_0\right) + \\ & \sum_{i=1}^{m} C_i\cdot\sin\left(\frac{4\pi d_i}{\lambda} - \theta_{ps} - \theta_0\right) + \\ & \sum_{j=m+1}^{n} B_j\cdot\sin(\theta_j)\,. \end{aligned} \tag{5}$$

Similar to the $R(t)$ expression, both $I(t)$ and $Q(t)$ contains three parts: the reflection from the moving target, reflections from the clutters, and TX/RX leakage. The target reflection forms a short arc on a circle with radius C_0 and the other two parts contribute to the DC offset which moves the center of circle away from the origin of the I-Q coordinate. After the analog-to-digital conversion (ADC), the target motion pattern recovery can be achieved by processing the digitized $I(t)$ and $Q(t)$ in the following way. First, circle center drift caused by DC offset is estimated a least squares fitting method with Levenberg-Marquardt (LM) algorithm [12]. Then DC offset is removed and the circle that the arc lies on is moved back to origin

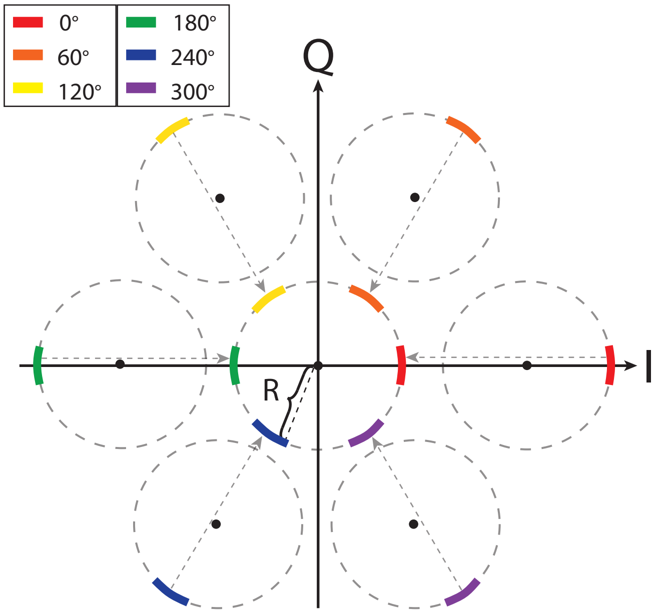

Fig. 2. Basic idea of Multi-Arc method: Apply LM algorithm for each individual arc to drag the circle centers back to origin, then recover motion use data from all arcs

$$I(t) = C_0\cdot\cos\left(\frac{4\pi x(t)}{\lambda} + \frac{4\pi d_0}{\lambda} - \theta_{ps} - \theta_0\right), \tag{6}$$

$$Q(t) = C_0\cdot\sin\left(\frac{4\pi x(t)}{\lambda} + \frac{4\pi d_0}{\lambda} - \theta_{ps} - \theta_0\right) \tag{7}$$

Then the target motion $x(t)$ can be recovered as

$$x(t) = \arctan\left(\frac{Q(t)}{I(t)}\right) - \frac{4\pi d_0}{\lambda} + \theta_{ps} + \theta_0. \tag{8}$$

Therefore, the motion recovery is actually a circle recovery problem. With better estimation of circle radius, the accuracy of detection can be enhanced.

With a digital variable phase shifter, arc can be moved to various angles by controlling θ_{ps}

$$I_{\sum}(t) = \sum_{k=1}^{p} C_0\cdot\cos\left(\frac{4\pi x(t)}{\lambda} + \frac{4\pi d_0}{\lambda} - \theta_{ps}^{k} - \theta_0\right) + V_I^k, \tag{9}$$

$$Q_{\sum}(t) = \sum_{k=1}^{p} C_0\cdot\sin\left(\frac{4\pi x(t)}{\lambda} + \frac{4\pi d_0}{\lambda} - \theta_{ps}^{k} - \theta_0\right) + V_Q^k. \tag{10}$$

However, equation (4) and (5) suggests that when θ_{ps} changes, not only does the arc rotate along the circle, the DC offset V_I^k and V_Q^k, i.e. circle center, also moves. The characteristic of this movement is dependent on the characteristics of the clutters and the TX/RX leakage. As shown in Fig. 2, in order to take advantage of multiple arcs, the motion recovery algorithm is implemented as follows:

1) For each circle, use LM algorithm to estimate the corresponding circle center (V_I^k, V_Q^k), then subtract the

arc data by (V_I^k, V_Q^k). Now those arcs are dragged back onto the circle whose center is located at coordinate origin (0, 0).

2) Combine data from all arcs into I^{comb} and Q^{comb}, use LM algorithm the second time to get a new DC offset (V_I^{comb}, V_Q^{comb}) and radius R for combined data.
3) Subtract I^{comb} and Q^{comb} by (V_I^{comb}, V_Q^{comb}) to remove residual DC offset by estimation error of LM estimation for each individual arc.
4) Then drag each arc to the same circle with radius R along the corresponding polar angle.
5) Use equation (8) to conduct motion recovery for the combined data obtained from the last step.

III. MEASUREMENT RESULTS AND DISCUSSION

A 2.41 GHz Doppler radar with 2-dBm output power was used in the experiments. A USB controlled programmable phase shifter was implemented at the transmitting chain before TX antenna. The phase shifter is pre-characterized with a vector network analyzer (VNA) so that its attenuation at each individual phase value under the same measurement condition is recorded for calibration. During the measurement, the phase shifter sweeps through 360° in N increments. The target used for evaluation is a Griffin Motion linear motion phantom (linear accuracy 10 μm). It carries a metal plate at front to increase reflection, outputs a sinusoidal motion with an amplitude of 3 mm and frequency of 1 Hz. Radar outputs are recorded by a National Instruments USB-6002 data acquisition device. A measurement of the target motion under each phase shift is recorded for 5 s at a sampling rate of 1 ksps.

From Table I, it can be seen that LM based circle fitting results in an average error of 2.769% and 5.519%, respectively, for 2 individual arcs. When the multi-arc circle fitting procedure is applied, the error is lowered to 2.374%. Compared with the mean error of individual arc measurements (4.529% in this case), the 2-arc estimation gives only half the error (2.374%).The performance of circle fitting is further evaluated on measurements with up to 10 arcs, and summarized into Table I. The error rates associated with more than 2 arcs are all below 2%, whereas that of individual arc goes up to 23.938%. Fig. 3 plots the overall trend of multi-arc method performance. With additional arc information, it can be seen that the accuracy is getting better for motion amplitude estimation. Although there are cases when individual arc yields very bad accuracy, the proposed method can still achieve good estimation.

IV. CONCLUSION

We have presented a phase-shifter based multi-arc method for enhancement of accuracy of Doppler radar vital sign detection. Effectiveness of the proposed method was validated via experiments of detecting 3 mm peak to peak target motion. The mean error of 100 tests drops from 4.529% to 1.073% when multiple shifting arcs are applied. The accuracy improves more when more arcs are applied.

TABLE I. COMPARISON OF MEASURED MOTION ACCURACY BETWEEN MULTI-ARC AND SINGLE-ARC MEASUREMENTS

Total Arc #	**Individual Error (%)**	**Combined Error (%)**	**Total Arc #**	**Individual Error (%)**	**Combined Error (%)**
1	2.769	n/a	8	2.769 2.700 2.488 5.438 5.519 10.418 3.921 4.948	1.448
2	2.769 5.519	2.374			
3	2.769 5.174 23.938	1.563			
4	2.769 2.488 5.519 3.921	1.476	9	2.769 3.218 2.942 5.174 5.890 3.667 23.938 3.054 6.206	1.073
5	2.769 2.613 5.532 5.169 2.829	1.662			
6	2.769 2.569 5.174 5.519 23.938 4.529	1.182	10	2.769 3.847 2.613 1.898 5.532 5.519 5.169 23.340 2.829 5.726	1.132
7	2.769 3.483 2.799 5.444 2.920 18.763 3.499	1.305			

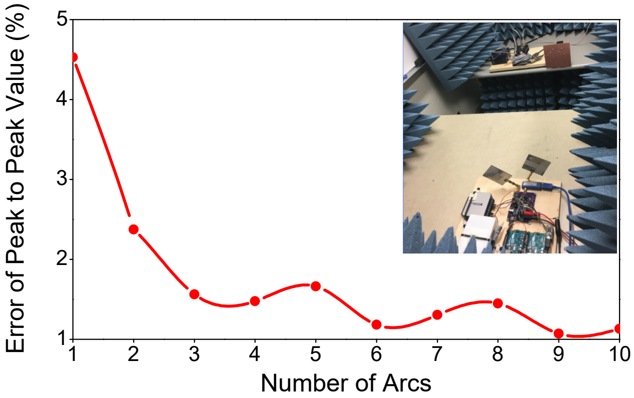

Fig. 3. Mean error over 100 times repeated tests of recovered motion peak-to-peak values. As the number of arcs increases from 1 to 10, detection error drops from 4.5% to 1.1%

It should be noted that the phase shifter was added as an additional component to a customized radar board right after the low noise amplifier, it will reduce the strength of the transmitting signal and detecting range. This could be improved in future designs by increasing the VCO output power or selecting a higher gain LNA. The current orientation of the antennas may cause a degradation in signal strength as the two patch antennas are not circular polarized. In the meantime, the direct coupling between TX and RX antenna are also alleviated. It is worth further investigation on this trade-off associated with TX/RX antenna orientation in our future work.

V. ACKNOWLEDGEMENT

This research was supported by the National Science Foundation under STTR Phase II award IIP-1660253. We would also like to thank Dr. Changzhi Li from Texas Tech University for his generous donation on the testing antennas.

REFERENCES

[1] W. Massagram, V. Lubecke, A. Host-Madsen, and O. Boric-Lubecke, "Assessment of heart rate variability and respiratory sinus arrhythmia via doppler radar," *IEEE Trans. on Microwave Theory and Techniques*, vol. 57, no. 10, pp. 2542–2549, Oct 2009.

[2] L. Li, C. Li, and D.Y.C.Lie, "Experimental demonstration of noncontact pulse wave velocity monitoring using multiple doppler radar sensors," in *IEEE EMBC*, August 2010, pp. 5010–5013.

[3] M. Kagawa, K. Ueki, and H. Tojima, "Noncontact screening system with two microwave radars for the diagnosis of sleep apnea-hypopnea syndrome," in *IEEE EMBC*, July 2013, pp. 2052–2055.

[4] S. Bi, X. Liu, and D. Matthews, "An experimental study of 2-d cardiac motion pattern based on contact radar measurement," in *IEEE WAMICON*, April 2015.

[5] W. Pan, J. Wang, J. Huangfu, C. Li, and L. Ran, "Null point elimination using rf phase shifter in continuous-wave doppler radar system," *Electronics Letters*, vol. 47, no. 21, pp. 1196–1198, October 2011.

[6] Y. P. Chen, T. T. Chen, K. T. Sun, and Y. C. Chiang, "Null point elimination using biphase states in a direct conversion vital signal detection radar," in *IEEE MTT-S IMWS-Bio*, Dec 2014, pp. 1–3.

[7] D. Girbau, A. Lazaro, A. Ramos, and R. Villarino, "Remote sensing of vital signs using a doppler radar and diversity to overcome null detection," *IEEE Sensors J.*, vol. 12, no. 3, pp. 512–518, March 2012.

[8] I. Mostafanezhad and O. Boric-Lubecke, "An rf based analog linear demodulator," *IEEE Microwave and Wireless Components Letters*, vol. 21, no. 7, pp. 392–394, July 2011.

[9] S. Guan, J. A. Rice, C. Li, and C. Gu, "Automated dc offset calibration strategy for structural health monitoring based on portable cw radar sensor," *IEEE Trans. on Instrumentation and Measurement*, vol. 63, no. 12, pp. 3111–3118, Dec 2014.

[10] S. Bi, J. Zeng, M. Bekbalanova, D. Matthews, and X. L. Liu, "Contact-based radar measurement of cardiac motion - a position and polarization study," in *IEEE BioWireleSS*, Jan 2016, pp. 29–31.

[11] B. K. Park, O. Boric-Lubecke, and V. M. Lubecke, "Arctangent demodulation with dc offset compensation in quadrature doppler radar receiver systems," *IEEE Trans. on Microwave Theory and Techniques*, vol. 55, no. 5, pp. 1073–1079, May 2007.

[12] M. Zakrzewski and H. Raittinen, "Comparison of center estimation algorithms for heart and respiration monitoring with microwave doppler radar," *IEEE Sensors J.*, vol. 12, no. 3, pp. 627–634, March 2012.

[13] M. Zakrzewski, A. Vehkaoja, and et al, "Noncontact respiration monitoring during sleep with microwave doppler radar," *IEEE Sensors J.*, vol. 15, no. 10, pp. 5683–5693, Oct 2015.

[14] X. Gao and O. Boric-Lubecke, "Radius correction technique for doppler radar noncontact periodic displacement measurement," *IEEE Trans. on Microwave Theory and Techniques*, vol. 65, no. 2, pp. 621–631, Feb 2017.

[15] X. Gao, J. Xu, A. Rahman, V. Lubecke, and O. Boric-Lubecke, "Arc shifting method for small displacement measurement with quadrature cw doppler radar," in *2017 IEEE IMS*, June 2017, pp. 1003–1006.