Measurement of the Complex Human Atrial-Ventricular Motions using Contact-Based Doppler Radar

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Abstract—Contact-based cardiac motion detection using Quadrature Doppler radar faces a challenge of the I/Q-formed non-arc constellation. In this work, a hypothesis is brought forward that such complicated constellation originates from not one, but two moving targets. The dual-motion model may very well explain that contact-based Doppler radar detects both atrium and ventricle motions during cardiac cycles. In this work, dual-motion simulation and phantom measurements are presented, verifying that the atrial-ventricular motions are the reason that I/Q baseband signals transcribe a complex non-arc constellation. It offers the first evidence that contact-based Doppler radar measures actual heart motion.

Index Terms—doppler radar, cardiac motion, contact sensing, complex motion.

I. Introduction

Radar based non-contact vital sign monitoring has been applied to extracting heart rate [1], heart rate variability [2], heart sound [3] and cardiac motion-encoded biometric information [4]. Non-contact radar monitoring relies on measuring the phase variation of the radar return signal due to the minute (6–10 mm) movement of the surface of the chest. Such motion is induced when the heart apex strikes thoracic wall during cardiac cycles and provide an indirect indication of the heart rate and heartbeat-associated features.

Contact-based heart monitoring remains a vast topic that many emerging technological solutions have been explored, such as photoplethysmography (PPG) [5], bio-impedance analysis (BIA) [6], which detect accurate heart rate readings in a wearable device. Radar-based cardiac monitoring in the contact-mode, however, is still a relatively open topic. Limited

studies on contact radar cardiac monitoring have demonstrated initial feasibility of probing motion pattern of human heart [7]–[10], estimating systolic time interval [11].

Compared to conventional cardiac monitoring techniques such as echocardiography (ECG) and magnetic resonance imaging (MRI) which must be administered in a hospital/clinic, radar based monitoring is portable and amenable for long-term and take-home use. Providing persistent monitoring may potentially allow for much greater insight into chronic heart diseases and much better preventative and personalized care.

Compared to non-contact radar measurement, contact measurement eliminates the strong reflections from the surface of the skin and provides a more direct measurement of the motion of the heart motions [13]. However, being closer to the heart also introduces several challenges. Assumptions regarding the characteristics of the radar return signal, such as small phase variation ("small arc") and negligible amplitude variation, may no longer hold true.

In this work, we demonstrate that contact radar measurement (Fig. 1) is capable of resolving complex motions of the heart. In particular, through simulation and experimental studies, we show that the opening in the I/Q trajectory in contact radar measurements of real human heart motions can only be explained by a separation of two motion centers moving with a relative delay between each other, presumably corresponding to the complex atrial and ventricular motions of the heart.
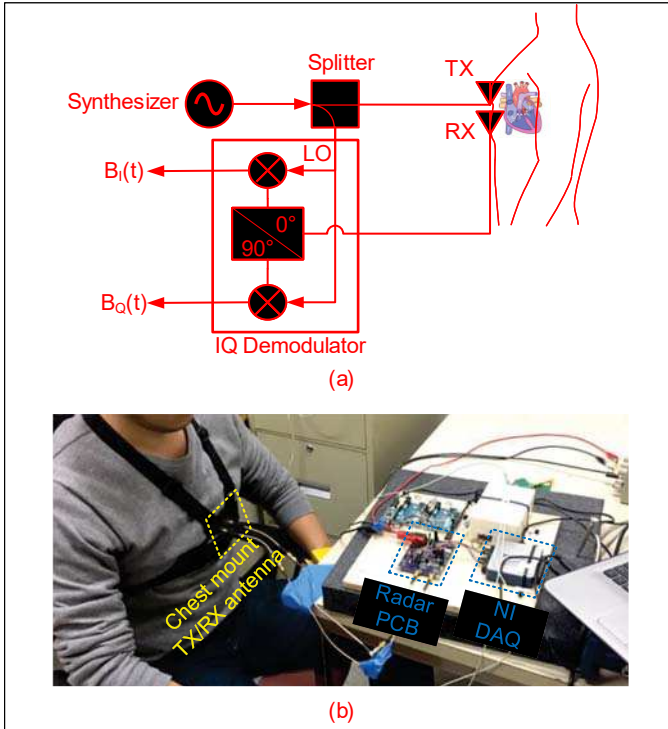
Fig. 1. (a) Quadrature Doppler radar architecture for contact heart sensing. Diagram of human heart illustration by [12]; (b) Contact measurement setup.

Fig. 2. IQ plot showing complex constellation measured by contact-based radar with body-coupled antenna.

II. CHALLENGES IN CONTACT-MODE RADAR MEASUREMENT OF CARDIAC MOTIONS

In non-contact radar measurement of the vital signs, the measured motion is very small compared to the wavelength as well as the distance to the subject. As such, the demodulated I/Q signals form a small arc on a circle. The length of the arc corresponds to the phase variation due to the subject's movement, the radius corresponds to the signal amplitude, and the center of the circle is determined by the measured dc offset [14].

Contact radar measurement, on the other hand, has several unique characteristics. First, the radar antenna is very close to the heart muscles. If the radar is placed directly on the chest, this distance is normally 2–5 cm. An estimated total layer thickness from skin to heart wall is 27 mm according to [13]. As such, the motion of the heart is not negligibly small compared to the distance, and the amplitude variation of the signal may not be neglected.

Second, the small phase change assumption may also be subject to question because of the relatively large motion of the heart muscles, as compared to the skin motion induced by heart motion, and the shorter propagation wavelength inside the thorax cavity due to the relatively high permittivity of human tissues. For example, with an average relative permit-
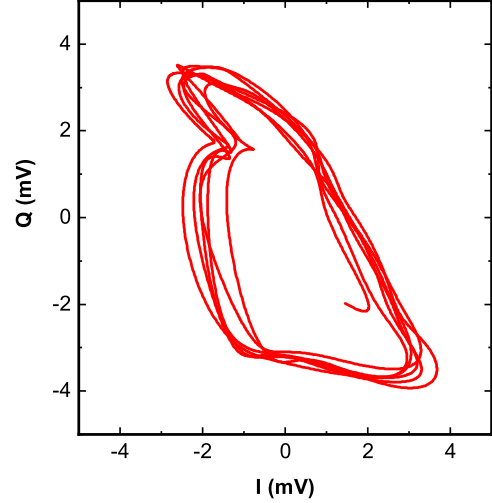
tivity $\epsilon_{r,body}$ of 25[1], a 2-GHz radar signal has a propagation wavelength λ_g of only 30 mm. According to [16], [17], total displacement of the left ventricle wall of human heart is on the order of 6-10 mm, which is equivalent to 0.2–$0.33\lambda_g$. Thus small angle approximation is no longer applicable.

Lastly, the physical motion of human heart is complicated as it involves atrium and ventricles contraction/relaxation with a relative time delay between them. This time delay of atrial and ventricular motions also causes a periodic "twist" motion. As a result, the measured the radar return signals in contact mode exhibit complex shapes and characteristics.

Using a 2-GHz Doppler contact-mode radar setup shown in Fig. 1, we show in Fig. 2 an example set of measured I/Q signals due to human heart motions. The radar system features a direct-conversion I/Q demodulator with the LO signal generated from a PLL-based synthesizer. The TX/RX antenna are custom-designed and placed over the sternum of the test subject to minimize antenna-body interface reflection and achieve minimal attenuation within the chest [**?**]. The sternum, which is a flat bone at the center of chest and rib cage protecting inner organs, was selected intentionally as the primer detection location as bone attenuates less microwave power than muscle or fat. A chest strap was used to attach the antenna firmly to the subject's body.

Fig. 2 captures measurement over several cardiac cycles. The measured I/Q signals form a complex contour with an "opening". It is clearly not an arc. This unique shape of the measured I/Q contours makes it difficult to estimate the dc offset because traditional circle fitting algorithm would result in highly ambiguous results. Unless dc offset is prop-

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[1]The average $\epsilon_{r,body}$ was chosen considering a variety tissue layers between radar and heart wall including skin, superficial fascia, bone and pericardium, whose relative permittivities are 47, 4.08, 17.09 and 4.08, respectively [15].

erly cancelled, displacement information cannot be accurately demodulated from the I/Q plot [18].

The "opening" of the I/Q contours have been considered by other researchers. For example, Kiriazi *et al.* considered the movement of the thorax and abdomen in non-contact Doppler radar respiration sensing to explain similar complex I/Q signal shapes [19]. Ø.Aardal *et al.* also reported such phase distortion in a respiration monitoring-oriented study [20], which attributes it to a two point scatter model. Inspired by these studies, we postulate that the opening of the I/Q contours in contact radar measurements is attributed to the presence of multiple motion centers.

The human heart consists of four chambers. The two upper ones are called atrium and the two lower ones ventricle. The two atrium chambers move in sync and can be treated as one motion center. Same is true for the ventricles. If both the atrium and the ventricle can be illuminated by the radar, then the motion detected by the radar can be considered from two distinct motion centers.

III. PARAMETRIC ANALYSIS

A. Signal Model

From aforementioned hypothesis, the complex cardiac motion can be modeled as two parts $x_1(t)$ and $x_2(t)$, which are modulated in the radar echoes. Since a direct-conversion Doppler radar is used for detection, the modulated phase content are included in the baseband outputs comprising of two superimposed terms in each component, in addition to dc offsets. The in-phase and quadrature-phase baseband signals are expressed in $B_I(t)$ and $B_Q(t)$ as

$$
\begin{aligned}
B_I(t) = \ & V_I + A_1 \cdot \cos\left(\frac{4\pi x_1(t)}{\lambda_g} + \frac{4\pi D_1}{\lambda_g}\right) + \\
& A_2 \cdot \cos\left(\frac{4\pi x_2(t)}{\lambda_g} + \frac{4\pi D_2}{\lambda_g}\right),
\end{aligned} \tag{1}
$$

$$
\begin{aligned}
B_Q(t) = \ & V_Q + A_1 \cdot \sin\left(\frac{4\pi x_1(t)}{\lambda_g} + \frac{4\pi D_1}{\lambda_g}\right) + \\
& A_2 \cdot \sin\left(\frac{4\pi x_2(t)}{\lambda_g} + \frac{4\pi D_2}{\lambda_g}\right).
\end{aligned} \tag{2}
$$

where V_I and V_Q represent dc offsets of the baseband signals, A_1 and A_2 are the amplitudes of in-phase and quadrature-phase terms, which are governed by a number of factors such as system gain and distance. $x_1(t)$ and $x_2(t)$ represent time-varying motion of the atrium and ventricle, respectively. D_1 and D_2 are the nominal distance between each chamber and the antenna. λ_g is the effective (average) propagation wavelength inside the thorax cavity. For simplicity, residual phase noise is neglected in our discussion.

The volumetric trajectories of left ventricle and left atrium in [21] were used to generate the profiles of $x_1(t)$ and $x_2(t)$. As a simplification, we assume that the atrium and ventricle each takes a spherical shape. Their one-dimensional surface displacements can thus be approximated as cubic root of the volumetric trajectories with a scaling factor $\left(\frac{3}{4\pi}\right)$. The exact
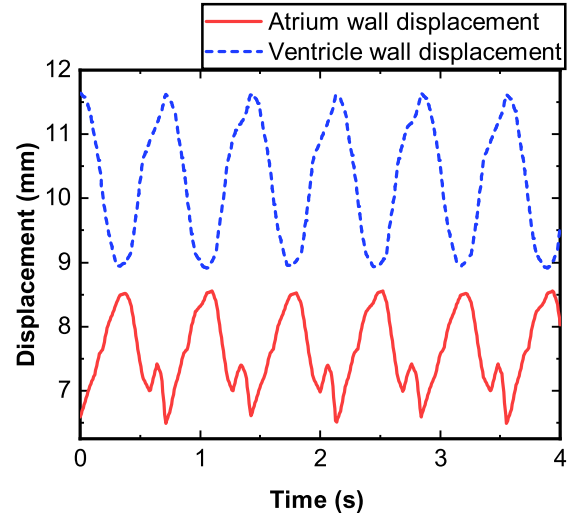

Fig. 3. Atrium and ventricle wall displacement profile approximated from healthy individual atrial and stroke volume [21].

profiles of $x_1(t)$ and $x_2(t)$ used in this study are shown in Fig. 3.

B. Parametric simulation

In the simulations performed in Matlab, the first motion was chosen as atrium motion, the second as ventricle motion with a 200-ms delay [22]. By changing the nominal distance of one chamber (ventricle) while maintaining that of the other chamber (atrium), relative distance between them were adjusted from 0 mm, 10 mm, to 20 mm. Since in later phantom measurement, a 2.41-GHz radar will be used to conduct measurement outside human thorax, the difference in permittivity needs to be taken into account.

$$
\lambda_g = \frac{\lambda_{air}}{\sqrt{\epsilon_{r,body}}}, \tag{3}
$$

where $\epsilon_{r,body}$ is 25. In other words, the nominal distance of 27 mm as mentioned in Sec.II was increased to 135 mm. Since the formation of the complex constellation is of prominent interest, dc offsets are not considered in parametric simulation. The transcribed constellations are shown in Fig. 4 (a–c). It can be seen that the atrium-ventricle motion yield non-arc constellations, despite relative distance offset. All three contours exhibit similar "openings" as shown in Fig. 2. When relative distance offset is 0, the "opening" is relatively smaller than that of the other two simulated scenarios.

IV. EXPERIMENTAL VALIDATION

A. Experiment setup

To further validate the simulation models, we use two programmable high-precision linear actuators to emulate the motion of two objects. Two identical plates were mounted on each of them to represent heart wall. The actuators are placed on a platform at the edge of a table, facing the radar
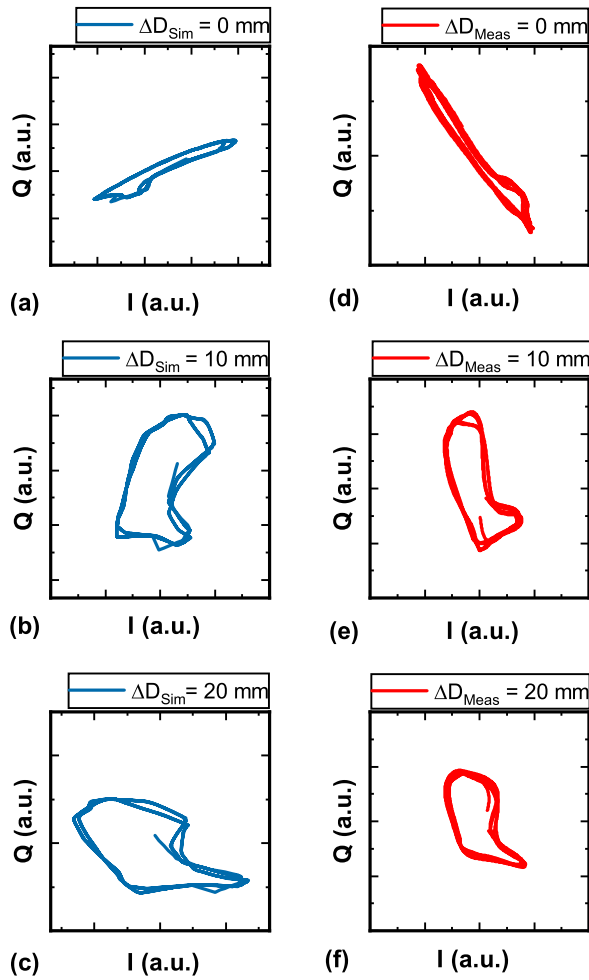
Fig. 4. Atrium and ventricle motions-associated IQ plots in simulation (a)-(c) and phantom measurement (d)-(f) at relative nominal distance offsets (ΔD) of 0 mm, 10 mm and 20 mm.
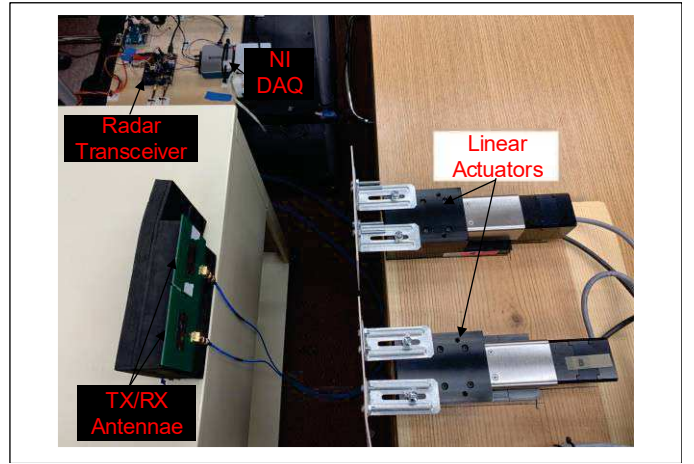

Fig. 5. Measurement setup.

note that Fig. 4(f) looks very much like the real heart measurement as illustrated in Fig. 2 with a separation of 20 mm between the two motion centers. The two contours' geometric shape resemble more closely if the latter rotates by 180°, which could be a result of constellation rotation caused by under/overestimated actual distance.

V. CONCLUSION

We have presented initial evidence on contact-based radar measurements can resolve complex cardiac motion. We postulate that separate motions of the atrium and the ventricle manifest themselves as openings in the measured I/Q contours. This claim is substantiated by semi-quantitative simulation and measurement. While more extensive investigations are undergoing, we expect that this study presents valuable insights into cardiac motion monitoring using contact radar sensors.

antenna. As in the simulation, the nominal distance offset between two plates was configured to be 0 mm, 10 mm and 20 mm. The actuators were programmed with preset atrium and ventricle motions respectively through a Galil DMC-4143 controller under manufacturer-defined *Contour Mode* because it allows arbitrary profile configuration. A standalone data acquisition device USB-6002 from National Instruments was used to collect data for offline processing.

B. Measurement Results

Fig. 4(d–f) shows the measured I/Q signals from the experimental setup. An almost identical "opening" feature can be seen from the measured I/Q plots. Specifically, when two actuators perform asynchronous atrial-ventricular motions, I/Q components hardly form a pure arc no matter how much the relative distance offset is. It should be mentioned during measurement due to alignment limitations, actual distance offset between actuators may be larger than that in simulation, thus causing the constellation's rotation. Nonetheless, their geometric features remain almost mutually identical. We also

REFERENCES

[1] J. C. Lin, "Microwave propagation in biological dielectrics with application to cardiopulmonary interrogation," pp. 47–58, 1986.

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

[3] C. Will, K. Shi, S. Schellenberger, T. Steigleder, F. Michler, J. Fuchs, R. Weigel, C. Ostgathe, and A. Koelpin, "Radar-based heart sound detection," *Scientific reports*, vol. 8, no. 1, p. 11551, 2018.

[4] F. Lin, C. Song, Y. Zhuang, W. Xu, C. Li, and K. Ren, "Cardiac scan: A non-contact and continuous heart-based user authentication system," in *Proceedings of the 23rd Annual International Conference on Mobile Computing and Networking*. ACM, 2017, pp. 315–328.

[5] T. Tamura, Y. Maeda, M. Sekine, and M. Yoshida, "Wearable photo-plethysmographic sensorspast and present," *Electronics*, vol. 3, no. 2, pp. 282–302, 2014.

[6] R. González-Landaeta, O. Casas, and R. Pallàs-Areny, "Heart rate detection from plantar bioimpedance measurements," *IEEE transactions on Biomedical Engineering*, vol. 55, no. 3, pp. 1163–1167, 2008.

[7] S. Bi, X. Liu, and D. Matthews, "An experimental study of 2-d cardiac motion pattern based on contact radar measurement," in *Wireless and Microwave Technology Conference (WAMICON), 2015 IEEE 16th Annual*. IEEE, 2015, pp. 1–4.

[8] R. R. Fletcher and S. Kulkarni, "Clip-on wireless wearable microwave sensor for ambulatory cardiac monitoring," 2010.

[9] Ø. Aardal, S. Brovoll, Y. Paichard, T. Berger, T. S. Lande, and S.-E. Hamran, "Detecting changes in the human heartbeat with on-body radar," in *Radar Conference (RADAR), 2013*. IEEE, 2013, pp. 1–6.

[10] S. Bi, J. Zeng, M. Bekbalanova, D. Matthews, and X. L. Liu, "Contact-based radar measurement of cardiac motiona position and polarization study," in *Biomedical Wireless Technologies, Networks, and Sensing Systems (BioWireleSS), 2016 IEEE Topical Conference on*. IEEE, 2016, pp. 29–31.

[11] D. Buxi, E. Hermeling, M. Mercuri, F. Beutel, R. G. van der Westen, T. Torfs, J.-M. Redouté, and M. R. Yuce, "Systolic time interval estimation using continuous wave radar with on-body antennas," *IEEE J. Biomed. Health Informat.*, vol. 22, no. 4, pp. 129–139, 2018.

[12] Wnauta. (2007) Diagram of the human heart. [Online]. Available: https://commons.wikimedia.org/w/index.php?curid=1741142

[13] S. Bi, "Monitor cardiac motion based on contacting radar technology," Ph.D. dissertation, University of California, Davis, 2017.

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

[15] M. Kawasaki and R. Kohno, "A toa based positioning technique of medical implanted devices," in *Third International Symposium on Medical Information & Communication Technology, ISMCIT09, Montreal*. Citeseer, 2009.

[16] J. O. Mangual, B. Jung, J. A. Ritter, and A. Kheradvar, "Modeling radial viscoelastic behavior of left ventricle based on mri tissue phase mapping," *Annals of biomedical engineering*, vol. 38, no. 10, pp. 3102–3111, 2010.

[17] C.-Y. Hsieh, G. Gladish, and C. E. Willis, "Evaluation of a commercial cardiac motion phantom for dual-energy chest radiography," *Journal of applied clinical medical physics*, vol. 15, no. 2, pp. 235–251, 2014.

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

[19] J. E. Kiriazi, O. Boric-Lubecke, and V. M. Lubecke, "Modeling of human torso time-space characteristics for respiratory effective rcs measurements with doppler radar," in *Microwave Symposium Digest (MTT), 2011 IEEE MTT-S International*. IEEE, 2011, pp. 1–4.

[20] Ø. Aardal, S. Brovoll, T. Berger, I. Balasingham, and S.-E. Hamran, "Phase distortions in radar respiration monitoring," in *2017 First IEEE MTT-S International Microwave Bio Conference (IMBIOC)*. IEEE, 2017, pp. 1–4.

[21] P. Piras, C. Torromeo, A. Evangelista, S. Gabriele, G. Esposito, P. Nardinocchi, L. Teresi, A. Madeo, M. Schiariti, V. Varano *et al.*, "Homeostatic left heart integration and disintegration links atrioventricular covariations dyshomeostasis in hypertrophic cardiomyopathy," *Scientific reports*, vol. 7, no. 1, p. 6257, 2017.

[22] J. E. Hall, *Guyton and Hall textbook of medical physiology e-Book*. Elsevier Health Sciences, 2015.