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Non-contact Displacement Estimation Using Doppler Radar

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***Abstract*— Non-contact Doppler radar has been used extensively for detection of physiological motion. Most of the results published to date have been focused on estimation of the physiological rates, such as respiratory rate and heart rate, with CW and modulated waveforms in various settings. Accurate assessment of chest displacement may take this type of monitoring to the new level, by enabling the estimation of associated cardiopulmonary volumes, and possibly pulse pressure. To obtain absolute chest displacement with highest precision, full nonlinear phase demodulation of the quadrature radar outputs must be performed. The accuracy of this type of demodulation is limited by the drifting received RF power, varying dc offset, and channel quadrature imbalance. In this paper we demonstrate that if relatively large motion is used to calibrate the system, smaller motion displacement may be acquired with the accuracy on the order of 30 µm.**

I. Introduction

Non-contact Doppler radar has been used extensively to detect physiological motion, with CW and modulated radar waveforms, at microwave and millimeter-wave frequencies [1]-[3]. Quadrature radar configuration has been used to overcome detection sensitivity to relative position between the radar and the subjects [4]. Quadrature outputs have been combined using linear and non-linear demodulation [4]-[6]. Linear demodulation offers a simple means of obtaining approximate displacement waveforms, which is adequate for obtaining rates. Though displacement can also be estimated through linear demodulation, its accuracy is limited to about 33% of the wavelength of radar frequency [7]. On the other hand, non-linear demodulation enables full phase recovery, which may lead to highly accurate estimation of absolute displacement. The accuracy of both linear and non-linear demodulation methods are subject to noise and channel imbalance [8]. It was reported in [9] that imbalance influence on linear demodulation can be minimized by either changing the target distance or tuning circuit's phase delay, with about a 10% error of detected motion amplitude.

In this paper, we propose a system calibration method that enables accurate non-linear demodulation, and thus absolute displacement estimation. Our results demonstrate that by using this calibration method, accuracy on the order of 30µm can be achieved. Since high accuracy displacement estimation is required for accurate monitoring of heart traces and may lead to pulse pressure measurements, our method may take this type of monitoring to the new level.

II. Non-contact Displacement Estimation

A. Physiological Motion and Measurement

During the period of systole with heart contraction, the heart moves within the chest cavity, hitting the chest wall and creating a measurable displacement at the skin surface. Scholars have used various kinds of techniques of detecting this movement and determine its displacement, including contact methods such as impulse cardiogram, capacitive transducer, magnetic displacement sensor, and non-contact methods such as optical detection and Moiré Effect [4]. The average value for displacement obtained using non-contact techniques is 0.6mm. Although this value is expected to vary due to a combined causes of age, health, physiology, it is still expected to fall within the detection capability of a Doppler radar system. The chest wall movement caused by respiratory effort is a combination of abdominal and rib cage movements. Overall there is a 4mm to 12mm radial expansion of the thorax during breathing, depending on individual physiology and how much air is inspired [4].

Recent work suggests that a high pulse pressure is an important risk factor for cardiovascular diseases [10]. The consideration of this particular parameter may offer us a track of medical device innovations. Its measurement involves accurate measurement of displacement of chest motion [10].

B. Non-linear Demodulation

In a simple form, the baseband outputs from the CW quadrature Doppler radar can be represented as:

$$B_I(t) = V_I + A_B\cos(\theta + \frac{4\pi x(t)}{\lambda})$$
$$B_Q(t) = V_Q + A_B\sin(\theta + \frac{4\pi x(t)}{\lambda}) \quad (1)$$

Where λ is the wavelength, θ is the phase shift due to the position of the object with respect to the radar, $x(t)$ is the time varying motion, V_I and V_Q are the dc offsets associated with I and Q channels, respectively. Fig.1 shows the Doppler

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radar quadrature baseband outputs forming an arc in the complex plane.

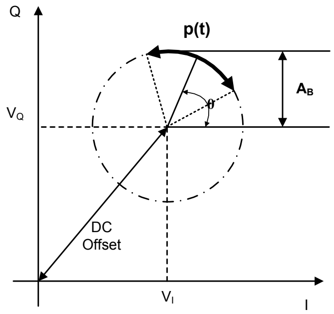


Figure 1. Complex constellation of Doppler radar quadrature outputs.

The radius of the arc is determined by the amplitude of the received RF power. From (1), the received signal power is A_B^2, the square root of which gives the radius of the circle A_B as shown in Fig. 1. The length of the arc is determined by the Doppler phase shift and it depends on the radar frequency and displacement amplitude. Linear demodulation is simply a projection of this arc on a straight line.

Arctangent demodulation or non-linear demodulation uses the arc formed by I and Q channels to obtain the displacement. The equation governing the extraction of angle/phase from I and Q channels is given by [11]:

$$\theta(t) = \arctan\left(\frac{B_Q(t)}{B_I(t)}\right) = \arctan\left(\frac{\sin(\theta + p(t))}{\cos(\theta + p(t))}\right) = \theta + p(t) \tag{2}$$

where p(t)=4πx(t)/λ is the phase information due to periodic motion. With 2.4 GHz radar, chest displacement due to heart contractions corresponds to a phase change of 3.5^o. For normal breathing, the average displacement from 4mm to 12mm can be detected by radar in forms of phase change from about 23^o to 70^o.

C. Challenges

The radar receiver channels are not always in quadrature because of inherent amplitude and phase imbalance present in the system due to imperfect system components. Though they are unavoidable, to recover displacement information accurately, the imbalances have to be corrected before application of arctangent demodulation. The known imbalance factors can be compensated with Gram-Schmidt procedure [4].

Radius estimation is another issue that should be taken into account [8]. During arctangent demodulation, arc's center is first estimated based on available arc length through center estimation [12]. Then arc radius is obtained by moving arc's center back to the origin of complex plane. However for relatively short arcs, center estimation may be ambiguous due to limitation of available sample points. Hence its radius information may not be accurate. The issue can be corrected if radius is uniform for all displacement estimation.

The radar system also has to be dc-coupled to avoid filter distortion yet obtain useful dc information. The challenges are to recover accurate displacement information with baseband signals not sufficiently amplified to prevent low noise amplifier saturation.

III. SYSTEM OVERVIEW

Fig.2 is the block diagram of the Doppler radar system for displacement measurement. The measurement was carried out using CW microwave quadrature Doppler radar, and a mechanical target mounted on a high resolution linear stage. The reason for using linear actuator with programmed motion parameters is by providing reference to the measurement, accuracy of displacement estimation can be verified for the system.

The Griffin Motion MLS series linear stage has exceptional levels of repeatability, flatness, straightness and a linear accuracy of 5μm. It can be programmed by GalilTools to perform smooth motion on one axis. In order to simulate chest cardiac activity, stage was set in a periodic sinusoidal motion with frequency of 0.2Hz. The target mounted on the stage was a Styrofoam hemisphere with diameter of 19mm covered by aluminum foil.

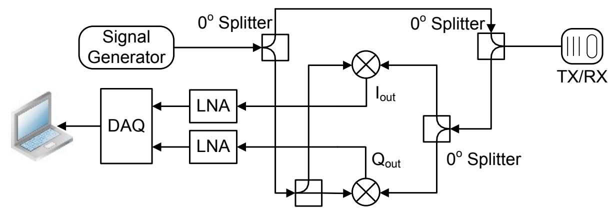


Figure 2. Quadrature Doppler radar block diagram.

Quadrature Doppler radar was used to detect the movement of the target. The TX/RX antenna used for sensing was Antenna Specialist's ASPPT2988 with 8dBi gain and 60 degree E-plane beam width. The 0^o and 90^o power splitters, mixers employed in the system were all Mini-Circuit coaxial connectors. Signal source was set to operate at 2.4GHz with 10dBm gain. It is necessary to use the same signal source for transmitter and receiver's local oscillator to benefit from coherent reception [10].

The baseband signals labeled as I_{out} and Q_{out} were obtained from mixer outputs. Two Stanford Research Systems' SR560 low noise amplifier's were used for preserving the minimal displacement information and dc content in the two channels. Both of them were set in dc-coupled, with 6dB/octave low-pass filter working at a cutoff frequency of 10Hz and a gain of 20dBm. Data was recorded using a DAQ (NI-USB 6259) and LabVIEW at sampling frequency of 1kHz. Each recording took 30 seconds to complete.

IV. EXPERIMENTAL RESULTS

A. Calibration Method

In this paper, we propose a system calibration method that enables accurate non-linear demodulation from CW quadrature Doppler radar outputs, and accurate absolute displacement recovery.

Initially four periodic motions with displacement range of 1.0cm, 2.0cm, 3.0cm and 4.0cm were programmed on the linear stage, respectively. All of them were sinusoidal with frequency of 0.2Hz. Target was placed at a fixed distance of 1 meter away from the radar. Linear stage motion was recorded in GalilTools software simultaneously as a reference. Its scope capture function offers real-time data display and gives a precise motion profile of the stage as a reference. Quadrature channel data of four groups of motions were then processed in Matlab as initial absolute displacement estimation. These results will be saved for later reference with calibrated data estimation.

Second, imbalance factors from each group of data were obtained and listed in Table I. They were used for compensating the initial data at the beginning of estimation. Corresponding radius values were also estimated after center estimation [12], respectively. When the center of the arc is shifted back to the origin of complex plane, arc's radius can be obtained by finding its crossing point on the I-axis. Since arc radius is determined by the level of received power, theoretically under same measurement settings with target in the far field, estimated radius for longer arc and shorter ones should be the same. Hence the longest radius value was chosen for system calibration. For finding shorter arc's center, radius value from 4.0cm (or the longest available) group is applied. After rotating the arc so that it is parallel to the Q-axis, the crossing point on the I-axis is found. By shifting this point by minus radius value, shorter arc's center is determined. Using this calibrated arc center in arctangent demodulation, displacement with less error can be obtained. Estimation results through this process were compared with the results from initial data to verify its improved accuracy.

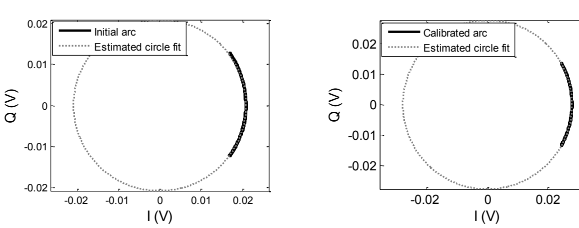
B. Results

Table I shows imbalance factors and radius values estimated from initial data. We can see that the largest radius 0.0279V is estimated from the longest motion.

TABLE I. IMBALANCE FACOTRS

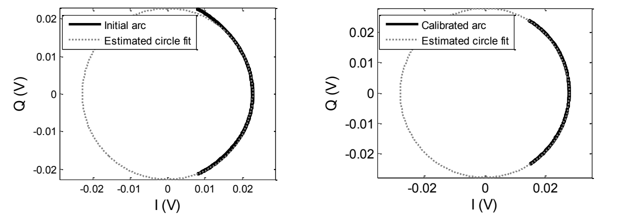
Motion Range	**Imbalance Factors**		**Radius (V)**
	Amplitude Imbalance	***Phase Imbalance***	
4.0cm	1.0803	10.7890	0.0279
3.0cm	1.1045	10.4389	0.0251
2.0cm	1.0642	5.4930	0.0228

Fig. 3 and Fig. 4 show comparison of arc and estimated circle fit between the initial data and compensated data of 1.0cm and 2.0cm motion, respectively. After the calibration process of imbalance compensation and radius correction, we can clearly see that the arc fits more to the estimated circle.



(a)Initial data (b)Calibrated data

Figure 3. Comparison of initial arc (solid line) and estimated circle (dotted line) before and after calibration on 1.0cm data.



(a)Initial data (b)Calibrated data

Figure 4. Comparison of initial arc (solid line) and estimated circle (dotted line) before and after calibration on 2.0cm data.

Fig. 5 and Fig. 6 compare the results from displacement estimation for initial data and calibrated data. Results are in the form of deviation rate in percentage between estimation and reference. Calibration techniques are performed in imbalance compensation only and combined with radius correction. To be specific, to perform radius correction, 4.0cm data's radius value 0.0279V is employed. In Fig. 5, the black bar of group #1 gives out displacement estimation without imbalance compensation or radius correction. Group #2, #3 and #4 are under compensation with imbalance factors derived from 2.0cm data, 3.0cm data and 4.0cm data, respectively. Results with radius correction were compared as the white bars. From Fig. 5#4 we can see if initial 1.0cm data is compensated using 4.0cm arc's imbalance factors , and combined with its radius for correction, estimated displacement is 1.0027cm with a deviation rate of 0.2674%. Compared with the results without any calibration technique in group #1, 1.2700cm with deviation rate 26.9993%, estimation accuracy was improved by 99%. Fig. 6 is in the same plot structure. It can be seen that 2.0cm data also yields good accuracy under the same calibration technique. The absolute estimated displacement is 2.0029cm with a deviation rate of 0.1426%, the accuracy of which is on the same order of 30μm.

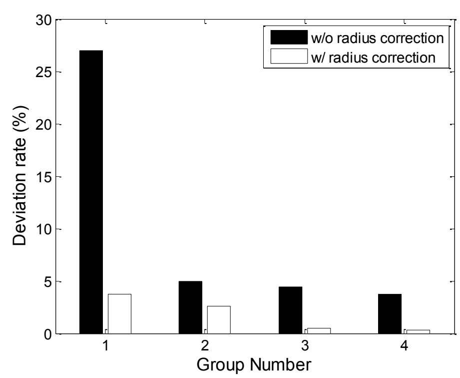


Figure 5. Displacement estimation results due to imbalance compensation/radius correction on 1.0cm data.

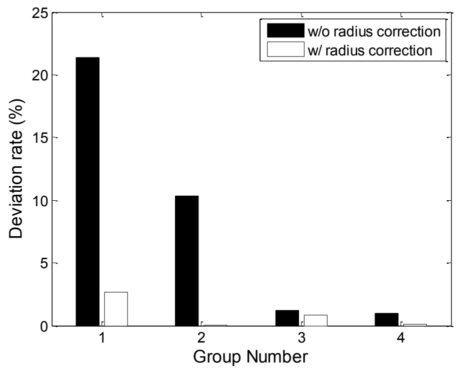


Figure 6. Displacement estimation results due to imbalance compensation/radius correction on 2.0cm data.

The displacement profile from radar detection and that captured in GalilTools plotted together for comparison as in Fig. and Fig. . The results on 1.0cm and 2.0cm data show very good agreement. It should be noted that since the sample counts for GalilTools is only 350, while DAQ has up to 30,000 sample points. Thus radar data was first used to estimate displacement, then down-sampled in Matlab to compare with its reference captured in GalilTools.

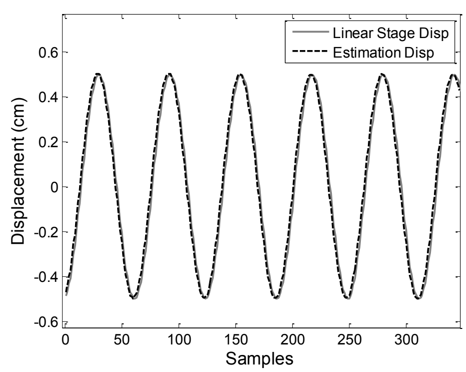


Figure 7. Comparison between reference displacement of stage and radar data estimation. Reference = 1.0cm

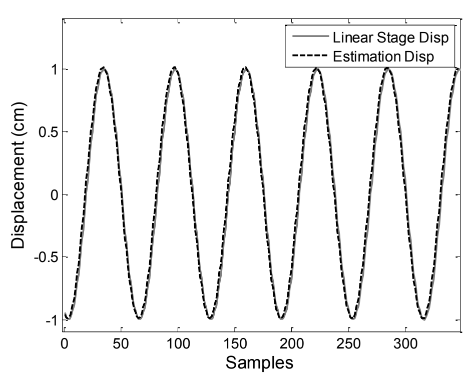


Figure 8. Comparison between reference displacement of stage and radar data estimation. Reference = 2.0cm

V. CONCLUSION

Quadrature Doppler radar displacement estimation is of interest in physiological sensing for cardiopulmonary activities and non-invasive medical monitoring. This paper presents a method of calibrating the quadrature Doppler radar system in displacement estimation. Under proposed method, high accuracy displacement recovery can be achieved. Experimental results showed that accuracy order on 1.0cm and 2.0cm displacement estimation has achieved 30μm, with linear actuator output resolution of 5μm.

The results were preliminary but offer a good indication for accurate displacement measurement using medical Doppler radar. It offers a track towards possible future applications. Cardiovascular volume related parameters like pulse pressure may be estimated using such techniques. Further study is needed in finding out correlation between chest cardiac displacement and pulse pressure. Human testing will also be carried out under IRB approval for chest displacement measurement. In real practice we may ask the subject to take several deep breaths in order to calibrate the system.

REFERENCES

[1] J. C. Lin, "Microwave sensing of physiological movement and volume change: a review", *Bioelectromagnetics*, vol. 13, pp. 557-565, 1992.

[2] K. Chen, J. Zhang, A. Norman, "Microwave life-detection systems for searching human subjects under earthquake rubble or behind barrier," *IEEE Trans.Biomedical Engineering*, vol. 27, no. 1, January 2000.

[3] J. Geisheimer, E. F. Greneker, E.F., III, "A non-contact lie detector using radar vital signs monitor (RVSM)technology," *IEEE Aerospace and Elect. Systems Magazine*, Volume 16, Issue 8, Aug 2001 Page(s):10 – 14.

[4] A. Droitcour, "Non-contact measurement of heart and respiration rates with single-chip microwave Doppler radar," Ph.D dissertation, Dept. Elect. Eng., Stanford University, Stanford, CA, 2006.

[5] C. Gu, C. Li, J. Lin, J. Long, J. Huangfu, and L. Ran, "Instrument-Based Noncontact Doppler Radar Vital Sign Detection Systems Using Heterodyne Digital Quadrature Demodulation Architecture", *IEEE Trans. Instrumentation and Measurement*, Vol. 59, NO. 6, June 2010.

[6] D. Morgan, and M. Zierdt, "Novel signal processing techniques for Doppler radar cardiopulmonary sensing," *Signal Processing*, vol. 89, issue 1, Jan. 2009.

[7] C. Li and J. Lin. "Non-Contact Measurement of Periodic Movement by a 22-40 GHz Radar Sensor Using Nonlinear Phase Modulation". *IEEE MTT-S International Microwave Symposium,* pp. 579-582, Honolulu, June, 2007.

[8] M. Zakrzewski, H. Raittinen, and J. Vanhala, "Comparison of Center Estimation Algorithms for Heart and Respiration Monitoring with Microwave Doppler Radar," *IEEE J. Sensors*, vol. 12, issue 3, March, 2012.

[9] Y. Yan, C. Li and J. Lin. "Effects of I/Q Mismatch on Measurement of Periodic Movement Using a Doppler Radar Sensor". *IEEE Radio and Wireless Symposium*, pp. 196-199, New Orleans, Jan. 2010.

[10] A. Singh, V. Lubecke, and O. Boric-Lubecke, "Pulse Pressure Monitoring Through Non-Contact Cardiac Motion Detection Using 2.45 GHz Microwave Doppler Radar," Engineering in Medicine and Biology Society, *EMBC*, pp.4336-4339, 2011 Annual Int. Conf. of the IEEE.

[11] Byung-Kwon Park, O. Boric-Lubecke and V. Lubecke. "Arctangent demodulation with DC offset compensation in quadrature Doppler radar receiver systems", *IEEE trans.Microwave Theory and Techniques*, vol.55, NO.5, pp.1073-1079, May 2007.

[12] B.-K. Park, V. Lubecke, O. Boric-Lubecke, and A. Høst-Madsen "Center tracking quadrature demodulation for Doppler radar motion detector," *IEEE/MTT-S Int. Microwave Symposium*, pp. 1323– 326, 2007.