Respiratory and Heart Rate Detection Using Continuous-Wave Radar Testbed Implemented in GNURadio

Isabella Lenz ILENZ@ASU.EDU
Jacob Holtom JHOLTOM@ASU.EDU
Andrew Herschfelt AHERSCHF@ASU.EDU
Yu Rong YRONG5@ASU.EDU
Daniel Bliss DWBLISS@ASU.EDU
Wireless Information Systems and Computational Architectures (WISCA) at ASU, Tempe, AZ, 85281, USA

Abstract

Demand for non-contact health monitoring devices has motivated a variety of radar-based vital sign measurement techniques. To demonstrate these techniques, we implement a simple respiratory and heart rate monitor using GNURadio and a commercial-off-the-shelf (COTS) software-defined radio (SDR). This implementation executes a Doppler-only, bi-static, continuous-wave radar application using an Ettus X310. We use GNURadio signal processing blocks to execute a simple respiratory and heart rate detection algorithm that extracts these vital signs from a subject within the radar's field of view. In several experimental trials, we demonstrate that the proposed technique successfully extracts the respiration rate and estimates the heart rate to within ± 5 BPM of a traditional heart rate monitor.

1. Introduction

Respiratory rate (RR) and heart rate (HR) are important metrics for assessing human health. These vital signs provide insight into a patient's respiratory and circulatory systems, which can aid clinical diagnosis and disease prevention (He et al., 2017).

The current standard for HR monitoring is the electrocardiogram (ECG), which requires electrodes to be attached directly onto a patient's body. This can be uncomfortable for the patient, and the measurement must be taken in a supervised clinical environment (Singh et al., 2021). RR is commonly measured informally by an observer counting chest wall movements, so RR assessments are usually intermittent and subject to human error (Van Loon et al., 2016). While the clinical standard only requires intermittent monitoring approaches, transitioning to continous. non-contact HR and RR monitoring techniques can provide healthcare professionals with significantly more information, allowing them to identify abnormalities faster and intervene sooner to improve overall patient outcomes (Tarassenko et al., 2006).

Since the 1970's, micro-power radar systems have been applied to non-contact human vital sign detection (Costanzo, 2019). Different types of radar systems have demonstrated limited success in the this area, including: continuous-wave (CW) Doppler (Hu et al., 2013; Xiao et al., 2006); ultra-wideband (UWB) impulse (Rong & Bliss, 2019; Leib et al., 2010); frequency-modulated, continuous-wave (FMCW) (He et al., 2017; Van Loon et al., 2016); and stepped-frequency, continuous-wave (SFCW) (Liu & Liu, 2014; Zhang et al., 2019). To extract RR and HR from these radar systems, various signal processing techniques have been applied with varying degrees of success, including: time-frequency analysis, numerical analysis, auto-regression algorithms, ranging and localization approaches, motion cancellation, and algorithms based on mathematical and experimental modelling (Kebe et al., 2020).

Most of this research was performed using small form factor (SFF) commercial radar sensors. While these devices are efficient and affordable, they typically only support the specific radar technique for which they were optimized.

To enable a broader set of radar techniques, we leveraged GNURadio and COTS software-defined radios (SDRs) to implement a non-contact RR and HR detection testbed. This testbed allows us to evaluate and compare multiple different radar techniques using the same hardware components. Furthermore, GNURadio provides the infrastructure to quickly implement these different radar and signal processing techniques, simplifying the development process and accelerating experimental validation of novel techniques.

Proceedings of GNU Radio Conference 2022,

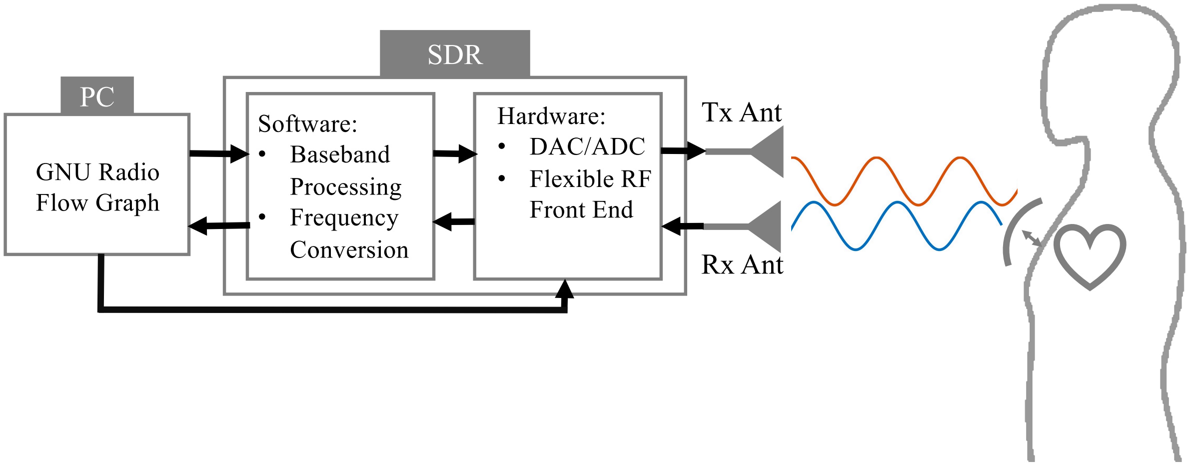


Figure 1. Processing diagram of the COTS SDR vital sign testbed. This application is implemented using a GNURadio flowgraph controlling an Ettus X310, which transmits and receives a continuous-wave (CW) radar waveform. We use GNURadio signal processing blocks to execute a simple respiratory and heart rate detection algorithm that extracts these vital signs from a subject within the radar's field of view.

2. Background

Non-contact, vital sign radars have demonstrated promising results, but these systems must be further improved before they are considered robust and reliable enough for consumer and clinical environments.

2.1. Ettus USRP SDR

Ettus research developed the Universal Software Radio Peripheral (USRP), a suite of programmable SDRs that combine field-programmable gate arrays (FPGAs) and RF front-ends (RFFEs) to streamline deployment of RF systems. The USRP's RF network-on-chip (RFNoC) framework allows a user to build an SDR application on the FPGA without having to interact with the digital infrastructure. GNURadio is an open-source tool that further simplifies this process (Ettus Research, 2022).

2.2. GNURadio

GNURadio is a radio software ecosystem that provides predefined signal processing blocks to simplify the implementation of RF applications (Project, 2001). GNURadio is free and open-source, and has a large community that contributes to the popularity and advancement of the platform. GNURadio applications are built by assembling a "flow graph" using these pre-defined signal processing blocks, then defining their connections to transport data through the processing chain (Patton, 2007).

2.3. Radar Based Vital Sign Detection

Vital sign radars measure respiratory rate (RR) and heart rate (HR) by transmitting a waveform at a patient and processing the reflection, which contains periodic modulations induced by the target's RR and HR (He et al., 2017). Several types of radars have been applied to this problem, including continuous-wave (CW) Doppler (Hu et al., 2013; Xiao et al., 2006); ultra-wideband (UWB) impulse (Rong & Bliss, 2019; Leib et al., 2010); frequency-modulated, continuous-wave (FMCW) (He et al., 2017; Van Loon et al., 2016); and stepped-frequency, continuous-wave (SFCW) (Liu & Liu, 2014; Zhang et al., 2019; Kebe et al., 2020).

Continuous-wave (CW) radar is one of the simplest and most common techniques applied to this applications In a typical configuration, a transmit (Tx) antenna sends a single-tone, continuous waveform towards a patient's chest, which is reflected and captured by the receive (Rx) antenna(s) (Kebe et al., 2020). The patient's RR and HR induce a modulation on the phase of this waveform as it is reflected, which can be measured at the receiver to estimate the RR and HR over time (Xiao et al., 2006).

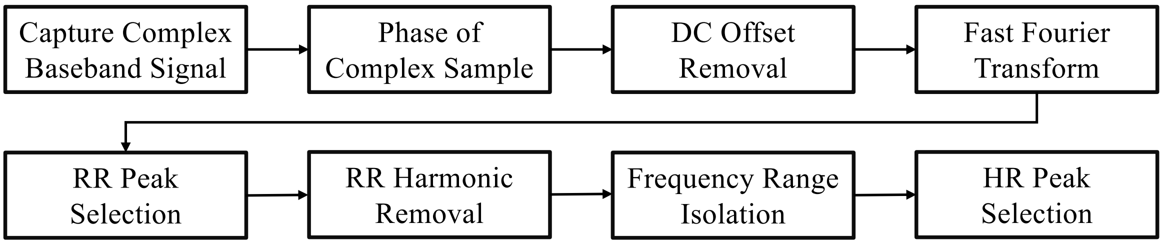


Figure 2. Processing chain of the simple RR and HR estimation technique executed in GNURadio.

3. System Design

We implemented a simple respiratory and heart rate monitor using GNURadio and a commercial-off-the-shelf (COTS) software-defined radio (SDR). This implementation executes a Doppler-only, bi-static, continuous-wave radar application using an Ettus X310. We use GNURadio signal processing blocks to execute a simple respiratory and heart rate detection algorithm that extracts these vital signs from a subject within the radar's field of view. The processing chain for this system is depicted in Figure 2.

3.1. Subject

To conduct a measurement trial, a subject sits in a chair approximately two meters from the bi-static SDR radar system. We align the antennas with the subject's chest and ask them to remain motionless and breathe normally. Each measurement trial lasts for two minutes.

3.2. Data Acquisition

We assembled a GNURadio flow graph to deploy the bi-static, continuous wave application on an Ettus X310. This application transmits a tone at 4 GHz and captures the reflection at a sampling rate of 4 MHz. We use an embedded Python block to implement in-line processing of the received data, while using other GNURadio signal processing blocks to execute real-time analysis. This flow graph is depicted in Figure 6.

3.3. Signal Processing

The processing chain for this application is summarized in Figure 2. This processing is executed using both GNURadio and MATLAB. Upon capturing a received complex baseband signal, we calculate the phase of each sample using a GNURadio signal processing block. We write this phase data to a file and execute the remainder of the processing in MATLAB.

After estimating the phase of each sample, we remove the DC offset, which consists of a static component induced by environmental clutter and a drift component induced by subject movement. This drift typically overpowers the respiration rate, so we remove it using a fifth-order polynomial fit over 60 seconds (implemented using MATLAB's `polyfit` function). We then remove the DC offset by simply subtracting this fit from the original data. This process is depicted in Figure 3.

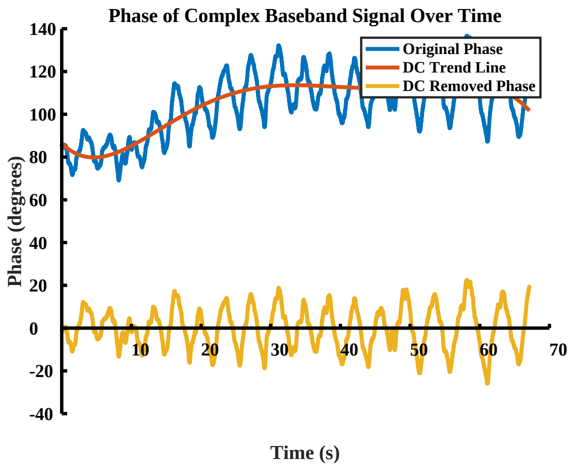


Figure 3. Depiction of the DC offset removal process. The original phase measurements (blue) are fitted using a fifth-order polynomial over 60 seconds (red). This fit is subtracted to remove the DC offset (yellow).

After removing the DC offset, we window the signal into 15-second segments with 5 seconds of overlap. We apply an FFT to each window and identify the largest peak in the frequency spectrum. We attribute this peak to the respiratory rate given that chest wall movements are an order of magnitude larger than heart movements. The FFT of one window is illustrated in Figure 4. To visually isolate the fundamental heart rate, we select peaks at integer multiples of the estimated RR (in this case 16 CPM) and zero-force them to the mean value of the noise floor. The result is illustrated in Figure 5.

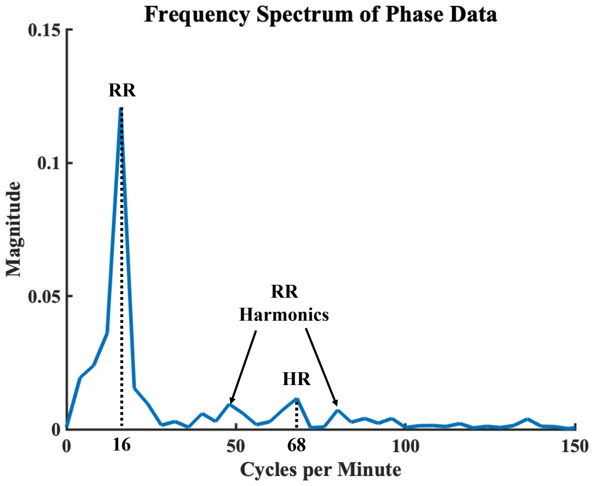


Figure 4. FFT of one 15-second window after DC offset removal. The respiratory rate and its harmonics are clearly visible at 16, 48, and 80 CPM. The heart rate is somewhat less visible at 68 CPM.

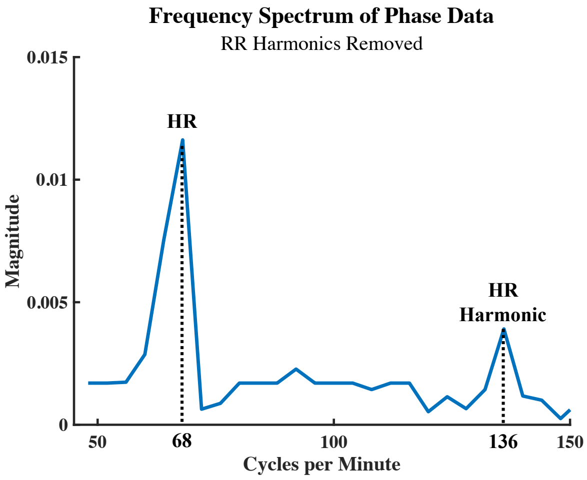


Figure 5. FFT after removal of respiratory rate harmonics. The heart rate and its harmonic are now clearly visible at 68 and 136 CPM.

3.4. Real-Time Processing Extension

To enable real-time processing of the received radar return, we extended the GNURadio implementation to process the data directly instead of exporting it to MATLAB. Using GNURadio's embedded Python block, we added a simple vector maximum detector and evaluate the angle of the maximum, which efficiently implements the previously discussed peak detection. We stream this data over ZeroMQ to a small Python script to display the results in real-time and execute batched post-processing. In the future, this post-processing could also be executed in GNURadio using a custom, out-of-tree module.

4. Results

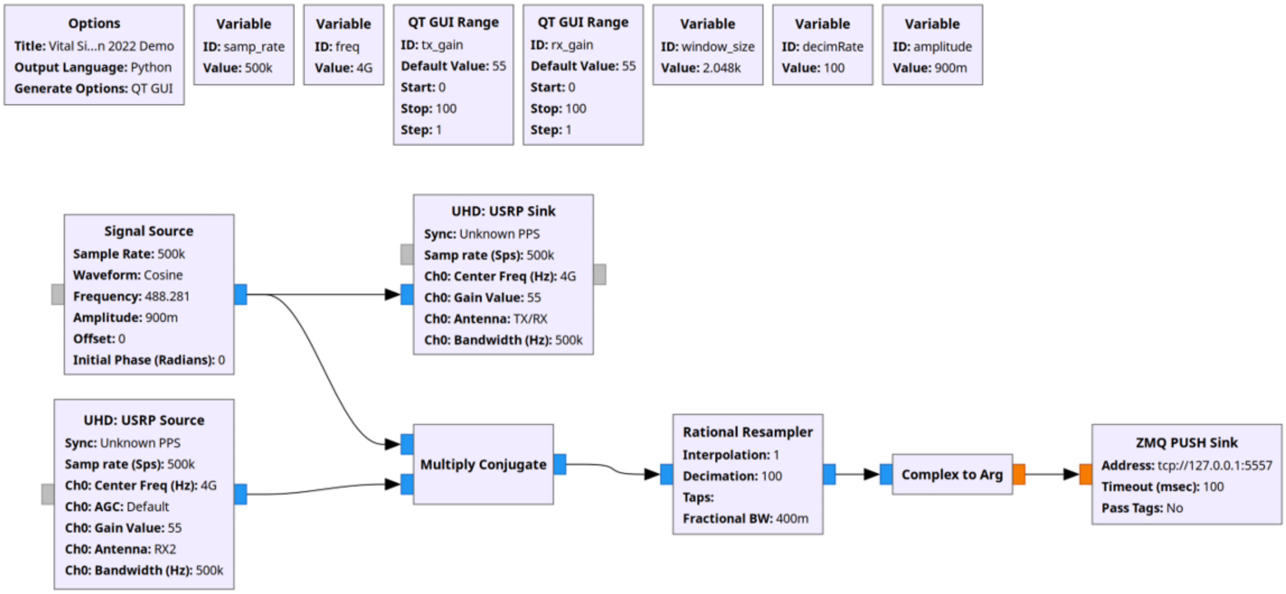
We collected two sets of data from two subjects for a duration of 90 seconds each. We estimated RR and HR using 15-second windows with 5 seconds of overlap for a total of 8 frames. We compared the RR estimates to a manual breath count and the HR estimates to a pulse oximeter worn during the data collection. For Subject 1, the estimated HR was within ± 5 BPM of the reference oximeter. For Subject 2, the estimated HR was within ± 8 BPM of the reference oximeter. These results are summarized in Table 1.

5. Conclusion

We implemented a simple respiratory and heart rate monitor using GNURadio and a COTS SDR. We use GNURadio signal processing blocks to execute a simple respiratory and heart rate detection algorithm that extracts these vital signs from a subject within the radar's field of view. In several experimental trials, we demonstrate that the proposed technique successfully extracts the respiration rate and estimates the heart rate to within ± 5 BPM of a traditional heart rate monitor.

Window	Subject 1				Subject 2			
	RR		HR		RR		HR	
	Reference	Results	Reference	Results	Reference	Results	Reference	Results
1	16	16	67	64	8	16	84	92
2		16		68		4		84
3		16		68		8		68
4		16		68		8		76
5	12	12		68		8		84
6		12		72		8		84
7		12		72		8		76
8		12		72		8		76

Table 1. Experimental RR and HR results compared to reference measurements for two subjects over 90 seconds.



Options
Title: Vital Si...n 2022 Demo
Output Language: Python
Generate Options: QT GUI

Variable
ID: samp_rate
Value: 500k

Variable
ID: freq
Value: 4G

QT GUI Range
ID: tx_gain
Default Value: 55
Start: 0
Stop: 100
Step: 1

QT GUI Range
ID: rx_gain
Default Value: 55
Start: 0
Stop: 100
Step: 1

Variable
ID: window_size
Value: 2.048k

Variable
ID: decimRate
Value: 100

Variable
ID: amplitude
Value: 900m

Signal Source
Sample Rate: 500k
Waveform: Cosine
Frequency: 488.281
Amplitude: 900m
Offset: 0
Initial Phase (Radians): 0

UHD: USRP Sink
Sync: Unknown PPS
Samp rate (Sps): 500k
Ch0: Center Freq (Hz): 4G
Ch0: Gain Value: 55
Ch0: Antenna: TX/RX
Ch0: Bandwidth (Hz): 500k

UHD: USRP Source
Sync: Unknown PPS
Samp rate (Sps): 500k
Ch0: Center Freq (Hz): 4G
Ch0: AGC: Default
Ch0: Gain Value: 55
Ch0: Antenna: RX2
Ch0: Bandwidth (Hz): 500k

Multiply Conjugate

Rational Resampler
Interpolation: 1
Decimation: 100
Taps:
Fractional BW: 400m

Complex to Arg

ZMQ PUSH Sink
Address: tcp://127.0.0.1:5557
Timeout (msec): 100
Pass Tags: No

Figure 6. GNURadio Flow graph used for the real-time processing implementation

References

Costanzo, Sandra. Software-defined doppler radar sensor for human breathing detection. *Sensors*, 19(14):3085, 2019.

Ettus Research, a National Instruments Brand. The leader in software defined radio (sdr), 2022. URL `https://www.ettus.com/`.

He, Mi, Nian, Yongjian, and Gong, Yushun. Novel signal processing method for vital sign monitoring using fmcw radar. *Biomedical Signal Processing and Control*, 33:335–345, 2017. ISSN 1746-8094. doi: https://doi.org/10.1016/j.bspc.2016.12.008. URL `https://www.sciencedirect.com/science/article/pii/S1746809416302208`.

Hu, Wei, Zhao, Zhangyan, Wang, Yunfeng, Zhang, Haiying, and Lin, Fujiang. Noncontact accurate measurement of cardiopulmonary activity using a compact quadrature doppler radar sensor. *IEEE Transactions on Biomedical Engineering*, 61(3):725–735, 2013.

Kebe, Mamady, Gadhafi, Rida, Mohammad, Baker, Sanduleanu, Mihai, Saleh, Hani, and Al-Qutayri, Mahmoud. Human vital signs detection methods and potential using radars: A review. *Sensors*, 20(5):1454, 2020.

Leib, Mario, Menzel, Wolfgang, Schleicher, Bernd, and Schumacher, Hermann. Vital signs monitoring with a uwb radar based on a correlation receiver. In *Proceedings of the Fourth European Conference on Antennas and Propagation*, pp. 1–5. IEEE, 2010.

Liu, Lanbo and Liu, Sixin. Remote detection of human vital sign with stepped-frequency continuous wave radar. *IEEE journal of selected topics in applied earth observations and remote sensing*, 7(3):775–782, 2014.

Patton, Lee K. A gnu radio based software-defined radar. Master's thesis, Wright State University, 2007.

Project, GNU Radio. The free & open source radio ecosystem · gnu radio, 2001. URL `https://gnuradio.org/`.

Rong, Yu and Bliss, Daniel W. Remote sensing for vital information based on spectral-domain harmonic signatures. *IEEE Transactions on Aerospace and Electronic Systems*, 55(6):3454–3465, 2019.

Singh, Anuradha, Rehman, Saeed Ur, Yongchareon, Sira, and Chong, Peter Han Joo. Multi-resident non-contact vital sign monitoring using radar: A review. *IEEE Sensors Journal*, 21(4):4061–4084, 2021. doi: 10.1109/JSEN.2020.3036039.

Tarassenko, L, Hann, A, and Young, D. Integrated monitoring and analysis for early warning of patient deterioration. *BJA: British Journal of Anaesthesia*, 97(1):64–68, 2006.

Van Loon, K, Breteler, MJM, Van Wolfwinkel, L, Rheineck Leyssius, AT, Kossen, S, Kalkman, CJ, Van Zaane, B, and Peelen, LM. Wireless non-invasive continuous respiratory monitoring with fmcw radar: a clinical validation study. *Journal of clinical monitoring and computing*, 30(6):797–805, 2016.

Xiao, Yanming, Lin, Jenshan, Boric-Lubecke, Olga, and Lubecke, M. Frequency-tuning technique for remote detection of heartbeat and respiration using low-power double-sideband transmission in the ka-band. *IEEE Transactions on Microwave Theory and Techniques*, 54 (5):2023–2032, 2006.

Zhang, Zhu, Nian, Yongjian, Chen, Jiawei, and He, Mi. An experimental study to optimize the stepped-frequency continuous-wave radar parameters for noncontact multi-target vital sign monitoring. In *2019 IEEE International Conference on Computational Electromagnetics (ICCEM)*, pp. 1–4. IEEE, 2019.