Detecting Heart Rate Variability using Millimeter-Wave Radar Technology

Eyhab Al-Masri, Misba Momin
School of Engineering and Technology
University of Washington Tacoma
{ealmasri, misbam}@uw.edu

***Abstract*—Identifying cardiac abnormalities has mainly been determined by the observation of electrocardiogram (ECG) signals. To collect ECG signals, it is often necessary to place ECG electrodes on the body for critical analysis of ECG data transmitted by such electrodes. By analyzing this collected data, it is then possible, for example, to examine the intervals between the heartbeats (or R-R intervals) to measure the heart rate variability (HRV). However, this process requires a multilayered setup for both hardware and software which can be costly and time consuming. To overcome these challenges, we introduce in this paper a real-time millimeter-wave radar-based, non-contact vital sign monitoring system that is capable of detecting the heart variability rate without the use of any heart rate sensors or wires required. Through this system, it is then possible to detect any heart rate abnormalities by analyzing the collected data. Throughout the paper, we present results for three individuals and compare our approach to heart rate monitoring devices and Apple Watch.**

I. Introduction

In order to accurately determine any cardiac abnormalities, it is common to utilize electrodes that can detect Electrocardiogram (ECG) signals for further analysis. In this process, an individual is required to place such electrodes in a certain orientation in order to detect ECG signals which are used to then represent the heart activity. Researchers on separate efforts have explored various methods to identify cardiac abnormalities such as power spectrum analysis [1], Hilbert transform analysis [2], neural networks [3], among many others. However, very little research has been conducted on the feasibility of detecting cardiac abnormalities remotely or from a distance without the use of electrodes or wiring systems. It would be desirable to determine the viability of using new technologies that can detect heart rates from a distance with minimal or no wiring required.

Recent advancements in the development of low cost wearable technologies and body sensor devices have provided a mechanism for monitoring an individual's health. For example, mobile devices such as Samsung Galaxy (S5, S6 Edge+, S8+, S9+, Note 9), Lenovo Zuk Z2 Pro, Nokia 8, among many others are equipped with heart sensors that can measure the heart rate. In addition to mobile phones, some watches, chest straps, armbands and fitness trackers are also equipped with sensors that can detect or monitor heart rates such as Apple Watch, Polar (A370, H10), Fitbit (Charge), Garmin (Forerunner, Tactix, Vivosport, Vivofit), Suunto (Spartan), TomTom (Spark 3), Scosche (Rhythm24 HR) among many other devices. Some of these devices apply light to track blood movements by illuminating the capillaries using a light-emitting diode (LED) [4] or via photoplethysmogram (PPG). However, whether these devices are accurate or medically beneficial still remains under investigation by members of the research community [5-7].

Furthermore, traditional approaches used in hospitals for monitoring and detecting cardiac abnormalities has mainly relied on placement of ECG electrodes on the body of patients while clinical staff observe heart conditions. These electrodes measure, for example, electric current caused by the electronic pulses as a result of the depolarization and repolarization of the heart chambers. Such measurements enable the extraction of valuable information that can be used for heart rate monitoring such as beats per minute (BPM), QRS waveforms, breathing patterns, among others. Using this information, it is then possible to determine abnormal heart rhythms, or what is known as arrhythmia.

Although analyzing ECG signals for heart abnormalities has proven to be successful, the setup time and cost associated with the application of the necessary hardware and software required remains cumbersome. It would be desirable to investigate the use of existing technologies such as millimeter-wave (mmWave) radar in the detection of heart rate abnormalities while minimizing the hardware and software required in this process. A mmWave signal is a type of radar that operates in the range of short-wavelengths from 1cm to 1mm [8]. The short wavelength in this electromagnetic spectrum makes mmWave a suitable technology for collecting readings with high accuracy. For example, a mmWave system operating at 76-81 GHz (with wavelength of 4mm) is capable of detecting object movements that are small as a fraction of 1mm and can reliably detect moving or stationary objects [9].

Using existing technologies such as that of mmWave, it is then possible to detect vital signs at early stages to avoid sudden cardiac failures. To achieve this, we investigate the use of the mmWave technology using the frequency-modulated continuous wave (FMCW) to continuously monitor the heart activity and detect any heart abnormalities. Our current research work emphasizes on developing a wearable device that examines the heart rate variability (HRV) which can be used as an arrhythmia detection system at early stages using the mmWave technology. We tested our system and results show high accuracy compared to existing wearable devices such as Apple Watch and heart rate monitoring devices.

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II. METHODOLOGY

Our methodology for detecting heartbeat abnormalities is based on the AAMI's convention [10] that focuses primarily on the heart beats per minute (bpm). Examining the heart rate data over a period of time (e.g. days or months) can help us identify the degree of the variability in the heart rate with respect to the beat-to-beat alterations. By analyzing the heart's data, it is then possible to detect arrhythmia and determine any heart abnormalities at early stages. We use AAMI's convention for heart rate classification such that (a) a normal sinus heart rhythm ranges between 60-100 bpm, (b) a bradycardia represents a heart rate with lower than 60 bpm and (c) a tachycardia with heart rate exceeding 100 bpm. By analyzing the collected data, we would like to determine the frequency of any abnormal heartbeat readings (assuming an individual is not performing any activity such as walking, running, etc.).

To achieve the objectives of this project, we used a sensor from Texas Instruments that uses mmWave radar technology. In particular, we used the IWR-1443 evaluation board [11] to conduct the experiments for the purpose of this research. The EVM is powered by a 5V/2.5A power supply and connects to a laptop via a micro USB cable. We use TI's mmWave SDK and libraries [12] for running an application that continuously capture the readings from the mmWave board.

In order to test the accuracy of the mmWave readings, we integrated an Apple Watch into the system to be able to compare the results generated by the mmWave and that of Apple Watch. We applied the readings during mornings and evenings. We also integrated a blood pressure reading machine. A high-level overview of the developed system is shown on Figure 1 and Figure 2 presents a graphical user interface displaying the real-time results.

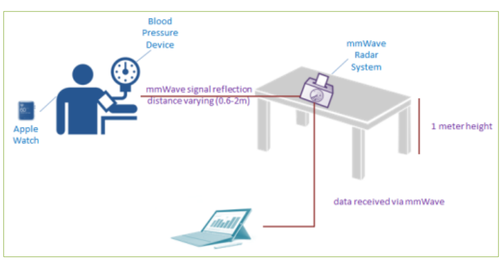

Fig. 1. An Overview of our mmWave Radar System Architecture

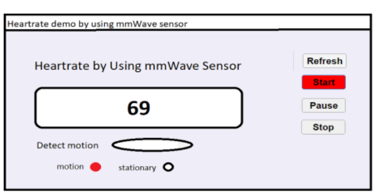

Fig. 2. Heart Rate Monitoring Software Interface

III. EXPERIMENTS AND RESULTS

In order to test the accuracy of our mmWave radar system, we conducted real-time heart rate data collection for three individuals who have volunteered to use the system. The contactless mmWave system was placed approximately 1 meter from ground. Each user was asked to remain stationary during the experimentation process. To determine the most effective readings of mmWave radar technology, we varied the distance between the board and the users from 0.6 meter up to 2 meters. In parallel, readings from Apple Watch and the heart rate monitoring device were also acquired for the users. Figure 3 presents the heartbeat readings over four distances: (a) 0.6 meter, (b) 1 meter, (c) 1.5 meter and (d) 2 meters for user 1.

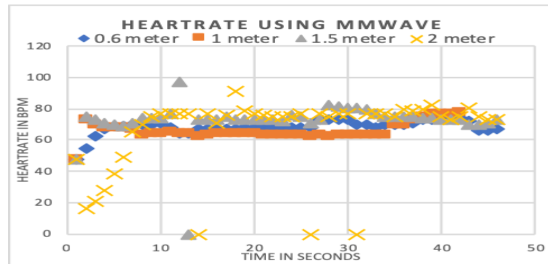

Fig. 3. Heat Rate Readings for User 1

As can be seen from Figure 3, the range of heartbeats with varying the distance is primarily between 62 and 74 bpm. It is observed that the 0.6 meter and 1 meter distance provide more comparable readings while those of 1.5 meter and 2 meter show some spikes. This suggests that the accuracy of mmWave readings for heartbeats degrades as distance increases. This is evident with the 2 meter readings which are less consistent in terms of the providing accurate readings. For example, in the first ten seconds, Figure 3 shows an exponential increasing pattern for the 2 meter experiment.

In addition, for the longest distance experiment (2 meters), it is observed that the readings become more stable after the 10th second while they begin to fluctuate after the 40th second. These observations were also compared to the remaining two users that tested the system and appear to also hold true. The same interpretation also applies to 0.6 meters readings in which the system begins to read at lower values below 50bpm and after 10 second begins to stabilize or provide consistent readings. We further tested the accuracy of the readings by comparing them to the blood pressure machine. Results generated from the blood pressure (BP) machine for user 1 during the same reading period of the mmWave sensor is shown on Figure 4. Furthermore, recordings of heart beats per minute using Apple Watch for user 1 is shown on Figure 5.

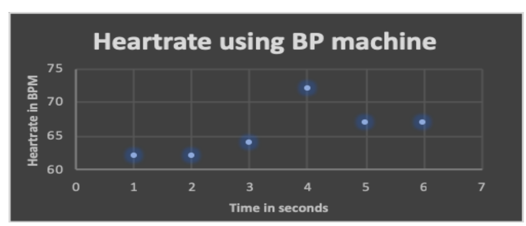

Fig. 4. Heartrate Reading using the BP Machine of User 1

As can be seen from Figure 5, the range of heartbeat readings for Apple Watch matches that of the mmWave lower bound but has a slightly higher upper bound. For example, Apple Watch provides bpm in the 80s in the initial stages and gradually decreases for few seconds and then begins fluctuating every 8 to 9 seconds. Based on the results from Figures 3, 4 and 5, we observe that the readings of the blood pressure device appear to closely resemble that of our mmWave system.

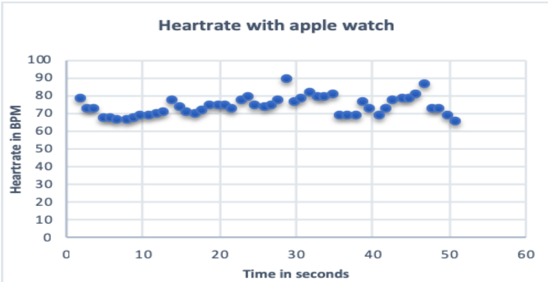

Fig. 5. Heartrate Readings using Apple watch for User 1

Blood pressure devices have proven to be successful in measuring and reporting accurate heart rate readings. Hence, by investigating the standard deviation and analyzing the data from three users who tested our mmWave system, we believe that the mmWave provides accurate readings that closely resemble that of blood pressure devices. Furthermore, We also observed that Apple's Watch readings seem to be inconsistent particularly when the watch goes to idle mode (i.e. home screen) which is represented by the spikes appearing during 13th, 28th and 47th seconds.

Based on the results from Figures 3, 4 and 5, we also observe that the readings of the mmWave at 0.6 meter or 1 meter are consistent with those of the blood pressure machine. This suggests that the preferred distance for obtaining accurate readings for mmWave is between 0.6-1 meters. As distance increases, the number of false readings begins to increase significantly. This is evident by the readings of user 1 for the two meters' distance. Furthermore, we provide on Table I additional data collected from the three users who tested our system at a distance of 0.6 meters.

TABLE I. HEARTRATE OF USER I, II AND III FOR 0.6 METERS

User I	User II	User III
48	68	77
48	48	48
69	75	70
73	75	70
67	79	70
67	74	71
67	74	73
67	74	74
67	76	75
68	71	75
68	70	75
68	70	75
68	76	75
68	77	75

As can be seen in Table I, the first two readings for User I and second reading for Users II and III show a heartbeat of 48. This can be attributed to the fact that the mmWave radar system requires some calibration or time to transmit the first signal when turned on. We observed that the mmWave sensor requires approximately 2.5 seconds for properly transmitting the correct readings. The results from Table II show that the heartbeat readings for all users fall within the sinus normal rhythm (i.e. between 60-100 bpm). We can use this information to determine the heart rate variability (HRV) and hence detect any abnormal heartbeats. In addition, this information can then be used in more advanced machine learning algorithms that can detect heart rate abnormalities and further classify them into sinus normal rhythm, bradycardia or tachycardia.

IV. CONCLUSION

In this paper, we presented a mmWave radar system that can be used to detect heartbeat readings in a contactless manner. Results from testing our system show that mmWave radar technology provides high accuracy compared to conventional heartbeat monitoring devices such as blood pressure devices. We further compared our results for three users who tested our mmWave system to that of Apple Watch and we also determine consistency in terms of the heart rate variability. In addition, we tested the impact of distance on the accuracy of the mmWave and determined that mmWave radar technology provides more accurate readings or performs best when the radar system is placed near the user in the range of 0.6m-1.0m. Furthermore, based on our analysis in this study, we believe that the mmWave radar technology can be used as an alternative solution for collecting heart rate monitoring. In addition, we believe that it also provides a reliable, contactless mechanism for detecting heartbeats.

For future work, we plan to extend this system to utilize a neural network that can be used to analyze collected data and classify heart activity as normal, bradycardia or tachycardia. In addition, we plan to extend this project to investigate the use of mmWave technology to collect ECG features such as QRS complexes, RR-interval, among others.

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