Less Contact: Heart-rate detection without even touching the user

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Abstract

Heart-rate sensing is very important. Whereas there are different methods and commercial products available, they all have a common drawback: the user has to mount some piece of sensor to his body. This paper provides a case study on how micro-impulse radar (MIR) can be used to sense heart-rate in a contact-free manner. With a sequence of tests the robustness of radar to different placements and even distances from the subject is shown. Since MIR is also cheap and power-efficient this paper suggests heart-rate sensing through radar as a promising approach.

1. Introduction: The importance of heart-rate

Vital sensing has become very important today due to a variety of reasons. Aging of our society has never been more relevant nor more problematic than today: people aged 65 and older are the fastest-growing segment of the US population; by 2030 over 4 million Americans will be over age 85 [8]. This creates new demands of providing adequate and effective health care.

The goal of wearable and ubiquitous computing is to support users in their everyday physical environment with information and computing. This same concept of computing everywhere can support independent living of elderly adults in their home environments [7]. Furthermore, real-life long-term monitoring of health could also be useful for measurement of treatment effects at home, in the situation where the subjects live their daily life. Additionally, continuous heart-rate monitoring can also provide more safety in critical situations (e.g. car-driving, ski-hiking [15]) by initiating actions based on the sensor readings (e.g. emergency call, automatic conrol).

Though health monitoring in out-of-hospital conditions has been of interest to researchers and health care practitioners for a long time [12], novel ubiquitous computing technologies can provide opportunities to implement these scenarios in real-life settings, with allowable cost and with improved user satisfaction.

From interviews with emergency physicists in a previous project we learned that heart rate is the most important vital sign [15]. The huge variety of available heart-rate monitoring wrist watches indicates a high demand on those devices. Many research projects, e.g. [14], as well as a number of commercially available products, provide solutions [4] [1] to reveal the user's heart rate in mobile settings: most common are heart-rate monitors that obtain ECG measurements through a worn chest strap and wirelessly transmit this data to a watch on the user's wrist. The chest strap has to be fixed quite tight, which users may dislike. Another possibility for measuring heart rate is oximetry [6]. It has a firm place in clinical practice, but it is also used in various research projects [13] [15] In the experiments we conducted [15], subjects reported that the sensor did not disturb them during their activities, once wrapped around toe or finger. However, both ECG and oximetry require the user to attach and wear a sensor on his body. This sensor has to be placed appropriately in order to guarantee valid measurements. People are not used to sensors in their everyday life, thus their compliance is very low. The ideal solution would consist of a sensing system that does not require any contact to the user: the user is not touched by a sensor at all. Accordingly, the sensing process could be unobtrusive to the user. One's heart-rate could be continuously monitored and wireless transmission of this data could allow remote signal analyzation. In this paper we show how a low-distance radar can come very close to this vision.

2. Heart-rate detection with radar

The basic principle of radar is to transmit a microwave (radio) signal towards a target. The strength of the backscattered signal is measured. With regards to heart rate detection it is noteworthy that electro-magnetic pulses are able to probe the human body.

There are different variants of radar. Constant wave (CW) radar emits a continuous beam of electro-magnetic radiation. The radar vital sign monitor (RVSM) [11] is one example for this technology. A gun device transmitter radiates a signal to a target, the energy reflected from the target is detected by a mixer diode: any Doppler shift from subject movement, including heart movements, causes a change in the phase between the transmitted and received signal. Several filters separate heartbeat and respiration. Valid measurements could be taken at a range exceeding 10 meters. However, this requires a microwave sender/receiver unit mounted onto a parabolic dish.

Another variant of radar is micro impulse radar (MIR) [9]. MIR uses very short radar impulses lasting only a few nanoseconds. Unlike conventional radar, emitted MIR pulses are spread over a wide frequency spectrum, referred to as ultra-wide-band. The advantage of MIR is the low energy consumption due to the short pulses. A MIR exists of several units. A pulse generator defines when the transmitter should emit a pulse over the antenna. Simultaneously, the pulse-generator activates a so-called delay line. This delay line is used for controlling the sampling of the received echoes at the receiver: the receiver is only activated at very short time intervals triggered by the delay-line (range gating). Thus, the length of the delay-line ensures that only pulses back-scattered from a certain distance are received. In the context of heart-rate detection the goal is to adjust the delay-line such that the receiver is activated only if echoes from the heart wall can be expected ([17] predicts a time interval of approx. 1.7 ns).

MIR technology opens new possibilities for contact-free heart-rate sensing as it works through clothes or blankets and at a distance of several meters, whereas previous projects mostly focussed on sensing of humans behind barriers exceeding several meters [10] [11] [2]. Moreover, MIR technology is cheap (costs are only a few euros) and power efficient.

In this paper we want to shape a wearable heart-rate sensing solution that operates in the close proximity of the user: the radar unit is worn by the user without the need of placing any additional sensor onto the body.

3. Prototype implementation

We have built a first prototype on a bread-boarded layout based on the description of [18]. Then the signal is amplified by a factor of thousand and passed to a bandpass filter that allows signals from 0.5 to 2.5Hz to pass. This filtered signal is feed to a second amplifier digitally adjustable between 1-20 fold amplification. After that the signal is shifted to a zero-to-five-volts range, such that it can be sampled by the A/D converter of a microprocessor. Currently a sampling rate of approximately 80Hz is achieved. Besides signal sampling and evaluation, the PIC micro-processor also controls both the second amplifier and the delay-line determining the travelled distance of received radar waves. This allows to control the radar parameters by software. For implementation the DIY Smart-it platform [3] was chosen, since its infrastructure has proven useful for rapid prototyping in projects before (see Fig. 1). A serial interface on the Smart-it provides connectivity to a PC for both controlling the radar parameters, amplification and delay-line, and for evaluating the radar output. In addition, an oximeter [5] connected to a second serial port of the PC serves as a reference signal [1] for verifying the radar output. A PC client software (see Fig. 1) plots both radar and oximeter data as well as the derived heart rate in real-time. The software also allows to manually tune the radar parameters by keyboard inputs.

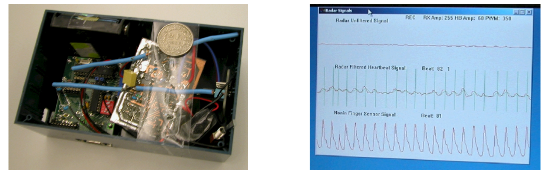

Figure 1. Smart-It with radar (l.), PC client (r.)

This direct-manipulation of the radar parameters and the real-time visualization was important for proving the concept of detecting heart-rate with radar in the simplest situation: person lying on the ground with the radar on his chest.

Logs of the data allow further analysis and a comparison of different sensor placements (see section 4).

As the ultimate goal of this project is the development of a wearable heart-rate sensing device, an algorithm was designed that is able to run with low computing power such as is available on a microprocessor. Due to the memory constraints of the micro-controller (326 bytes working memory), it is important to process data on-the-fly without the need of additional flash memory. The algorithm comprises the following five steps containing only basic arithmetic operations: filtering, local maxima detection, evaluation of distance between maxima, and division.

1. **Filtering.** From practical experience we found that simple data filtering could improve the data although the analogous radar signal had been filtered before. A simple filter only balancing between two consecutive values proved sufficient:

   $$\tilde{x}(t_{i+1}) = cx(t_{i+1}) + (1-c)x(t_i)$$

   The constant c weights the influence of the previous and the current value onto the new value: if chosen 0 the new value is equal to the previous, if chosen 1 the new is equal to the current value. We found 0.15 as an appropriate weight for the radar signal sampled at a frequency of approximately 80Hz. With this filter the radar signal can be smoothed for better processing without requiring data storage.

[1] due to the natur of continuous radar readings the plethysmograph oximetry readings represented a better reference than discrete HR readings of an ECG monitor

2. **Local maxima detection.** Local maxima are searched inside a search window of 20 samples. Filtering of the previous step ensures that frequencies producing more than 8 maxima per 20 samples are cut off. The detected local maxima are stored in an array.

3. **Evaluation of distances between maxima.**. Then the distances in time (period) between all local maxima are calculated and analyzed for regularly occurring patterns: occurrences of a distance four times or higher has proven as a reliable indication of a regularly occurring maximum: all maxima with this distance are presumably stemming from the heart-beat.
4. **Division** As the last step the regularly occurring distance is divided through a constant and delivers the heart rate as a result.

This simple algorithm is run on the PIC micro-controller. This allows for a wearable implementation of a radar heart-rate sensing device without the need for sophisticated PC infrastructure.

4. Measurement results

We conducted several measurements to evaluate the usability of MIR for detecting heart rate. We measured a sequence of data over 30s and collected the raw signal data on a computer. Simultaneously the test person wore an oximeter [5] at the finger. This allowed us to compare how the raw radar data matched the oximeter signal. First, we tested different distances between radar device and test person in order to evaluate the robustness to displacements. Secondly, we explored different placements on the human body for determining placements with valid measurement results. Finally, we also tested whether equal measurement results can be obtained from different test persons. We also tested the influence of varying heart-rate.

4.1 Distance Test

In this test the goal was to compare radar measurements from different distances to the test subject. We mounted the radar unit to a wall and placed a subject in front of the device (see Fig. 2). The distances we measured were 5cm, 10cm and 15cm. Beyond 15cm we could not obtain reasonable results anymore.

d	HR: radar	HR: oxim.	rel. err	std err
5cm	83.28	83.61	2%	1%
10cm	95.90	92.66	8%	8%
15cm	89.18	91.25	5%	4%

Table 1. Distance test results

Table 1 shows a statistical evaluation of the distance test. The first column of values contains the mean of heart-rate measurements over the measurement period obtained by radar and evaluated by the algorithm described in section 3. The second column shows the oximeter results. The third and fourth column show the mean and standard deviation of the relative error comparing radar with oximeter measurements. Though radar measurements are obviously less accurate than oximeter measurements it is an interesting result that even at distance of 15cm the relative error is in a range of 5%. Radar has the great potential of reporting reasonable heart-rate measurements from a greater distance of the test person. In contrast to that, if an oximeter or ECG chest strap is moved away for some millimeters it cannot report any meaningful results anymore. This opens the space for radar heart-rate detection to support applications were sensors can get ripped off but measurements, even with less quality, are still important.

Figure 2. Distance Test

4.2 Placement Study

We also tested different placements of the radar at a test person's arm, femoral, left and right side, at the height of the chest, and at the back.

placement	HR: radar	HR: oxim.	rel. err	std err
arm	73.98	73.86	1%	1%
femoral	69.98	69.97	3%	2%
side l 0cm	78.87	82.05	4%	3%
side l 5cm	76.78	77.83	9%	7%
side r 0cm	81.06	84.45	6%	5%
back	92.85	88.17	13%	9%

Table 2. Placement study results

Table 2 shows the results of the placement study. It is remarkable that the measurements at the arm and femoral have a high validity. This stems from the fact, that in this case the radar does not measure movements of the heart but movements of vessels which correlate with the heart rate as well. Measurements at the sides of the body reveal less good results due to the greater distance to the heart. Another reason is organs on the way between radar and heart from this viewing perspective, accordingly the measurements at the right side are worse than on left side. Again, the measurement quality also varies with the distance. With a relative mean error of 13% measurements, taken at the back of the person's back lead to the lowest measurement quality.

However, for revealing more qualitative vital sign data, e.g. distinction between ”dead” or ”alive”, even measurements at the back could be sufficient. Accordingly, the placement study shows that radar is very tolerant with regards to placement. This fact makes radar heart-rate detection very distinct from other measurement methods.

4.3 Gender differences

In the course of several tests with five subjects (3 male, 2 female) we found slight differences in the measurement quality of radar compared to oximeter readings. The validity of the measurements is higher with males: Due to the female breast the distance between radar and heart is bigger. Measurements taken from male subjects are slightly more reliable. However, more extensive studies will have to be conducted to quantify the measurement differences among genders.

5. Discussion

Within this paper we have shown how micro-impulse radar can be used for detecting heart rate. In contrast to many other vital sensing techniques, radar offers a very cheap and power efficient way for achieving this goal. It could be shown that the output signal of the radar and oximeter signal correlate at different distances, placements, and with different persons. However, parameter tuning of the radar is essential. The most critical parameter is the delay-line: it has to be adjusted such that the radar receiver only samples backscattered signals from the heart rate. Different distances and placements require adjustments of the delay line. Also different test persons require different settings due to their anatomic properties. On the one hand the delay-line defining the reach of the radar signals makes the use of radar very flexible. Even if the radar unit gets ripped off it can still provide meaningful data. On the other hand, the process of parameter tuning is tedious, so that future work will have to focus on automating this tuning process, i.e. gradually changing the parameter until a well-formed heart signal can be received. Since radar can sense movements of the heart, it simultaneously also senses all kinds of other movements of the body. Whereas there is a variety of applications where movements are not an issue, e.g. avalanche victims, monitoring elderly overnight, future work may also focus on the usage of radar as a new sensor for detecting or classifying body movements. Other improvements could be the use of more elaborate signal processing techniques, or research on new antennas improving the analogous received signal [16].

6. Conclusions

We have shown that radar offers an interesting way of heart-rate sensing for wearable computing. Especially its robustness to different placements offers the opportunity to integrate radar into existing devices and appliances, e.g. PDA's, laptops, mp3-players, mobile phones. Children, elderly, athletes, patients, etc. could take advantage of heart-rate sensing without the need of wearing additional sensors. Radar integrated into devices can make heart-rate sensing invisible and users do not have to be touched. On the other hand, also new privacy issues may arise: How can I keep my heart-rate secret from other people?

References

[1] Polar Electro. http://www.polar.fi.

[2] SIRIUS PLS. http://www.selectronic.de.

[3] Smart-its. http://ubicomp.lancs.ac.uk/smart-its/.

[4] SmartShirt technology. http://sensatex.com.

[5] XPOD. http://www.nonin.com/xpod.html.

[6] Principles of pulse oximetry. Clinical monograph, 1991.

[7] G. Abowd, A. Bobick, I. Essa, E. Mynatt, and W. Rogers. The Aware Home: Developing Technologies for Successful Aging. In *AAAI Workshop and Automation as Care giver*, 2002.

[8] R. N. Anderson. Method for Constructing Complete Annual U.S. Life Tables. National Center for Health Statistics. *Vital and Health Stat,*, 2(129), 1999.

[9] S. Azevedo and T. McEwan. Micropower Impulse Radar. *Science & Technology Review*, pages 16–29, January/February 1996. http://www.llnl.gov/str/.

[10] K. Chen, Y. Huang, H. Zhang, and A. Norman. Microwave life-detection systems for searching human subjects under earthquake rubble or behind barrier. *Biomedical Engineering, IEEE Transactions on*, 47:105–114, 2000.

[11] E. Greneker. Radar sensing of heartbeat and respiration at a distance with applications of the technology. In *Radar 97*, pages 150–154, 1997.

[12] I. Korhonen and P

[13] P. Lukowicz, U. Anliker, J. Ward, G. Troster, E. Hirt, and C. Neufelt. Amon: A wearable medical computer for high risk patients. In *Proceedings of the 6th International Symposium on Wearable Computers*, pages 133–134, 2002.

[14] T. Martin, E. Jovanov, and D. Raskovic. Issues in wearable computing of a wearable ECG monitoring device. In *Proceedings of the fourth International Symposium on Wearable Computing (ISWC 2000)*, pages 43–49. IEEE Press, 2000.

[15] F. Michahelles, P. Matter, A. Schmidt, and B. Schiele. Applying Wearable Sensors to Avalanche Rescue: First Experiences with a Novel Avalanche Beacon. *Computers & Graphics*, 27(6):839–847, 2003.

[16] H. Schantz. Bottom Fed Planar Elliptical UWB Antennas. In *IEEE UWBST 2003 Conference Proceedings*, 2003.

[17] E. Staderini. UWB radars in medicine. *Aerospace and Electronic Systems Magazine*, 17(1):13–18.

[18] E. M. Staderini. Everything you always wanted to know about uwb radar... Online Symposium for Electronics Engineers. Web broadcasted on Jan 16th 2001 ,http://www.osee.net/whitepapers/paper4.pdf.