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Contactless and Unobtrusive Measurement of Heart Rate in Home Environment

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Abstract—**Current technology trends, such as ubiquitous computing and calm technology, call for novel unobtrusive sensors. The commonly used heart rate monitoring techniques require direct contact to the patient which makes the patient well aware of the sensors. In this paper, a novel method for detecting the distance of an approaching patient and for measuring his or her heart rate with a microwave Doppler radar is presented. This enables a truly non-contact and unobtrusive measurement. In addition, the measurement can be performed even through thick clothing. Furthermore, the patient does not need to be aware of being monitored since the method enables measurement to be started automatically as the patient approaches the sensor.**

I. INTRODUCTION

The trendy visions of ubiquitous [1] and proactive technology [2] call for development of calm and non-disruptive sensor technology. Novel sensors and continuing development of old sensors are needed in order to design context aware devices. On the other hand, as the inhabitants of developed countries age, home-based healthcare offers a possibility for substantial savings and major decrease in time spent in a hospital or a nursing home. This is not possible unless there are as reliable monitoring methods available for home environment as there are for hospital care.

It is apparent that people do not want to be connected to the measuring devices nor to be aware of constant sensing and monitoring [3]. This is even more the case in home environment where people seek for comfort, relaxation, and safety. Although those who suffer from a serious illness or disability, or are on rehabilitation phase might have a lower threshold in making some compromises in the usability or comfort of a monitoring device, whereas healthy (not to mention sporty) persons are not willing to do so. The measurement has to be unobtrusive and it must not hamper the everyday life. Hence, unobtrusiveness is one of the enabling concepts in making healthcare measurements part of our every day life. Thus, there is a clear need for novel sensors that can make measurement as unobtrusive as possible for the patient or the user.

Heart rate (HR) can be measured by various methods: with electrocardiography (ECG) or with common commercial heart rate monitors that are based on ECG, with ballistocardiography (BCG), with photoplethysmography (PPG), and with impedance cardiography (ICG). Measurement with these methods can be made less obtrusive with careful product development and utilization of novel research results (such as using textile electrodes [e.g. 4] and wireless data transmission), by embedding sensors (for example in a chair [5] or in clothing) or by miniaturization [e.g. 6]. However, this does not remove the fact that all these methods require a direct contact to the patient – either in form of electrodes, photodiode, or some kind of pressure sensor.

The Doppler radar monitoring of HR was published by Lin *et al.* [7] already in the late 1970's, and later, in order to develop the method towards commercial use, by Boric-Lubecke [8]-[10], [12] and Droitcour [11]. The latter two have done several improvements and developments including integrating the radar in an IC-chip [9] [11], using WLAN (Wireless Local Area Network) PC card as a transmitter and a receiver [10] and using cordless telephone handset as a transmitter and an add-on module as a receiver of the microwave signal [12]. However, the method has not yet become widely known, although it offers many advantages over typically used HR monitoring methods.

In this paper, a microwave Doppler radar is used as a sensor for measuring patient's HR. In addition, the sensitivity of the placement of the sensor is discussed. Furthermore, this paper presents a novel method for detecting an approaching patient with the same kind of radar structure as used for HR measurement. The distance of an approaching patient can be used for starting the measurement automatically. The patient does not need to do any preparations prior the measurement. In addition, this enables a situation where the patient is not even aware of the fact that he or she is being monitored. This enables several highly interesting applications ranging from using HR as a parameter for controlling of home to HR lie detectors. In general, the method enables truly unobtrusive sensors. Furthermore, the method holds another highly significant advantage: measurement can be made even through a thick set of clothes. At first, basic principles of the measurement are explained. Then, the system design is described, and finally, the measurement arrangements and the results are presented.

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II. METHODOLOGY

A. Doppler Radar Monitoring

The measurement is based on the Doppler phenomenon. A microwave signal emitted from the radar module is reflected from all objects within the coverage area and the signal reflected from moving objects is Doppler shifted. The reflected signal is received by the radar module and mixed with a portion of the original one. The signal reflected from stationary objects will be removed in mixing since it has the same frequency as the transmitted signal. Hence, the output signal of the radar module is the signal reflected only from moving objects. The strength of the reflected signal can be estimated by the radar equation:

$$P_{\mathrm{r}} = \frac{P_{\mathrm{t}} G^2 \lambda^2 \sigma}{(4\pi)^3 R^4}, \tag{1}$$

where P_{r} and P_{t} are the received power and the power fed to the transmitting antenna respectively, λ is the wavelength of the signal, R is the distance to an object, G is the antenna gain, and σ is the radar cross section (RCS) of an object. The RCS is defined as follows:

$$\sigma = A_{\mathrm{p}} H S, \tag{2}$$

where A_{p} is the projection area of an object, H is the reflectivity, and S is the directivity of an object. Nevertheless, the radar equation (1) gives only rough approximation of the signal strength since the reflection event is highly simplified and does not take into account several losses. However, it can be stated that the strength of the output signal is strongly inversely proportional to the distance of an object – but to the size, material, and orientation of that object as well. [13]

B. Hardware Architecture

The block diagram and the hardware prototype of the sensor are presented in Fig. 1. The device consists of a microwave radar module, an analog signal processing unit, a microcontroller, and a data transmission unit. An inexpensive, commercially available microwave Doppler radar module, which is commonly used as a motion detector, is utilized. The microwave radar module used is MDU1000, manufactured by Microwave Solutions Ltd. [14]. The radar uses a 10.587 GHz carrier frequency in continuously emitting mode (CW). CW radars are typically utilized for measuring the relative velocity of an object, but in this study, the similar radar structure is used for estimating the distance to a patient and measuring his/her HR. The dependency of the received reflection signal strength on the distance R between the radar and a patient is used to calculate the distance (1) [15]. The emitted power of MDU1000 is 20 mW (EIRP, Equivalent Isotropic Radiated Power), thus, it meets the EN 300 440 specification. The output signal of the radar module is very small, below 1 mV, so it needs to be amplified before it can be digitized. This is done in a cascade of two logarithmic amplifiers. The signal is converted into digital form with sampling frequency of 100 Hz in the microcontroller and transferred to a PC for further processing with Matlab.

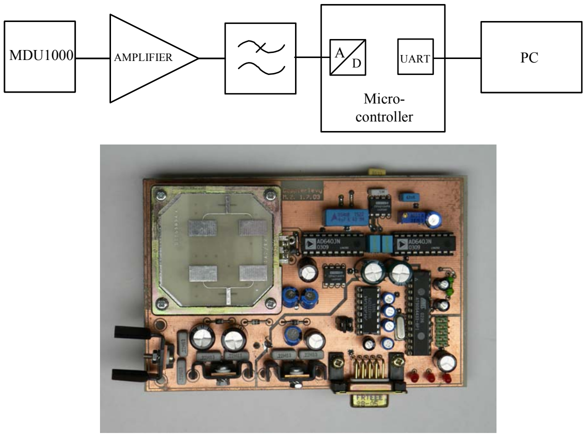

Fig. 1. Upper: The block diagram of the sensor. Lower: The hardware prototype of the sensor.

C. Measurements

To test the suitability of the Doppler HR monitoring, several experiments were conducted. The sensor was mounted at the height of one meter facing towards patient's chest so that the distance between the sensor and the patient was 15 cm. The patient was sitting in a chair at rest, holding his breath during the test. The test cases were chosen as follows:

1. The sensor was facing towards the thorax at about 10º tilt angle to the vertical axis. The patient was leaning forward.
2. The sensor was facing towards the thorax at about 10º tilt angle to the vertical axis. The patient was leaning backward.
3. The sensor was facing towards the thorax at about 45º angle to the median plane in the left hand side of the patient. The patient was leaning backward.

The duration of each test was 20–30 seconds.

The effect of differences in patients' physical size and moving velocity on the response was tested by conducting basic walk tests in a large room. The sensor was attached at the height of one meter facing towards a patient, who was moving back and forth at the distance of 0.5–7 meters. The range of seven meters can be considered adequate especially at home environment where distances are typically smaller. The test cases were chosen as follows:

A. short, small sized patient (155 cm – 55 kg) moving,
B. tall, large-sized patient (190 cm – 140 kg) moving,
C. small patient moving at different velocities.

The duration of each test was 30 seconds.

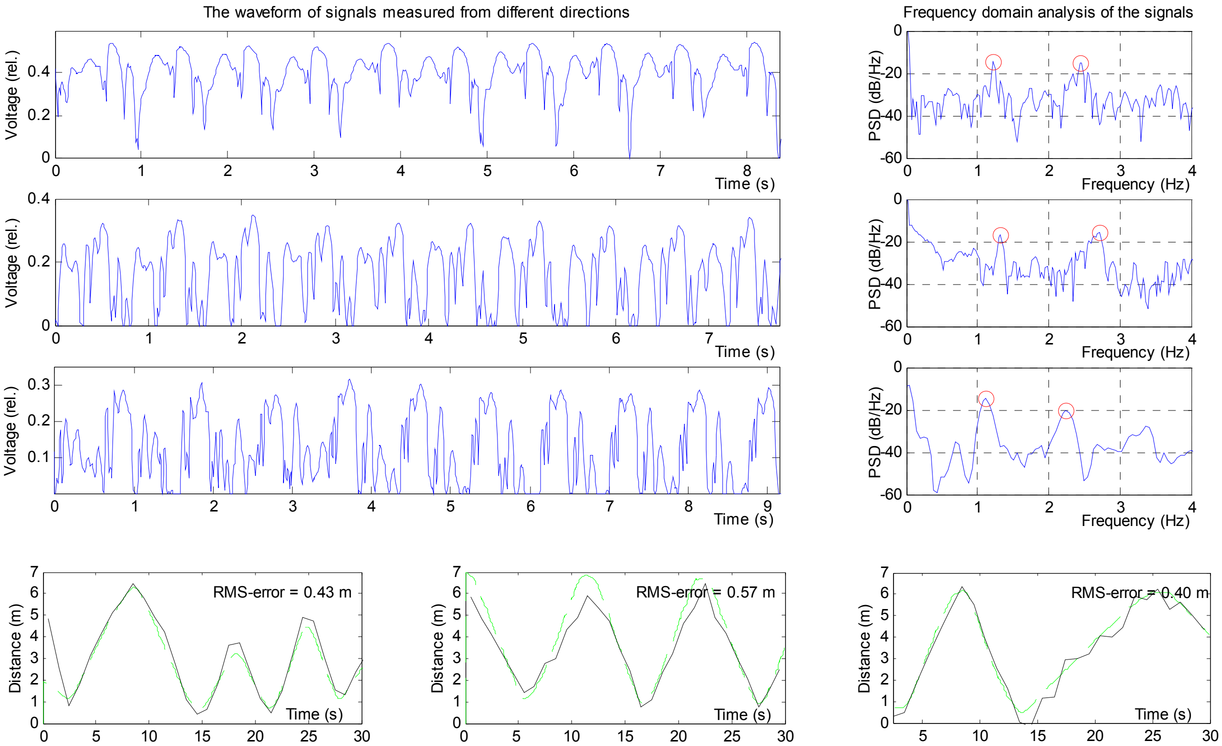

Fig. 2. Upper: The effect of differences in mounting of the sensor is shown. Samples of signals captured from test cases 1 to 3 are shown, from top to down, in time domain on the left hand side and in the frequency domain on the ride hand side. The waveform differs greatly depending on the placement of the sensor relative to the patient's thorax, yet, the accurate frequency can be measured. Note that the y-axes in the PSD charts are in decibel scale, and the units in y-axes in the time domain charts are linear relative values, value 1 representing the maximum value.
Lower: Typical responses of the sensor measuring patient's distance when patients with different physical size are moving back and forth. The response to movement of a small-sized patient (test case A) and a large-sized (test case B) patient and the effect of different moving velocities (test case C) are shown in charts from left to right respectively. The measured distance is shown in the solid line and the reference distance in the dashed line. The RMS-error is shown at the upper right hand side of each chart and it is approximately half a meter.

III. RESULTS

The signals measured in test cases 1 to 3 are shown in Fig 2. both in time and frequency domains. In the time domain curves, there can be seen several peaks during one phase. Yet, the shape of the curve remains the same from phase to phase. In the PSD graphs, there can be seen larger peaks in both the HR and twice the HR (marked with a red circle). The accurate frequencies of these peaks are presented in Table I along with calculated results in the unit beats per minute. The typical responses in test cases A to C are presented at the bottom of the Fig. 2. In addition, the RMS-error (Root Mean Square) is shown next to each curve. As seen, the error of the method is approximately half a meter.

IV. DISCUSSION

The HR can reliably be obtained by Doppler radar monitor. The position of the sensor in relation to patient's thorax affects greatly the measured waveform as seen in Fig. 2. The movement of thorax is not similar in all directions as it differs both in transversal, frontal and sagittal planes. As the patient is leaning back- (test case 2) and forward (test case 1), the measurement is made in slightly different angle in relation to the thorax. This causes the difference between the waveforms in test cases 1 to 3. A large alteration in the waveform caused by a small displacement of the sensor might cause problems if the sensor must be placed accurately to the same position for each measurement. Nevertheless, the interesting part of the signal, as HR is measured, is the frequency, which can be easily calculated in each test case regardless of the waveform.

The waveform of the Doppler radar monitoring has attracted little attention in the literature [16]. Only Lin *et al.* presents one waveform [7]. Similar waveform is seen in the test case 1 containing one wide peak with two smaller superpositioned peaks.

Although the signal processing needed for distinguishing respiration artifacts from the HR signal is not performed in

TABLE I
HRS OBTAINED BY DOPPLER RADAR MONITOR

Case	Results		
	Base frequency (Hz)	2. harmonic frequency (Hz)	(beats/ min)
1	1.22	2.44	73
2	1.32	2.71	80
3	1.12	2.25	67

this paper, this can be done with the means of digital signal processing [17]. It should be mentioned that breathing activity causes significant artifacts to the signal waveform and, if not correctly filtered, the heart signal can not be distinguished during the times of in- or exhale. Another challenge still remains: how to distinguish HR from the motion artifact of the patient and the interferences caused by background movements.

In the test cases A to C the data obtained by the Doppler radar correlate perfectly with the reference. Beforehand, it was expected that the physical size of the patient would significantly affect the received signal strength. Nevertheless, as we compare the results, it can be stated that the effect is only minor.

In the test case C the effect of the patient's velocity to the response was examined. In the beginning, the patient was moving roughly at a velocity of 1 m/s and in the second half at a velocity of 0.5 m/s. The measured trace is not smooth, although, the patient is moving at a constant velocity according to the reference measurement. This is probably due to the fact that the reference meter measures the distance of the patient's torso whereas the response of the tracking device is dependent on the movement of the whole body, including limbs.

Though there are still a few improvements that can increase the functionality of the method, the results are very promising. The method enables a truly non-contact measurement of HR. The method offers a possibility of measuring HR even through thick clothing. This could enable several novel applications and advantages for example in healthcare technology, home monitoring and sports – particularly in winter sports. As microwaves also easily penetrate several materials, for example plastic, the sensor can be hidden behind a cover so that it can be placed out of sight. These are major advantages both from the principle of calm technology [18] and from user-centered [3] point of views.

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REFERENCES

[1] M. Weiser, "Some Computer Science Issues in Ubiquitous Computing," *Communications of the ACM,* 36(7), July 1993, pp.75–84.

[2] D. Tennenhouse "Proactive computing," *Communications of the ACM,* vol. 43(5), May 2000, pp. 43–50.

[3] F. Mäyrä, A. Soronen, J. Vanhala, J. Mikkonen, M. Zakrzewski, I. Koskinen, K. Kuusela, "Probing a proactive home: Challenges in researching and designing everyday smart environments," *Human Technology,* accepted for publication.

[4] R. Paradiso, G. Loriga, N. Taccini, "A wearable health care system based on knitted integrated sensors," in IEEE Trans. On Information Technology in Biomedicine, vol. 9(3), Sept. 2005, pp. 337–344.

[5] T. Koivistoinen, S. Junnila, A. Värri, T. Kööbi, "A new method for measuring the ballistocardiogram using EMFi sensor in a normal chair," in *Proc. 26th Annu. Conf. Engineering in Medicine and Biology Society,* San Francisco, 2004, pp. 2026–2029.

[6] H. H. Asada, P. Shaltis, A. Reisner, R. Sokwoo, R. C. Hutchinson, "Mobile monitoring with wearable photoplethysmographic biosensors," *IEEE Engineering in Medicine and Biology Magazine,* vol. 22(3), May-June 2003 pp. 28–40.

[7] J. C. Lin, J. Kiernicki, M. Kiernicki, P. B. Wollschlaeger, "Microwave apexcardiography," *IEEE Trans. on Microwave Theory and Techniques,* vol. 27(6), June 1979, pp. 618–620.

[8] O. Boric-Lubecke, V. M. Lubecke, "Wireless house calls: Using communications technology for health care and monitoring," *IEEE Microwave Magazine,* vol. 3(3), Sept. 2002, pp. 43–48.

[9] O. Boric-Lubecke, A. D. Droitcour, V. M. Lubecke, J. Lin, G. T. A. Kovacs, "Wireless IC Doppler radars for sensing of heart and respiration activity," in Proc. of the 6th Int. Conf. on TELSIKS, Niš, Serbia and Montenegro, 2003, pp. 337–344.

[10] O. Boric-Lubecke, G. Awater, V. M. Lubecke, "Wireless LAN PC card sensing of vital signs," *IEEE Topical Conf. on Wireless Communication Technology,* Honolulu, Hawaii, 2003, pp. 206–207.

[11] A. D. Droitcour, O. Boric-Lubecke, V. M. Lubecke, J. Lin, G. T. A. Kovacs, "Range correlation and I/Q performance benefits in single-chip silicon Doppler radars for noncontact cardiopulmonary monitoring," *IEEE Trans. on Microwave Theory and Techniques*, vol. 52(3), pp. 838–848, March 2004.

[12] V. Lubecke, O. Boric-Lubecke, E. Beck, "A compact low-cost add-on module for Doppler radar sensing of vital signs using a wireless communications terminal," *IEEE MTT-S International Microwave Symposium Digest,* vol. 3, 2002, pp. 1767–1770.

[13] O. Klemola, A. Lehto, *Radar technology (Tutkatekniikka),* Helsinki: Otatieto, 1998, ch 3.

[14] Microwave Solutions Datasheet of MDU1000, Microwave Solutions Ltd. Available: http://www.microwave-solutions.com/products.htm

[15] M. Zakrzewski, A. Kolinummi, J. Vanhala, "A Tracking system based on received signal strength of microwave radar," in *Conf. Rec. Intelligent Ambience and Well-Being*, Tampere, Finland. 19.–20. Sept. 2005.

[16] P. A. Mahoney, E. A. Needham, M. Siegel "Heartbeat detection in a microwave monitor using an adaptive least squares lattice filter," in *Proc. of the Computers in Cardiology,* Los Alamitos, USA, 1988, pp. 151–152.

[17] B. Lohman, O. Boric-Lubecke, V. M. Lubecke, P. W. Ong, M. M. Sondhi, "A digital signal processor for Doppler radar sensing of vital signs, " in *Proc. of the 23rd Annu. Int. Conf. of the IEEE Engineering in Medicine and Biology Society,* Istanbul, Turkey, 2001, vol. 4, pp. 3359–3362.

[18] M. Weiser, J. S. Brown, (Oct. 1996) "The Coming Age of Calm Technology," Available: http://www.ubiq.com/hypertext/weiser/acmfuture2endnote.htm