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Evaluation of a Doppler radar sensor system for vital signs detection and activity monitoring in a radio-frequency shielded room

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ABSTRACT

This study presents an evaluation of an advanced Doppler radar-based method for detection of vital signs, presence, and activity of a human subject in a test room with radar-signal reflecting aluminum-coated surfaces. Ten test subjects lay in four positions, and they sat in two locations in the room, both breathing normally and holding their breath. The mean ratios of the pulse rates determined from the radar signal and electrocardiography and respiration reference signals were 110% (respiration) and 99% (heartbeat), and the mean occupied and empty room radar signal variance ratios were 608 (breathing) and 20 (breath-hold). In a one-subject activity monitoring test, walking, standing and lying activities could be well separated from the radar signal. The results are promising and the proposed system seems to have potential to be used in position-independent health and activity monitoring of, for example, elderly people in care homes or intoxicated people in police custody.

1. Introduction

Reliable contactless monitoring of vital signs is needed in many healthcare and medical surveillance applications. Radar-based detection can be utilized in emergency situations to find buried or hiding people [1–4]. Contactless monitoring of vital signs is also needed when attaching, e.g., ECG electrodes is not advisable due to burnt skin [4] or the possibility of exposing nursing staff to toxic materials [5]. A contactless radar-based detection system can also provide a cost effective and versatile method to monitor the vital signs of sleeping elderly in care homes or intoxicated people in police custody [6].

This study presents an evaluation of an advanced contactless Doppler radar-based system for detecting the vital signs of a human subject. To enable a comprehensive room-scale field of view and good reflections of the radar signal, the radar sensor is installed in the upper corner of an aluminum-coated radio-frequency-shielded test room in a tilted position. Using a human-sized metallic chamber for improving radar-based vital signs monitoring has been previously tested by Chen et al. [4]. To the authors' best knowledge, however, this is the first time the method is applied to a room-like setup. The configuration of the presented detection system is described, and its performance for vital signs detection and activity monitoring is evaluated using ten test subjects in several positions and locations in the test room. A small-scale general activity monitoring test with one test subject and different activity types is also carried out. Expanding the functions of the detection system to presence and activity monitoring diversifies remarkably its use and choice of applications.

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2. Materials and methods

2.1. Ethics statement

This study was conducted according to the principles expressed in the Declaration of Helsinki. The Research Ethics Committee of Aalto University stated that, since ethical approval, as stated in the Finnish Medical Research Act and as required by the National Advisory Board on Research Ethics in Finland, is necessary only for medical research, this study needs not undergo an ethical review, especially in the view that the integrity of the test subjects was not endangered in any way. The ethical principles of research in the humanities and social and behavioral sciences followed in Finland are available in [7]. The contents of the test and the course of its events were explained before-hand to each test subject individually, and written consent was received from each of them.

2.2. Radar sensor

A continuous-wave microwave Doppler radar sensor was assembled for the test setup (Fig. 1). The basic principle is that the Doppler radar signal reflected from the monitored subject is phase modulated by the subject's respiration and heartbeat [8], which allows the detection of vital signs. The test radar was implemented using waveguide technology, which may also improve the detection of vital signs by filtering off the sub-harmonics of the radar signal [9].

The transmitter of the radar uses an M/A-COM 4000-series Gunn diode oscillator at the single frequency of 34 GHz. The maximum power of the radar is 100 mW, but in the test setup it is operated at 10 mW. The radar signal's wavelength λ is about 9 mm, which is of the same order as the chest deviation due to respiration (4–12 mm) and is not too large compared that due to heartbeat (0.2–0.5 mm) [10]. The millimeter-level wavelength also enables the use of a relatively small-sized antenna. In the test radar, a horn antenna was used for its good directivity.

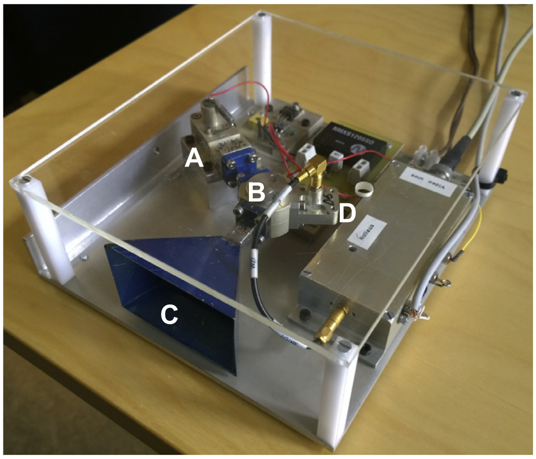

Fig. 1. Radar sensor used in the test setup. The main parts of the sensor are the transmitter (A), circulator (B), horn antenna (C) and, receiver and amplifier (D).

The receiver of the radar sensor employs one-diode phase detection to find the Doppler frequency of the reflected signal. The transmitter and antenna are connected to the receiver through a ferromagnetic waveguide circulator (Fig. 1). The circulator leaks the transmitted signal also to the receiver, where it is mixed with the reflected signal. The difference of these two signals is then phase detected. Due to the Gunn diode's temperature dependence, there is always some noise and drift present in this systems. In this prototype version, a multi-turn potentiometer was used to trim the radar output signal offset. The power density of the radar is far lower than the recommended safety limits in Finland for nonionizing radiation [11].

2.3. Test room

A test room having dimensions of 205 cm $\times$ 120 cm $\times$ 195 cm (length $\times$ width $\times$ height) was constructed of 30-mm (walls and door) and 50-mm (floor and ceiling) thick polyurethane insulation boards with 0.2-mm aluminum coating on both-sides (Fig. 2). The floor was coated with an additional 7-mm laminate-panel covering enabling movements of the test subject inside the room. While not reflecting the dimensions of a regular room, the room comfortably accommodated one person in different positions and allowed walking inside. To improve test subject comfort, a camping mattress made of 190T polyester with polyurethane foam and air filling of size 183 cm $\times$ 51 cm $\times$ 2.5 cm was placed in the middle of the test room. Ventilation of the test room was realized with two wall-mounted fans. The radar sensor was placed on a shelf in the corner near the ceiling of the room. The radar's antenna was at a height of about 173 cm from the test-room floor, and it was directed downwards vertically at a 33° angle and horizontally at 45° angles to the walls.

2.4. Radio-frequency shielding of the test room

Aluminum reduces the absorption of the radar signal in the building materials and guarantees maximum reflections of the signal [12]. Along with the tilted installation of the radar sensor, the aluminum coating was used to facilitate the best possible radar signal reflections and coverage in the test room.

2.5. Reference measurements and data acquisition

Reference measurements were performed to obtain direct information on the respiratory efforts and heartbeat of the test subjects. Electrocardiography (ECG) signal was measured with a wireless ECG monitor (BioNomadix BN-ECG2, BIOPAC Systems, Goleta, CA, USA) using the bipolar limb lead II. The respiratory efforts were detected with a wireless respiration monitor (BioNomadix BN-RESP-XDCR, BIOPAC Systems, Goleta, CA, USA) placed on the test subject's abdomen. All signals were recorded with commercial data acquisition hardware and PC software (MP150 and AcqKnowledge 4.3, BIOPAC Systems, Goleta, CA, USA) at a sampling rate of 1000 samples/second. The radar sensor was coupled to the data acquisition system