In-Cabin 120 GHz Radar System for Functional Human Breathing Monitoring in a 3D Scenario

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Abstract—**Driving is one of the activities that takes a significant part of a person's time, that is why monitoring vital signs is useful for the wellness of the occupants of the vehicle. One of the vital signs that provides more information about the state of the person, is the functional breathing. Compared to other vital signs indicators, breathing is more sensitive to cardiovascular events, emotional stress, physical exertion, or fatigue induced by long time driving, seen as variations in chest and abdomen elongation modes. Functional monitoring is a tool that can transcend, from measurement and detection to emotional changes through feedback of sounds, images, or videos to the driver. In this regard, this work proposes an imaging radar system to generate a topographic map with elongation modes of the driver's chest and abdomen, at 120 GHz. Numerical simulations have been deployed in order to reconstruct the image from the receiver signal in the radar using spatial convolution. Furthermore, a metronome has been used to calibrate the radar for elongations measuring with respect to time, and finally, the system has been tested experimentally in an adult person, to generate a preliminary topographic map that allows matching the chest elongation modes to breathing patterns.**

I. Introduction

Several studies support the idea that many traffic accident can be prevented by early recognition of abnormal vital signs. Cardiovascular events, emotional stress, physical exertion, or fatigue induced by long time driving can cause the driver to lose concentration on the road. Compared to other vital signs indicators, breathing is more sensitive to alterations in the condition of the subject and is a key predictor of unfavorable episodes such as drowsiness, fatigue, or emotional stress [1]. Lately, some studies are focused in breathing monitoring [2], [3], which has provoked the emergence of numerous commercial wearable devices, such as wrist bands, chest straps, or compression garment, but these may not be practical in all situations because continued skin contact can cause discomfort to the subject. In contrast, non-contact monitoring is a non-invasive procedure explored in the recent years, as in [4], [5], and it is this area where radar has attracted considerable attention, as presented in [6]–[8]. Even though advances in non-contact breathing monitoring has improve markedly, these methods provide incomplete information on chest wall and abdominal motion. Information from chest and abdomen motion is equally important as information on lung volumes, because variations can be caused by airways affection, muscle weakness or stress. As presented in [9], it is possible going beyond technology, to offer people a state of comfort according to his state of health, moods like anxiety can be reduced by a positive feedback. It is then possible to use the motion of chest and abdomen to determine the state of the driver.

With this goal, this paper introduces the term elongation modes to refer to the variations of movement in the chest and abdomen, and presents (i) a novel radar-based method for measuring elongations modes of human chest and abdomen, to build a topographical map, that allows to determine the driver status according to breathing patterns; (ii) numerical simulations to characterise the system and establish the optimal beamwidth of the radar that enables appropriate elongation modes measuring for in-cabin passengers; (iii) a calibrated radar system to deploy preliminary measurements of elongation modes.

On the basis of the findings presented in this paper, future work will be focused on using elongation modes to feedback the driver with visual or audible signals that enhance the in-cabin comfort.

II. Theoretical background

A. Types of breathing

There are different types of breathing that require a different process to allow for inspiration and expiration.

- Eupnea: it occurs at rest, diaphragm and external intercostals must contract. Normal breathing rate in an adult person, between 12 and 16 breaths per minute.
- Diaphragmatic breathing: it is also known as deep breathing, the diaphragm relaxes, air passively leaves the lungs. Breathing rate is 7 breaths per minute.
- Costal breathing: as the intercostal muscles relax, air passively leaves the lungs. It is also known as shallow breathing.
- Hyperpnea: occurs during exercise or actions that require the active manipulation of breathing. It is also known as forced breathing, inspiration and expiration both occur due to muscle contractions.

B. Breathing patterns

Chest and abdominal movements, from a medical point of view, can be labeled according to the site where the greatest range of motion take place. A interesting work is presented in [10], they study respiratory movements in a group of 50 men and 50 women aged between 20 and 69 years. They instructed subjects to breathe normally, deeply and slowly. The chest and abdomen have been divided into six sections, the right- and left sides of abdominal (LA, RA), upper thoracic (LUTh, RUTh) and lower thoracic (LLTh, RLTh). Results of measurements are shown in Tables I and II.

From the findings of [10], is established that respiratory movements are symmetrically, do not decrease significantly

TABLE I
QUIET BREATHING MOVEMENTS OF MEN AND WOMEN 20-69 YEARS (IN mm). DATA FROM [10].

Quiet breathing	Abdominal		Lower thoracic		Upper thoracic	
	RA	LA	RLTh	LLTh	RUTh	LUTh
Men	7.47	7.33	3.35	3.38	2.64	2.66
Women	6.49	6.20	3.87	3.92	3.38	3.39

TABLE II
DEEP BREATHING MOVEMENTS OF MEN AND WOMEN 20-69 YEARS (IN mm). DATA FROM [10].

Deep breathing	Abdominal		Lower thoracic		Upper thoracic	
	RA	LA	RLTh	LLTh	RUTh	LUTh
Men	24.68	24.57	19.72	20.66	18.37	17.62
Women	17.52	17.22	16.01	16.22	18.04	17.70

with age (from 20 to 69), and is different in men and women for abdominal motion during deep breathing.

C. Spirometry measurements

In accordance with the objectives of this paper, spirometry can provide additional information to determine the modes of chest elongation in certain situations. Spirometry measures the rate which the lung changes volume during forced breathing manoeuvres. Tidal volume is the quantity of air cycled through inhalation and exhalation, this quantity multiplied by the respiration rate is called minute ventilation, and it is and important indicator of lung function. These values vary from person to person. Infants and children have considerable higher respiratory rates than adults. Table III, summarizes the breathing rates by ages.

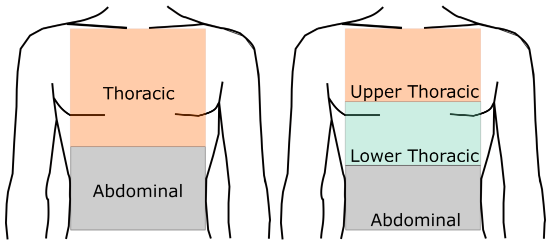
TABLE III
RESPIRATION RATE

Groups	Rate (times/min)
Newborn	44
Infant	50
Children	25
Adult man	16
Adult woman	14

D. Elongation modes definition

As a person performs the breathing process, as presented in the literature review, the chest and abdomen move depending on the breathing pattern. This variation can range from a few millimeters to about 25 mm. If the antennas of a radar are pointing the chest and abdomen, the signal received will vary in magnitude and phase. At this point, it is possible to define the elongation modes as the portion of the chest or abdomen, in which the movement is greatest during the breathing process. These elongation modes may vary depending on the person's age, gender, and state of health.

Whereas the movement in the chest and abdomen during breathing is symmetrical from right to left, two modes of elongation have been identified that allows classify the type of breathing as thoracic and abdominal. As shown in Fig. 1a. However, according to the breathing patterns analyzed, an approach that gives much more information is to use three elongation modes, abdominal, upper thoracic and lower thoracic, as shown in figure 1b.



(a) (b)

Fig. 1. (a) Two elongation modes enables the thoracic and abdominal breathing detection. (b) Three elongation modes are useful for breathing pattern identification.

III. METHODOLOGY

This study has been developed in two parts. The first part consists on constructing a topographic map of the chest of the human body by mean of numerical simulations from an image in a real driving situation. To do this, the beamwidth of the radar has been simulated, in terms of the longitudinal and transversal resolution, and the reconstruction of the image has been made from the received signal. The second part of the study focuses on achieving the sensitivity, in terms of resolution level, on the radar that enables constructing a real topographic map of the chest, whose elongation modes are related to breathing patterns. A radar calibration has been deployed, then experiments for target detection and finally breathing detection and elongation measurements. Figure 2 depicts a schematic of the proposed scenario. The radar is located in the rear-view mirror of the car pointing to the driver.

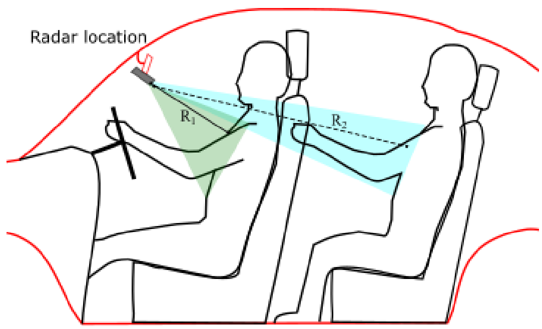


Fig. 2. The radar is located in the rear-view mirror, the distance to the driver is R_1=65 cm, and to the passenger is R_2=131 cm

A. Subjects

Experiments were carried out in the scenario shown in Fig. 2, and includes two people inside the car. One subject (height: 170 cm, weight: 65 kg, age: 32), named subject 1, was sitting in the front of the car positioning at 65 cm (R_1) away from the radar and the other subject (height: 179 cm, weight: 69 kg, age: 23), named subject 2, was in the back seat, 160 cm (R_2) away from the radar. Both of them were using normal clothing and met the following requirements: no smoking history and no previous disorders affecting the respiratory system. According to [11], the body max index

(BMI) influences in chest and abdomen motion; a person with BMI of 30 and above have reduced movement of the diaphragm. So, the selected subjects have BMIs 22,5 and 21,5 respectively. For numerical simulations, a real picture of the scenario was used.

B. Radar system

Chest and abdominal movements were measured with a radar that operates at the carrier frequency of 122 GHz with a 7 GHz bandwidth, has a range resolution of $10\,\mathrm{m}$ and noise figure of 8.7 dB. The radar front-end (RFE) is used in frequency-modulated continuous-wave (FMCW) mode, using chirp signals. A collimator lens of diameter D_l placed $10\,\mathrm{mm}$ from the RFE, is used to control the beamwidth and to focus correctly the human chest. The received data is packaged in the form of frames, that are transmitted by a serial communication to a host computer to be analyzed and plotted using Matlab. Target range information is extracted by applying a Fast Fourier Transform (FFT) to each chirp signal, each peak in the frequency domain represents the displacement in the target (chest and abdomen motion).

C. Numerical simulation

When a radar is pointing the human body, each movement of the persons can modify the signal both in phase and in magnitude. Compared to common environments for breathing rate monitoring, the space inside the vehicle is limited, for this reason, to determine the ideal monitoring conditions, an optimal beamwidth and lens size are of fundamental importance, since it directly provides a correct resolution for image reconstruction. Numerical simulations have been conducted to determine the optimal beamwidth and lens diameter with two objectives: (i) in-cabin passengers image reconstruction and then (ii) elongation chest measuring.

The resolution of the reconstructed image depends of the beamwidth of the radar, and it can be modified by mean of a lens, according to $\delta_t = R_i \cdot \frac{\lambda}{D_l}$, where R_i is the distance to the target, λ is the wavelength, and D_l is the lens diameter. If the driver is located at R_1=$65\,\mathrm{cm}$ and D_l=$3\,\mathrm{cm}$, the optimal beamwidth to reconstruct the driver is δ_t=$53\,\mathrm{mm}$. The reconstructed image is shown in Fig. 3.

(a) (b)

Fig. 3. (a) Real picture used for imaging reconstruction. (b) Reconstructed image using $3\,\mathrm{cm}$ lens.

When a passenger is sitting at the rear of the vehicle, the $3\,\mathrm{cm}$ lens is no longer sufficient for a correct definition of the person, because while the δ_t is $53\,\mathrm{mm}$ for driver, for the passenger it is $131\,\mathrm{mm}$, due to R_2=$130\,\mathrm{cm}$. In this case, a smaller beamwidth is required, therefore, it means that a larger lens it is necessary, so with D_l= $7\,\mathrm{cm}$ the δ_t=$56\,\mathrm{mm}$ for passenger. Figure 4 plots the reconstructed images for each lens.

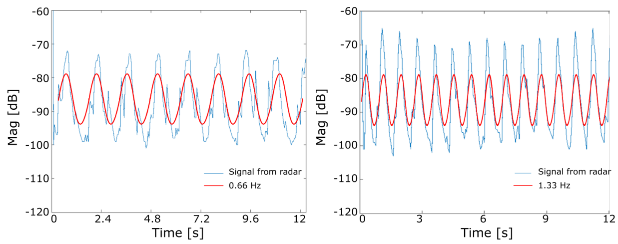
(a) (b) (c)

Fig. 4. (a) Real image used in radar simulations. Picture was taken from the rear-view mirror. (b) Reconstructed image using $3\,\mathrm{cm}$ lens. (c) Reconstructed image using $7\,\mathrm{cm}$ lens, δ_t=$23.8\,\mathrm{mm}$ at the passenger distance.

IV. RESULTS

A. Breathing rate measurements

A calibration process was deployed to test the sensitivity of radar in elongation chest movements measuring. A commercial metronome was placed $65\,\mathrm{cm}$ from the radar with the sliding weight moving longitudinally at two beat rates, 40 and 80 periods/min, corresponding to $0.66\,\mathrm{Hz}$ and $1.25\,\mathrm{Hz}$, respectively. The measured signal was represented over time in Matlab, along with a software-generated sinusoidal signal of the same frequency as beat rates, as shown in Fig. 5.



(a) (b)

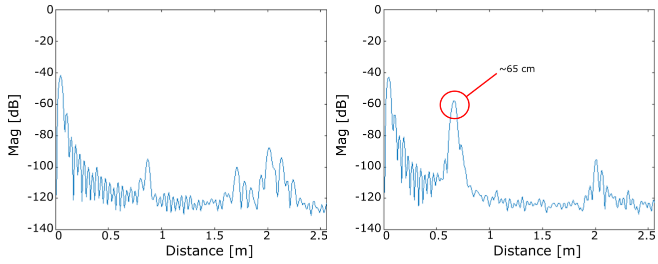
Fig. 5. a) Measured signal of 0.66 Hz. b) Measured signal of 1.33 Hz

Then, with radar connected to the computer, measurements were made to determine the distance to the target detected by the radar. The scenario is the same depicted in Fig. 2, a horizontal scan was carried out that covers the interior of the car. The received data is processed in Matlab and then plotted in terms of the received power and distance while the radar is scanning the interior of the vehicle. Fig. 6a, shows the received signal when nobody is in front the radar, the detected peaks are due to the seat of the vehicle. The Fig. 6b, show the peak produced by the presence of the driver inside the car.

Once the radar has been calibrated, breathing measurements have been carried out with a human subject. The first experiment consists of detecting and measuring respiration when the radar is fixed in front of the subject at a distance of 65 cm. Fig.7, shows the acquired signal from a experiment where the subject was instructed to normally breath during 20 seconds, stops for 10 seconds, and continues until arrive at 60 seconds.

B. Numerical simulations for elongation modes detection

Using a real photo of subjects 1 and 2, contours that represent the elongation of the chest were plotted. Then,



(a) (b)

Fig. 6. (a) Signal of the radar without passenger. (b) Received signal of the driver

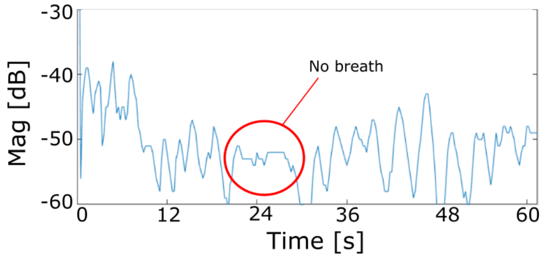
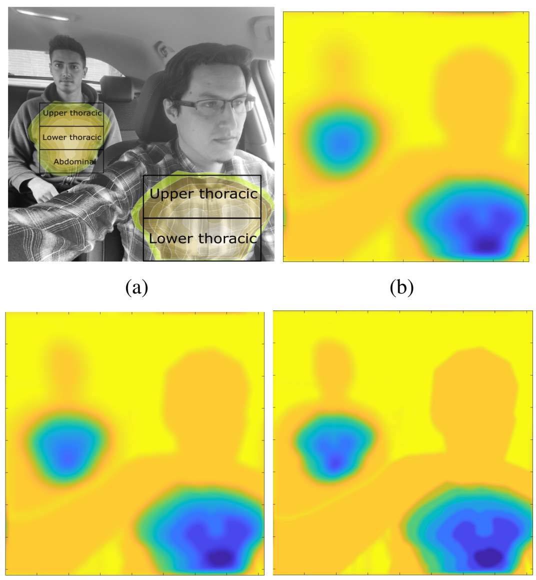


Fig. 7. Breathing rate of a human

the image has been subdivided into cells according with the number of modes defined. The 120GHz radar beamwidth has to be of comparable size of the cell of elongation mode, for this reason, three lens diameter where tested, 3, 5 and 10 cm. The elongation modes representation is achieved by measuring the distance of each quadrant and placing the information in a intensity matrix. Figure 8, shows the result of numerical simulations, where the lower thoracic mode is evaluated..



(a) (b)

(c) (d)

Fig. 8. (a) Real image used in radar simulations. Picture was taken from the rear-view mirror. Reconstructed image using 3 cm (b), 5 cm (c), and 10 cm (d) lenses

V. Discussion

Different types and patterns of breathing are the result of the movement of several muscles. Normal breathing moves the abdomen and lower thorax region, so a 2-mode elongation model might be enough to characterize breathing, however in men the chest sizes is 20% larger than women [12], and during deep breathing while the excursion is greatest in the upper thorax of females, for males is greatest in the abdominal region, therefore a 3-mode elongation system would be more suitable for use inside the vehicle.

VI. Conclusions

Based on scientific review, three vertical modes of chest elongation can be used to determine patterns or types of breathing in people. Elongation modes can be generated using radar to measure the distance and frequency of motion of the chest and abdomen.

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