Person detection counter based on mm-Wave radar technology

Đorđe P. Glavonjić, Ivan M. Milosavljević, Dušan P. Krčum, Veljko R. Mihajlović and Lazar V. Saranovac

***Abstract*— This paper presents novel technique for counting people passing through the door. Finding acceptable solution for the presented problem is of great importance, hence the information about the number of people located in the specific area may be significant for different emergency situations, such as entry control, marketing research, office security, building management and road traffic monitoring. Multiple solutions available on the market, based on different technologies, provide acceptable results only under certain lighting conditions, with limited accuracy, high costs and computational power. In this paper we present hardware solution based on mm-Wave radar technology and dedicated algorithm implemented on custom digital signal processing (DSP) platform. Performed measurements and testing results have proven that presented approach is very reliable, even in situations when multiple persons are passing through the door simultaneously, in different directions and in very short time intervals.**

***Index Terms*—person detection counter, mm-Wave Doppler radar, DSP algorithm**

I. Introduction

TECHNOLOGY development in recent years enabled integration of mm-Wave radar sensors into small sized systems on chip (SoC). This directly influenced growing usage of radar sensors in different applications such as breathing and hart rate detection, driver assistance systems, parking sensors, person detection, industrial high precision measurements applications, etc. Most of the mm-wave radar sensor applications available nowadays are focused on distance, angular and velocity measurements. Their usage in detection room occupancy applications has not been exploited yet.

Commercially available systems used for room occupancy are mainly based on camera surveillance technology [1-4]. However processing of 2-D image and video signal is complex and requires large computational power. On the other hand, these algorithms are also prone to false target detection, especially in low light conditions.

Another type of a sensor used in room occupancy applications is based on impulse-radio ultra-wide band (IR-UWB) technology [5], [6]. This technology is characterized by very low transmitting power and high penetration factor, which produces low signal levels at the receive side, making detection process more difficult.

In this paper we propose completely integrated room occupancy system based on 24 GHz radar sensor, with uniquely designed antennas. Dedicated algorithm solution, implemented on micro-processor, searches for energy peaks in the received signal, and further process extracted maximum points to increment/decrement counter value.

Presented paper is organized as follows. Section II provides brief overview of continuous-wave (CW) Doppler radar theory of operation with focus on demodulation procedure challenges and practical implementation. In the section III system architecture is presented, while section IV provides detailed insight into the proposed algorithm. Section V provides measurement results of the complete solution.

II. Doppler Radar Theory of Operation

Fig. 1 shows block diagram of the typical Doppler CW radar measurement system. Voltage-controlled oscillator (VCO) has been driven externally by using V_{COARSE} and V_{FINE} control voltages, to produce desired output frequency of 24 GHz. Firstly, synthesized high frequency signal is amplified (PA) and then sent over transmitting antenna (Tx), which is designed to radiate in its horizontal plane. Reflected signal is further received by receiving antenna (Rx), amplified by low-noise amplifier (LNA) and converted to baseband by means of in-phase/quadrature (I/Q) demodulator.

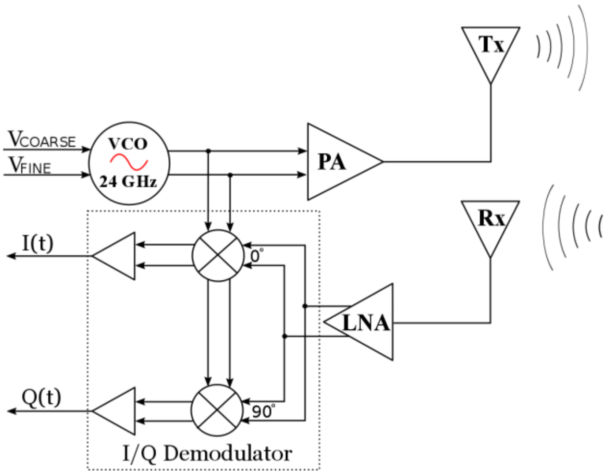

Fig. 1. Block diagram of quadrature Doppler radar measurement system

Đorđe P. Glavonjić – Department of Electronics, School of Electrical Engineering, University of Belgrade, Bulevar Kralja Aleksandra 73, 11020 Belgrade, Serbia; NovelIC Microsystems, Veljka Dugoševića 54, Belgrade, Serbia (e-mail: djordje.glavonjic@novelic.com).

Ivan M. Milosavljević – Department of Electronics, School of Electrical Engineering, University of Belgrade, Bulevar Kralja Aleksandra 73, 11020 Belgrade, Serbia; NovelIC Microsystems, Veljka Dugoševića 54, Belgrade, Serbia (e-mail: ivan.milosavljevic@novelic.com).

Dušan P. Krčum – Department of Electronics, School of Electrical Engineering, University of Belgrade, Bulevar Kralja Aleksandra 73, 11020 Belgrade, Serbia; NovelIC Microsystems, Veljka Dugoševića 54, Belgrade, Serbia, (e-mail: dusan.krcum@novelic.com).

Veljko R. Mihajlović – Department of Electronics, School of Electrical Engineering, University of Belgrade, Bulevar Kralja Aleksandra 73, 11020 Belgrade, Serbia; NovelIC Microsystems, Veljka Dugoševića 54, Belgrade, Serbia (e-mail: veljko.mihajlovic@novelic.com).

Lazar V. Saranovac – Department of Electronics, School of Electrical Engineering, University of Belgrade, Bulevar Kralja Aleksandra 73, 11020 Belgrade, Serbia, (e-mail: laza@etf.bg.ac.rs).

Proceedings of 4th International Conference on Electrical, Electronics and Computing Engineering, IcETRAN 2017, Kladovo, Serbia, June 05-08, ISBN 978-86-7466-692-0 pp. ELI3.3.1-4

In accordance with Doppler theory, when transmitted wave is reflected from the moving target, demodulated signal is directly proportional to the target speed as

$$f_b = \frac{2v_r}{\lambda}. \quad (1)$$

Without losing generality, transmitted signal with unit amplitude, can be written in a following form:

$$T(t) = \cos(2\pi f t + \phi(t)), \quad (2)$$

where *f* is oscillating frequency, *t* is the elapsed time and $\phi(t)$ is the phase noise of the oscillator. After transmitted signal is reflected from the target located at distance d_0, with time-varying displacement given by $x(t)$, I/Q components at the output of homodyne receiver are represented by:

$$I(t) = A_I \cos(\theta + \frac{4\pi x(t)}{\lambda} + \Delta\phi(t)) \quad (3)$$

$$Q(t) = A_Q \sin(\theta + \frac{4\pi x(t)}{\lambda} + \Delta\phi(t)). \quad (4)$$

Information about the target vibrations is incorporated in the phase of the demodulated signal. To be able to perform accurate phase detection from (3) and (4), without significant increase of computational complexity, small angle approximation is applied.

As explained in [7], two main problems associated with introduced approximation method are:

- Alternate "optimum" and "null" detection points result in the best and the worst noise performance
- Small angle approximation is not valid when vibration amplitudes are comparable to the carrier wavelength

Solution for the presented single channel phase evaluation problems is to combine I and Q channels by using *arctan* operation:

$$\phi(t) = \arctan\left[\frac{Q(t)}{I(t)}\right]. \quad (5)$$

Since *arctan* function is restricted to range of $(-\pi/2 \div \pi/2)$, in some cases, demodulated points obtained by (5) may exceed expected range. In these situations, presented demodulation process is not optimal, since dedicated calibration algorithm needs to be applied at discontinuity points.

In [8] alternative demodulation approach, based on difference and cross-multiply (DACM) algorithm is presented, as in:

$$w(t) = \frac{d}{dt}\left[\arctan\left[\frac{Q(t)}{I(t)}\right]\right] = \frac{I(t)Q'(t) - I'(t)Q(t)}{I(t)^2 + Q(t)^2}. \quad (6)$$

If derivation operator is substituted, with forward difference, digital domain representation of (6) is obtained:

$$w[n] = \frac{I[n]\frac{Q[n]-Q[n-1]}{\Delta t} - Q[n]\frac{I[n]-I[n-1]}{\Delta t}}{I[n]^2 + Q[n]^2}, \quad (7)$$

where Δt is sampling interval. Demodulation procedure presented in (7) has many advantages over traditional *arctan* demodulation such as retrieving frequency and amplitude information of the vibration and very simple HW/SW implementation procedures.

III. System Architecture

Proposed system solution is composed of two stacked boards: sensor board and digital signal processing (DSP) board, as shown in Fig 2.

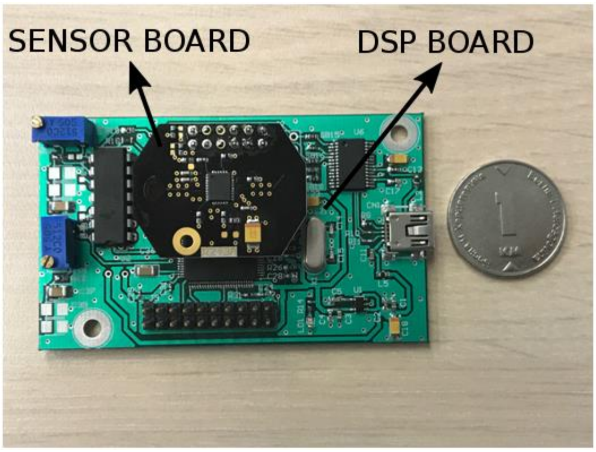

Fig. 2. Integrated sensing/DSP solution

Sensor board contains 24 GHz integrated radar sensor solution, with small sized transmitting and receiving antennas placed at the opposite sides. Analog I/Q baseband signals from the sensor boards are transferred directly to the DSP board.

DSP board consists of 12-bit analog-to-digital converter (ADC), and ARM based micro-processor for efficient algorithm implementation.

ADC samples the analog I/Q baseband signals at operating frequency of $F_s = 1$ kHz. ARM processor collects ADC samples in chunks of 512, processes digitalized data and over serial protocol sends extracted information about number of detected entrances/leavings from the room.

IV. Proposed Algorithm

As stated in section III, interleaved I/Q samples are continuously received by ARM processor, where complete signal processing algorithm is implemented. The k-th received chunk of data can be described as follows:

$$\begin{aligned} I_k &= [i_k(1)\ \ i_k(2)\ \ i_k(3) \ldots i_k(p)]^T \\ Q_k &= [q_k(1)\ \ q_k(2)\ \ q_k(3) \ldots q_k(p)]^T \end{aligned}, \quad (8)$$

where i_{kn} and q_{kn} are denoted as n-th sample of I/Q data in k-th received frame and $p = 256$. Processing of the received I/Q data is performed continuously after receiving each frame of 512 samples. The example of the complete digitized I/Q sequence, when three persons are entering and then leaving the room simultaneously is presented in Fig. 3.

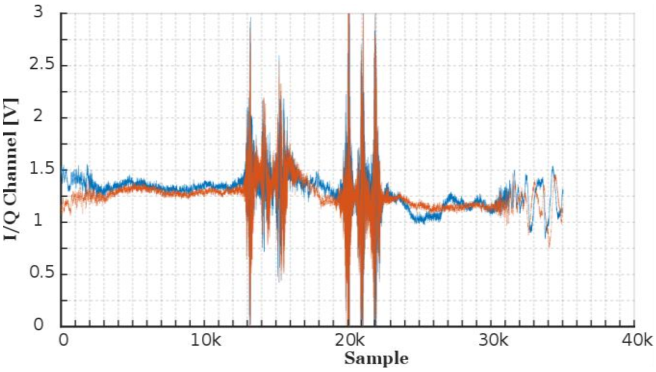

Fig. 3. I/Q signals for three different persons passing through the door

From the received discrete I/Q data (8) in each frame, only samples from one branch can be used for calculating received signal power according to:

$$E_k = \sum_{n=1}^{p} \left| i_k[n] \right|^2. \tag{9}$$

Since real time detection of a moving person is required in this application, obtained signal energy from the k-th frame is subtracted from the signal energy in the frame k-1:

$$E_{diffk} = E_k - E_{k-1}. \tag{10}$$

By continuously checking the value of E_{diffk}, the sign change from positive to negative is detected and declared as a point of maximal energy. To be able to ensure that detected sign change is not produced by background noise or clutter, simple thresholding technique is applied. Fig. 4 shows obtained results after applying presented maximum energy detection method on the data set from Fig 3.

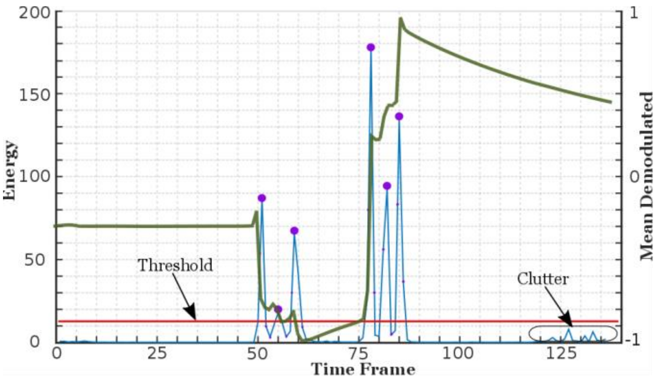

Fig. 4. Extracted signal energy diagram with marked maximum points

When positive to negative transition occurs and thresholding condition is satisfied, person detection counter is increment/decremented, based on the walking direction.

For the reason of detecting the desired direction, information from both I and Q branches is required. Hence, demodulation procedure from (7) is selected, due to its computational efficiency. After demodulation, moving average operation is directly applied on the demodulated signal values according to:

$$M_k = \frac{w[0] + w[1] + \ldots + w[p-1]}{p}. \tag{11}$$

The positive sign of the averaged demodulated signal indicates that the person has entered the room, while the negative sign indicates the opposite. Decision process on the walking direction is shown in Fig 4. Detailed algorithm solution summary is presented in Fig 5.

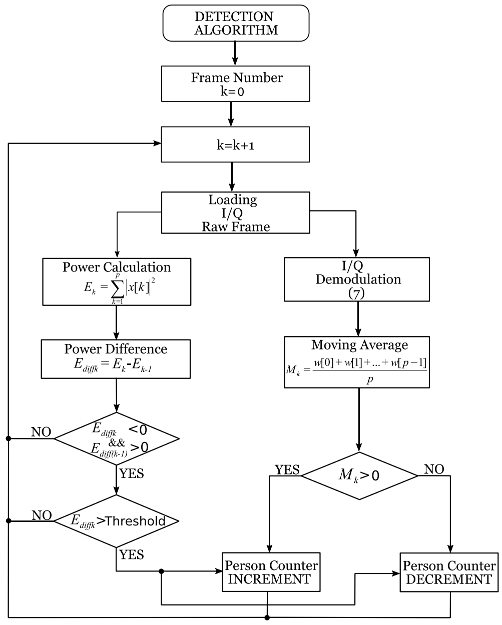

Fig. 5. Proposed people counter algorithm flow

V. MEASUREMENT RESULTS

Different type of measurements are performed in this chapter, validating the advantages of mm-Wave radar technology. In addition, the algorithm for detecting multiple persons passing through the door is presented. Experimental setup, with single radar sensor mounted 2.5 m above the ground, is shown in Fig. 6.

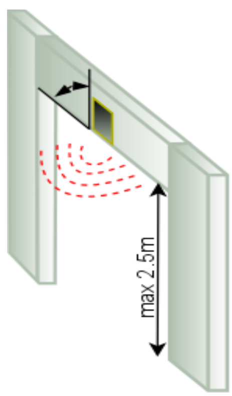

Fig. 6. Experimental setup

In order to evaluate complete solution two different scenarios are presented. The first scenario is created by calculating number of successful detection for single person entering/leaving the room at different speeds and in different directions. Evaluation results for single person detection are presented in Table I.

TABLE I

EVALUATED RESULTS FOR SINGLE PERSON

Speed	Direction	No. Of Passes	No. Of Detected Passes	Accuracy %
Slow	Uni-Dir.	30	29	96
Normal	Uni-Dir.	30	30	100
Fast	Uni-Dir.	30	30	100
Slow	Bi-Dir.	30	27	72
Normal	Bi-Dir.	30	29	80
Fast	Bi-Dir.	30	30	88

Results from Table II are showing that algorithm presented in section IV, provides very accurate results for single person walking in both directions. However, performances are slightly poorer for persons moving at slow speeds, because they produce smaller disturbances and therefore their energy level can be below the predefined threshold.

In the second scenario three different persons with different heights are involved, thus they are representing targets with various radar cross sections (RCS). Each of them are walking simultaneously in different directions (one person entering-two leaving or vice versa), while their speed is changing only in different sub-scenarios.

Evaluation results for the second scenario are presented in the Table II.

TABLE II

EVALUATED RESULTS FOR VARIOUS DIFFERENT PERSONS

Speed	Moving Direction	No. Of People	No. Of Detected People	Accuracy %
Slow	Uni-Dir.	90	86	95
Normal	Uni-Dir.	90	86	95
Fast	Uni-Dir.	90	89	98
Slow	Bi-Dir.	90	75	83
Normal	Bi-Dir.	90	80	88
Fast	Bi-Dir.	90	81	90

Obtained results from Table II are showing that sub-scenarios with single walking direction still have very high percentage of accuracy. However, sub-scenarios where multiple persons are walking in different directions have lower accuracy due to the fact that presented algorithm solution is not able to resolve targets which are extremely close to each other.

VI. CONCLUSION

In this paper we presented fully integrated solution for smart and autonomous people counting. High level of integration is obtained due to usage of 24 GHz radar sensor, specifically designed antennas and very simple detection algorithm, which is suitable for all types of HW/SW implementations. In comparison to traditional camera based people counting solutions, introduced system is much more reliable, especially in low light conditions, while having much simpler signal conditioning.

The same hardware platform, with different processing algorithm can be applied for detecting human vital signs parameters, such as breathing and hart rate.

REFERENCES

[1] T.H. Chen, T.Y. Chen and Z.X Chen, "An Intelligent People-Flow Counting Method for Passing Through a Gate," *IEEE Conference on Robotics, Automation and Mechatronics*, Bangkok, Thailand, 1-3 June 2006

[2] K. Terada, D. Yoshida, S. Oe and J. Yamaguchi, "A Counting Method of the Number of Passing People Using a Stereo Camera", *Industrial Electronics Electronics Society. IECON Proceedings*, San Jose, CA, USA, Nov. 1999

[3] S.D. Pore and B.F. Momin, "Bidirectional People Counting System in Video Surveillance," *IEEE International Conference On Recent Trends In Electronics Information Communication Technology.* Bangalore, India May 20-21, 2016.

[4] J. Keem, K. Choe and B. Choe, "Real Time Vision Based people counting system for security door", *International Technical Conference on Computers and Communications*, 2002

[5] J.W. Choi, J.H. Kim and S.H. Cho, "A Counting Algorithm for Multiple Object Using an IR-UWB Radar System" *IEEE Conf. Network Infrastructure and Digital Content*, 2012

[6] J.Q. Jeong, K.W. Choi and S.H. Cho, "In-bound/Out-bound Detection of People's Movements Using an IR-UWB Radar System", *International Conference on Electronics, Information and Communications*, 2014

[7] B. Park, O. Boric-Lubecke and V.B Lubecke, "Arctangent Demodulation With DC Offset Compensation in Quadrature Doppler Radar Receiver Systems", *IEEE Transactions On Microwave Theory And Techniques*, vol.55 pp. 1073-1079, May 2007

[8] F. Schadt, F. Mohr and M. Holzer, "Application of Kalman filter as a tool for phase and frequency demodulation of IQ signals", in *Proc. IEEE Int. Conf. Comp. Tech. Electr. Electron*, Engl. Jul. 2008