

Selected algorithms for measurement data processing in impulse-radar-based system for monitoring of human movements

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Abstract. The importance of research on new technologies that could be employed in care services for elderly and disabled persons is highlighted. Advantages of impulse-radar sensors, when applied for non-intrusive monitoring of such persons in their home environment, are indicated. Selected algorithms for the measurement data preprocessing – *viz.* the algorithms for clutter suppression and echo parameter estimation, as well as for estimation of the two-dimensional position of a monitored person – are proposed. The capability of an impulse-radar-based system to provide some application-specific parameters, *viz.* the parameters characterising the patient's health condition, is also demonstrated.

1. Introduction

The life expectancy has been growing in Europe for many years, while the healthy life expectancy has been slightly diminishing since the last decade of the XXth century (*cf.* <http://www.healthy-life-years.eu/>). The problem of organised care for elderly and disabled persons is, therefore, of growing importance. Hence the demand for research on new technologies that could be employed in monitoring systems supporting care services for such persons. The capability of those systems to detect dangerous events, such as person's fall, is of key importance [1]. The systems for monitoring of elderly and disabled persons are expected not only to detect dangerous events, but also to predict those events on the basis of acquired data, and therefore contribute to the prevention of such events. The analysis of gait, as well as of the itinerary and timing of activities of the monitored persons, may thus contribute to prevention [2, 3].

Recently, numerous attempts have been made to apply radar technology for monitoring of elderly and disabled persons (*cf.*, for example, the documents [4–6]). They are mainly motivated by the conviction that this technology may be less intrusive, less cumbersome, and less invasive with respect to the home environment than existing solutions. Another attractive feature of the radar-based systems is the possibility of the through-the-wall monitoring of human activity [7, 8].

A consistent set of algorithms, described in this paper, is designed for extraction of key information from measurement data – the information characterising the patient's health condition, and, therefore, enabling the automatic prevention of dangerous events. This set of algorithms constitutes a core of

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measurement data processing in impulse-radar-based system for monitoring of human movements; its practical validity is proved here on the basis of a set of real-world experiments.

2. Measurement data acquisition

Detailed technical considerations on the applicability of the impulse-radar sensors for monitoring of human movements can be found in [4]; the principle of operation of such a sensor is explained in figure 1.

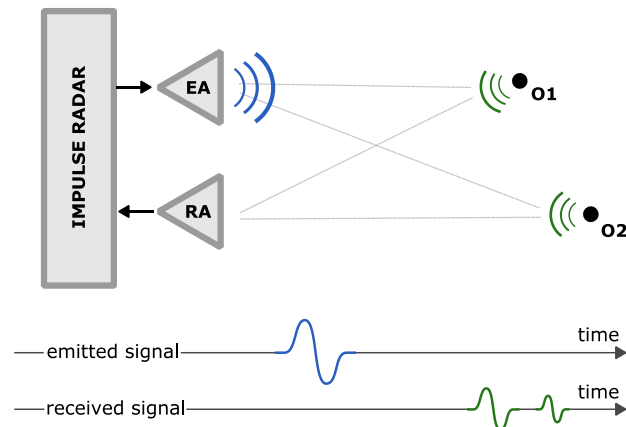


Figure 1. Principle of operation of the impulse-radar sensor.

A short impulse sent by the emitting antenna (EA) is reflected by various objects (O1, O2, ...) present in the space surrounding the sensor. All of the reflected copies of the emitted impulse (called *echoes*) are then captured by the receiving antenna (RA). Depending on the spatial structure of the object, the reflected impulse may have larger or smaller *magnitude*, *i.e.* the received echo can be stronger or weaker; moreover, depending on the distance between the object and the sensor, the reflected impulse may appear sooner or later, *i.e.* may have different *position*, depending on the total time of impulse propagation.

The impulse-radar sensor provides a sequence of raw measurement data representative of the received signal composed of several impulses reflected from all the objects "seen" by the sensor; those data are next subject to preprocessing aimed at extraction of informative parameters characterising the movement of a selected object, *e.g.* position or velocity of a monitored person.

3. Measurement data preprocessing

Measurement data preprocessing consists of the following operations: clutter suppression, estimation of the echo parameters and estimation of the two-dimensional position of the monitored person.

3.1. Clutter suppression

The raw measurement data (shown in figure 2a) are corrupted both with noise and with the so-called clutter, *i.e.* reflections from static objects (such as walls or furniture), and multiple reflections of static objects and moving objects. Therefore, before the extraction of the features characterising the monitored person, noise and clutter have to be suppressed. This can be achieved through the use of a family of algorithms reported by the authors in [9], combined with band-pass filters. The result of this preprocessing operation is shown in figure 2b.

3.2. Echo parameters estimation

After the clutter suppression, the estimation of the parameters of the echo reflected from the observed person becomes a lot easier. Those parameters, *viz.* position and magnitude, can be determined by means of many different algorithms, *e.g.* by means of those described by the authors in [10]. The result of this preprocessing operation is shown in figure 2c.

3.3. Position estimation and tracking

The estimates of the two-dimensional coordinates of the person in the monitored area can be acquired by means of two concurrently working radar sensors. Those estimates can be obtained by completing the following steps:

- calculation of the distances (d_1 , d_2) between the monitored person and the radar sensors (figure 2d);
- smoothing of the sequences of the (d_1 , d_2) values, *e.g.* by means of the method described in [11] (figure 2e);
- transformation of the pairs (d_1 , d_2) in the coordinates (x , y) (figure 2f);
- smoothing of the sequences of the (x , y) coordinates.

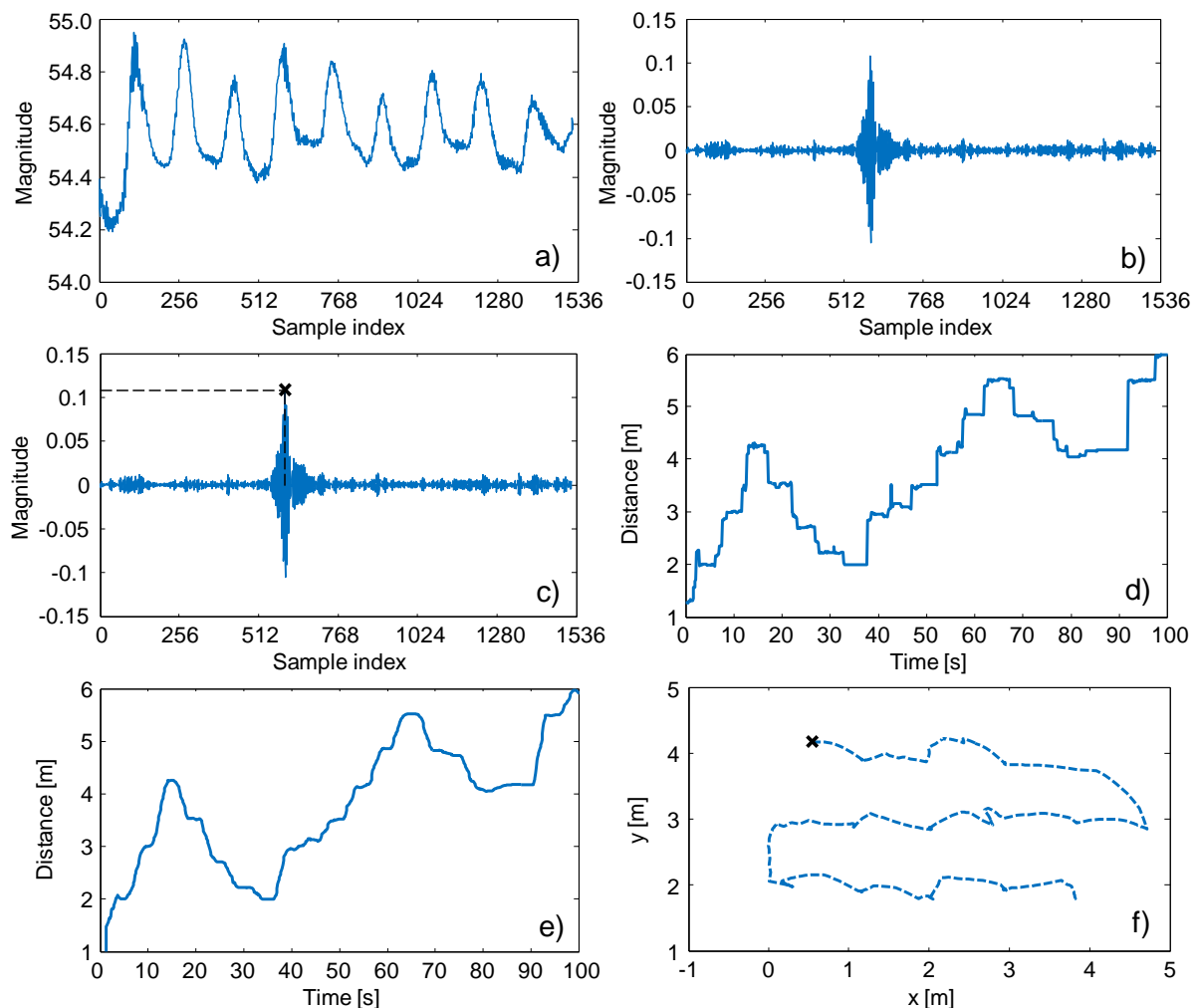


Figure 2. Preprocessing of data from impulse-radar sensors: a) the raw measurement data; b) data after clutter suppression; c) the estimates of useful signal parameters; d) the estimates of the distance between one of the radar sensors and the monitored person; e) the same sequence after smoothing; f) the estimate of the two-dimensional trajectory of the monitored person.

4. Extraction of application-specific parameters

On the basis of the data resulting from preprocessing of the raw measurement data, further parameters characterising the patient's health condition can be derived [2]. Here, due to space limitations, only the estimation of three of them will be introduced, *viz.* detection of motion, estimation of the walking velocity, and estimation of the travelled distance.

4.1. Detection of motion

Motion can be detected by comparing the distance, travelled in a given period of time, T , to a given threshold, \mathcal{G} . A Boolean sequence, indicating motion, is computed according to the formula:

$$b_n \equiv 1 \quad \text{if} \quad d_n > \frac{t_n - t_{n_0}}{T} \mathcal{G}, \text{ and } b_n \equiv 0 \quad \text{otherwise, for } n = 1, \dots, N \quad (1)$$

where:

$$d_n \equiv \sum_{v=n_0}^n \sqrt{(x_v - x_{v-1})^2 + (y_v - y_{v-1})^2}, \text{ with } n_0 \equiv \arg \inf_v \{v \mid t_v \geq t_n - T, v = 0, \dots, n-1\} \quad (2)$$

In the above equation $\{x_n\}$ and $\{y_n\}$ are the estimates of the sequences of coordinates, obtained during measurement data preprocessing (*cf.* Section 3.3). The values of T and \mathcal{G} should be optimised to prevent small deviations in the position from being considered as motion. To smooth the sequences at the output of the algorithm for motion detection, morphological opening and closing filters are applied [12].

4.2. Estimation of walking velocity

An estimate of the sequence of the instantaneous walking velocity may be obtained by numerical differentiation of the sequence of the position estimates, *e.g.* by means of the central-difference method [13], defined by the following formula:

$$\hat{x}_n^{(1)} \equiv \frac{x_{n+1} - x_{n-1}}{\Delta t_n} \quad \text{for } n = 1, \dots, N-1 \quad (3)$$

where $\{x_n\}$ is a sequence of data to be differentiated, and $\Delta t_n \equiv t_{n+1} - t_{n-1}$ are the differentiation steps, with t_n denoting the time moments at which the data have been acquired. The central-difference method is, however, very sensitive to errors corrupting the data used for derivative estimation; therefore, it should be regularised through, *e.g.*, optimisation of the differentiation step [14].

Estimation of the instantaneous walking velocity comprises differentiation of the sequences of the x and y coordinates separately, and calculation of the direction-independent velocity magnitude according to the following formula:

$$v_n = \sqrt{(\hat{x}_n^{(1)})^2 + (\hat{y}_n^{(1)})^2} \quad \text{for } n = 1, \dots, N-1 \quad (4)$$

An estimate of the average walking velocity can be obtained by averaging the estimates $\{v_n\}$ over the time intervals in which the monitored person is walking; these intervals are determined using the algorithm for motion detection described in the previous subsection.

4.3. Estimation of travelled distance

The estimation of the travelled distance should be preceded by smoothing of the monitored person's trajectory $\{x_n\}$. This operation is aimed at removing outlying values since those values could cause important overestimation of the distance. This can be done by using a median filter: $x'_n = \text{median}\{x_{n-1}, x_n, x_{n+1}\}$. The travelled distance can then be calculated by summing up the distances between consecutive locations of the monitored person:

$$s = \sum_{n=1}^N \sqrt{(x'_n - x'_{n-1})^2 + (y'_n - y'_{n-1})^2} \quad (5)$$

5. Results of experiments

In figure 3, exemplary results of motion detection, obtained by means of the procedure proposed in Section 4.1, are presented; while in table 1, some statistics of errors in the motion detection are shown.

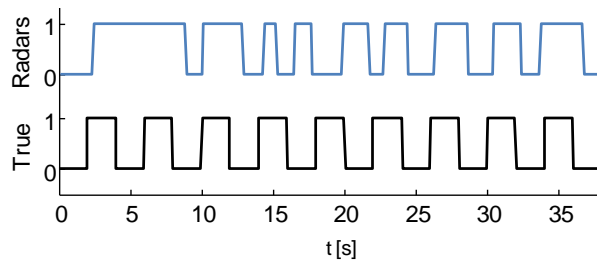


Figure 3. Results of motion detection, based on the data from the radar sensors; ‘0’ means standing still, ‘1’ – moving.

Table 1. Errors in start/stop estimation.

Mean error	0.33 s
Standard deviation	0.64 s
Maximum error	1.92 s

It can be seen that, according to the proposed procedure, the motion of the moving person can be correctly detected, though sometimes two separate moves are not distinguished, or one move is interpreted as two separate, shorter moves. Nevertheless, the mean and maximum error of start/stop estimation provided in table 1 indicate the practical validity of the procedure.

In figure 4a, the results of estimation of the average walking velocity are shown, while in figure 4b – the results of estimation of the travelled distance. The estimation task has been repeated for a number of real-world experiments, in which a person has been walking in the monitored area according to different scenarios and with varying walking velocity. The estimates of both quantities have been obtained by using the methods described in the previous section. In tables 2 and 3, some statistics of the errors of the velocity and travelled distance estimates are provided.

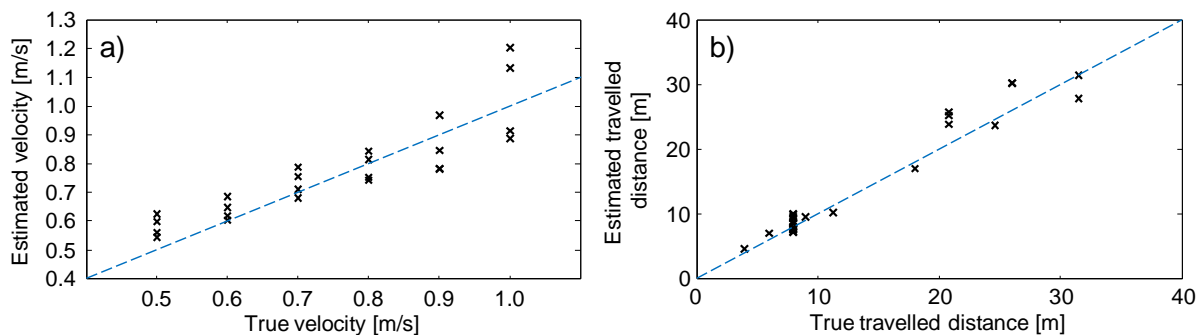


Figure 4. Estimates of the average walking velocity vs. true velocity (a) and estimates of the travelled distance vs. true travelled distance (b).

Table 2. Errors of walking velocity estimates.

Mean error	0.02 m/s
Standard deviation of errors	0.08 m/s
Maximum error	0.21 m/s

Table 3. Errors of travelled distance estimates.

Mean relative error	7.65 %
Standard deviation of relative errors	11.82 %
Maximum relative error	26.32 %

As it can be observed, in case of the velocity estimates, the mean absolute error is 0.02 m/s, with standard deviation of the errors equal to 0.08 m/s; the maximum absolute error reaches 0.21 m/s. In case of the estimation of the travelled distance, the mean relative error is 7.65 % with standard deviation of the errors equal to 11.82 %; here, the maximum relative error reaches 26.32 %.

As suggested in the literature, *e.g.* [15], the walking velocity lower than 0.6 m/s predicts future risk of falls and of hospitalisation of a patient. Taking into account the presented statistics of the estimates errors, it can be seen that mid- and long-term changes in the walking velocity could be reliably detected using the presented estimation procedures.

6. Conclusions and prospects for further work

The applicability of impulse-radar sensors for non-invasive monitoring of human movements has been analysed and demonstrated by means of a consistent set of algorithms for processing of measurement data provided by such sensors. In particular, selected algorithms for measurement data preprocessing – including clutter suppression, echo parameter estimation, and position estimation – have been described.

It has been shown that the presented set of algorithms enables one to quite accurately detect the motion of the monitored person and estimate his/her walking velocity and travelled distance. These are two basic quantities which can be used by the medical and healthcare personnel to assess the overall health condition of the patient; however, some more would be desirable – *e.g.* number of turns made during a walk, or the person's acceleration in three types of situations, *viz.* starting to walk, stopping, and changing the direction.

Further works will focus on the tuning of the algorithms of measurement data processing described in this paper, and on the development of new algorithms for estimation of other healthcare-related quantities to be used in impulse-radar-based system for monitoring of human movements.

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