

Measurement data preprocessing in a radar-based system for monitoring of human movements

Roman Z. Morawski¹, Andrzej Miękina and Paweł R. Bajurko

Warsaw University of Technology, Faculty of Electronics and Information Technology, Institute of Radioelectronics, Warsaw, Poland

E-mail: r.morawski@ire.pw.edu.pl

Abstract. The importance of research on new technologies that could be employed in care services for elderly people is highlighted. The need to examine the applicability of various sensor systems for non-invasive monitoring of the movements and vital bodily functions, such as heart beat or breathing rhythm, of elderly persons in their home environment is justified. An extensive overview of the literature concerning existing monitoring techniques is provided. A technological potential behind radar sensors is indicated. A new class of algorithms for preprocessing of measurement data from impulse radar sensors, when applied for elderly people monitoring, is proposed. Preliminary results of numerical experiments performed on those algorithms are demonstrated.

1. Introduction

It is expected that the proportion of European people reaching the age of 65 years or more will increase by at least 50% during the next 30 years. The problem of organised care over elderly people, especially those suffering dementia is, therefore, of increasing importance. Hence the demand for research on new technologies that could be employed in care services for such people. Its primary objective is to examine the applicability of various sensor systems for non-invasive monitoring of the movements and vital bodily functions, such as heart beat or breathing rhythm, of elderly persons in their home environment. The capability of such systems to detect dangerous events, such as person's fall, is of principal importance. A fall is defined as *"unintentionally coming to the ground or some lower level and other than – as a consequence of sustaining a violent blow, loss of consciousness, sudden onset of paralysis as in stroke or an epileptic seizure"* [1]. A fall can occur not only when a person is standing, but also while sitting on a chair or lying on a bed during sleep. Falls among elderly people are the main cause of their admission and long-term stay in hospitals: it is the sixth cause of death for people over the age of 65, the second for people between 65 and 75, and the first for people over 75 [2]. The fall risk factors are of various nature:

- intrinsic: age, low mobility and bone fragility, poor balance, chronic disease, cognitive and dementia problems, Parkinson disease, sight problems, use of drugs that affect the mind, incorrect lifestyle (inactivity, use of alcohol, obesity), previous falls;
- extrinsic: individual (incorrect use of shoes and clothes), drugs cocktail;
- environmental: internal (slipping floors or stairs, need to reach high-located objects) and external (damaged roads, crowded places, dangerous steps, poor lighting).

¹ To whom any correspondence should be addressed.



2. Existing monitoring techniques

There are three main categories of monitoring techniques already applied in care practice: vision-based, environmental and wearable [2–4].

The vision-based techniques are based on fixed cameras that continuously record the movement of a patient; the acquired data are processed by means of algorithms of pattern recognition that trigger an alarm in case of fall. They usually contain three types of operations: detection of inactivity, based on the idea that after a fall, the patient lies on the floor without moving; analysis of the body-shape change, based on the change of posture after the fall; and analysis of the head motion, based on the monitoring of the position and velocity of the head. The main limitations of the vision-based techniques are: the time and cost of installation, the limited space of application (within the range cameras) and privacy violation.

The environmental techniques are based on the installation of sensors in the places to be monitored – *e.g.* pressure sensors on chairs, cameras, and RFID tags embedded throughout the home of the elderly people, as well as in their furniture and clothing.

The wearable – unlike visual-based and environmental techniques which require a pre-built infrastructure – may be used outdoor. The signals from movement sensors (mainly accelerometers, and gyroscopes), worn by a patient, are transmitted via radio to a computer and analysed. This solution makes also possible the acquisition of physiological data (blood pressure, ECG, EEG, *etc.*).

3. Formulation of the research problem

Since several years numerous attempts have been made to apply radar technology for monitoring of elderly persons. They are mainly motivated by the conviction that this technology may be less intrusive than vision-based solutions, less cumbersome than the wearable solutions and less invasive with respect to the home environment than the environmental solutions. The research directions related to this topic may be broadly classified according to the spectrum of the radar signals applied. So, some researchers prefer to focus on narrow-band solutions, especially those using the Doppler principle [5–36], others opt for broad-band solutions, especially those using pulse-type signals [37–54]. The research reported in this paper belongs to the latter category: it is devoted to the analysis of measurement data acquired by means of an impulse radar sensor. A typical sequence of such data, after removing the static background, is shown in Figure 1.

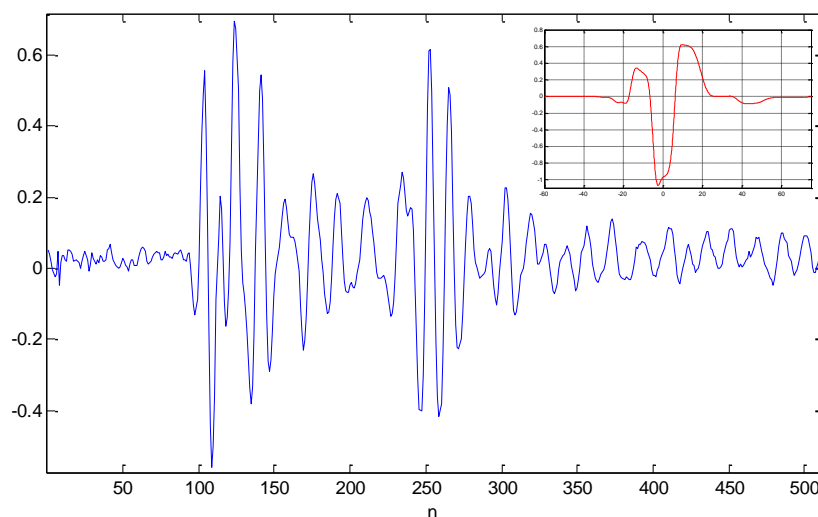


Figure 1. A typical sequence of measurement data acquired by means of a radar sensor (blue line) and the shape of the emitted pulse (red line).

The problem addressed here consists in identification of sub-sequences of data containing information on echoes. Each echo should be characterised by an estimate of its location on the time

axis and an estimate of its magnitude. This is called the preprocessing of radar data, because the estimates of echo parameters, obtained for a series of emitted pulses, are to be next processed by decision-making algorithms detecting various kinds of person's abnormal behaviours, falls in particular.

4. Proposed methods for data preprocessing

4.1. Sectioning of data sequences

The first stage of data preprocessing is aimed at partitioning of the sequence $\{\tilde{y}_n | n = 1, \dots, N\}$ into sub-sequences – each carrying information on a single echo only. It is, therefore, assumed here that such partitioning is possible without deconvolution-type preprocessing of the data sequence $\{\tilde{y}_n\}$. Three methods for data preprocessing, proposed in this subsection, are based on the use of an operator $\odot \mathcal{M}[\circ]$ generating the so-called *max-envelope* of a data sequence being its argument. The max-envelope of the data sequence $\{x_n\}$ is a sequence whose elements are determined by the piecewise-linear interpolation of the non-strict maxima of $\{x_n\}$, *i.e.* the maxima satisfying the inequalities: $x_n \geq x_{n-1}$ and $x_n \geq x_{n+1}$. For example, the max-envelope of the data from Figure 1 is shown in Figure 2.

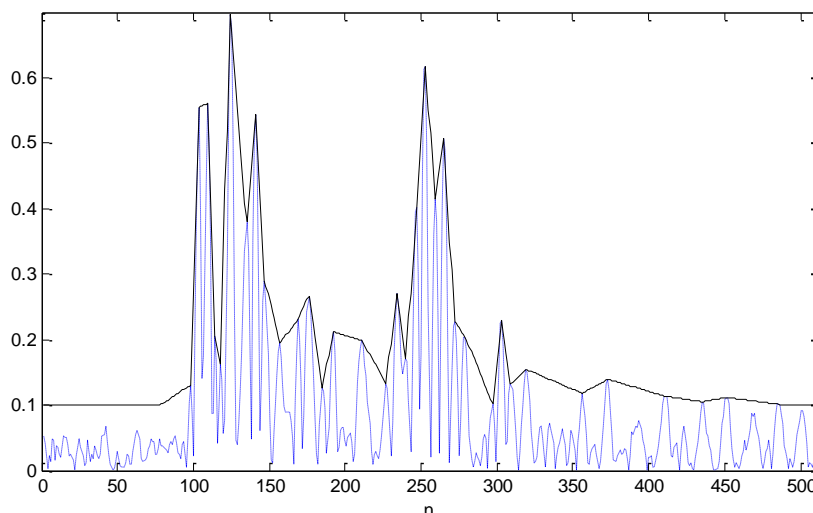


Figure 2. The sequence of the absolute values of the data from Figure 1 $\{|\tilde{y}_n|\}$ (blue line) and its max-envelope $\odot \mathcal{M}[\{|\tilde{y}_n|\}]$ (black line).

Three, structurally similar, algorithms of sectioning are compared here; each of them is composed of three steps:

- transformation of the original sequence of radar data $\{\tilde{y}_n\}$ into an auxiliary sequence of non-negative numbers $\{\tilde{y}_n^+\}$;
- determination of the envelope $\{y_n^E\}$ of the sequence $\{\tilde{y}_n^+\}$ according to the formula:

$$\{y_n^E\} = \odot \mathcal{M}[\{\max(\tilde{y}_n^+ - y_{th}^{(0)}, 0)\}] \quad (1)$$

where $y_{th}^{(0)}$ is a discrimination level fit to the level of errors in the data $\{\tilde{y}_n\}$;

- determination of the borders between sections according to the equation:

$$n_k = \frac{1}{2}n'_k + \frac{1}{2}n'_{k+1} \quad \text{for } k = 1, \dots, K-1 \quad (2)$$

where n'_k are ordered abscissas of all the maxima of the envelope, *i.e.*:

$$n'_k = \arg_n \max \left\{ \max(y_n^E - y_{th}^{(1)}, 0) \mid n=1, \dots, N \right\} \text{ for } k=1, \dots, K \quad (3)$$

with $y_{th}^{(1)}$ being a discrimination level fit to the level of errors in the data $\{\tilde{y}_n^+\}$.

The compared algorithms are labelled with two-letter acronyms (ME, HE and FE) associated with the corresponding definitions of the sequence $\{\tilde{y}_n^+\}$:

- $\{\tilde{y}_n^+\} \equiv \{|\tilde{y}_n|\}$ in the ME algorithm;
- $\{\tilde{y}_n^+\} \equiv \{|\tilde{y}_n\} + j\mathcal{H}[\{\tilde{y}_n\}]\}$ in the HE algorithm;
- $\{\tilde{y}_n^+\} \equiv \mathcal{F}[\{\tilde{y}_n\}, n_{coi}]$ in the FE algorithm;

where $\mathcal{H}[c]$ is the operator of the discrete Hilbert transformation, and $\mathcal{F}[c; n_{coi}]$ is the operator of the ideal low-pass filtering with the cut-off index n_{coi} .

The comparative study has been based on the semi-synthetic data generated according to the formula:

$$\tilde{y}_n = \sum_{k=1}^K r_k \cdot x_{n-n_k} + \eta_n \text{ for } n=1, \dots, N \quad (4)$$

with $K=4$, $N=1000$; $r_1=1$, $r_2=2$, $r_3=0.3$, $r_4=3$; $n_1=100$, $n_2=400$, $n_3=450$, $n_4=800$; and η_n being pseudorandom numbers following the uniform distribution $\mathcal{U}(-d\eta, +d\eta)$. The sequence $\{x_n\}$ is representative of the impulse emitted by the impulse radar sensor NVA6100, manufactured by Novelda AS (<https://www.novelda.no/content/radar-ics>), whose shape is shown in the right upper corner of Figure 1. The study has been carried out under the following assumptions:

- $d\eta \in \{0.1, 0.08, 0.06, 0.01, 0.001\}$;
- $\frac{y_{th}^{(0)}}{d\eta}, \frac{y_{th}^{(1)}}{d\eta} \in \{0.5, 1.0, 1.5, 2.0, 4.0, 6.0, 8.0, 10.0, 20.0\}$;
- $n_{coi} \in \{100, 120, 140, 160, 180, 200, 220, 240\}$.

The statistical evaluation of the results of study has been based on $R=1000$ repetitions of each experiment defined by a fixed combination of the above mentioned parameters – the repetitions differing in the realisations of the sequence of random errors $\{\eta_n\}$. For each experiment the number of repetitions resulting in the correct sectioning, R_{cor} , has been determined, as well as the rate of failure:

$$r_f \equiv \frac{R - R_{cor}}{R} 100\% \quad (5)$$

Selected results of comparison – obtained for the combinations of parameters (the thresholds $y_{th}^{(0)}$ and $y_{th}^{(1)}$, plus n_{coi} in case of the FE algorithm) optimised for each algorithm and for each level of errors $d\eta$ – are shown in Table 1. An example of sectioning is provided in Figure 3.

Table 1. The values of the rate of failure (r_f) characterising the compared algorithms of data sectioning, and the optimised values of their parameters: $y_{th}^{(0)}$, $y_{th}^{(1)}$, and – in case of FE – n_{coi} .

$d\eta$	Algorithm of sectioning		
	ME	HE	FE
0.001	100.0%	0.0% (0.01, 0.008)	0.0% (160, 0.01, 0.015)
0.010	100.0%	0.0% (0.06, 0.060)	0.0% (160, 0.04, 0.040)
0.060	100.0%	9.0% (0.09, 0.090)	0.0% (160, 0.06, 0.060)
0.080	100.0%	14.9% (0.12, 0.080)	2.2% (180, 0.08, 0.040)
0.100	100.0%	25.2% (0.05, 0.150)	13.7% (180, 0.10, 0.050)

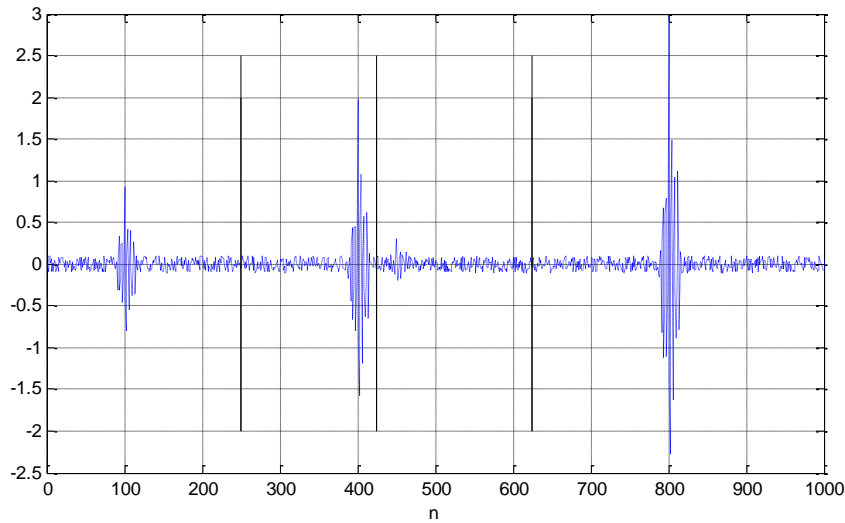


Figure 3. The results of sectioning of the data sequence defined by Eq.(4).

The higher the discrimination levels $y_{th}^{(0)}$ and $y_{th}^{(1)}$, the greater is the probability that smaller echoes may be overlooked. Two complementary strategies, aimed at diminishing the possible loss of information, seem worth being considered, *viz.*: re-sectioning of each section of data and partitioning of the discrimination process. Due to the space limitation, they will not be presented in this paper.

4.2. Estimation of echo parameters

The second stage of data preprocessing consists in estimation of the position and magnitude of an echo in each sub-sequence of the data $\{\tilde{y}_n\}$. For the sake of simplicity, a data sub-sequence will be characterised here using the same symbols as those used for the whole sequence: $\{\tilde{y}_n\}$, N , *etc.* First, the time limits of the echo, n_L and n_R , will be identified using piecewise-linear least-squares approximation of the cumulant sequence defined by the formula:

$$\tilde{y}_v^C \equiv \sum_{v=1}^n \max(y_v^E - y_{th}^{(1)}, 0) \text{ for } n = 1, \dots, N \quad (6)$$

Next, the estimates of the echo position, \hat{n} , and of its magnitude, \hat{m} , will be computed, *viz.*:

$$\hat{n} = \frac{1}{2}(n_L + n_R) \text{ and } \hat{m}^2 = \sum_{v=n_L}^{n_R} \tilde{y}_v^2 \quad (7)$$

The piecewise-linear approximation is based on the use of three "independent" linear functions, *i.e.*:

$$\hat{y}_n^C = \begin{cases} a_1 n + b_1 & \text{for } n \in [1, n_L - 1] \\ a_2 n + b_2 & \text{for } n \in [n_L, n_R] \\ a_3 n + b_3 & \text{for } n \in [n_R + 1, N] \end{cases} \quad (8)$$

For a fixed pair $\langle n_L, n_R \rangle$, the least-squares estimates \hat{a}_k and \hat{b}_k of a_k and b_k ($k=1, 2, 3$) are expressed by the formulae:

$$\begin{bmatrix} \hat{a}_1 \\ \hat{b}_1 \end{bmatrix} = \begin{bmatrix} 1 & 1 \\ \vdots & \vdots \\ n_L - 1 & 1 \end{bmatrix}^+ \cdot \begin{bmatrix} \tilde{y}_1^C \\ \vdots \\ \tilde{y}_{n_L-1}^C \end{bmatrix}, \begin{bmatrix} \hat{a}_2 \\ \hat{b}_2 \end{bmatrix} = \begin{bmatrix} n_L & 1 \\ \vdots & \vdots \\ n_R & 1 \end{bmatrix}^+ \cdot \begin{bmatrix} \tilde{y}_{n_L}^C \\ \vdots \\ \tilde{y}_{n_R}^C \end{bmatrix} \text{ and } \begin{bmatrix} \hat{a}_3 \\ \hat{b}_3 \end{bmatrix} = \begin{bmatrix} n_R + 1 & 1 \\ \vdots & \vdots \\ N & 1 \end{bmatrix}^+ \cdot \begin{bmatrix} \tilde{y}_{n_R+1}^C \\ \vdots \\ \tilde{y}_N^C \end{bmatrix} \quad (9)$$

where $[o]^+$ is the Moore-Penrose pseudo-inverse of the matrix $[o]$. The improved estimates of n_L and n_R may be now obtained by solving two linear algebraic equations:

$$\hat{a}_1 n_L + \hat{b}_1 = \hat{a}_2 n_L + \hat{b}_2 \quad \text{and} \quad \hat{a}_2 n_R + \hat{b}_2 = \hat{a}_3 n_R + \hat{b}_3 \quad (10)$$

The iterative estimation of the vectors $\mathbf{a} \equiv [a_1 \ a_2 \ a_3]^T$ and $\mathbf{b} \equiv [b_1 \ b_2 \ b_3]^T$, followed by correction of n_L and n_R , has turned out to be convergent and quite efficient algorithm for determination of n_L and n_R .

Example 1: The result of piecewise-linear approximation – obtained for a realisation of the data generated according to Eq.(4) with $K=1$, $N=400$, $r_1=1$, $n_1=200$ and $d\eta=0.1$ – is shown in Figure 4. In this case, the worst-case error of position estimation, assessed for $R=100$ realisations, of data is 1.5, and the relative worst-case error of magnitude estimation is 10.8%.♣

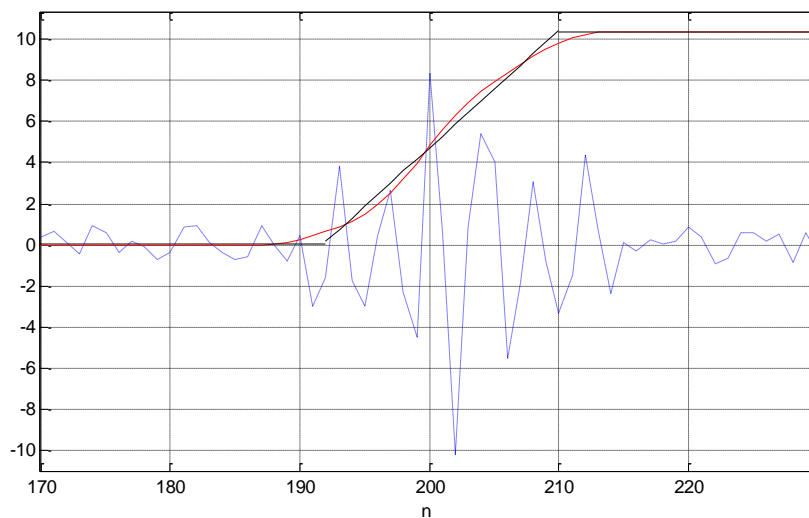


Figure 4. The piecewise-linear approximation (black line) of the sequence $\{\tilde{y}_n^C\}$ (red line) on the background of the original data $\{10\tilde{y}_n\}$ (blue line).

The uncertainty of estimation of the echo parameters depends on the echo position: it increases quickly when the echo position is approaching 1 or N . The extrapolation of the approximated sequence of data is a partial remedy for that negative effect. According to the experience acquired during numerical experiments described here, the prolongation of the sequence by $N/5$ elements to the left and by $N/5$ elements to the right seems to be sufficient.

Example 2: Some exemplary results of estimation of echo parameters – obtained on the basis of the data generated according to Eq. (4) with $K=1$, $N=400$, $r_1=1$, varying n_1 , and $d\eta=0.1$ – are collected in Table 2. The indicators of estimation uncertainty, presented there, have been computed for $R=100$ realisations of each data sequence. ♣

Table 2. Results of numerical experiment described in Example 2.

Estimated parameter	Indicator of estimation uncertainty	Exact echo position						
		10	20	50	200	350	380	390
position	Bias	1.015	0.69	0.61	0.715	0.63	0.515	-0.13
	Standard deviation	0.49	0.56	0.58	0.52	0.48	0.61	0.79
	Worst-case error	2	2	2	1.5	2	2	3
magnitude	Relative bias	-4.13%	-3.54%	-4.10%	-4.01%	-3.93%	-3.93%	-7.32%
	Relative standard deviation	2.92%	3.09%	3.22%	3.00%	3.21%	2.65%	3.55%
	Relative worst-case error	11.02%	10.84%	11.00%	10.80%	11.92%	12.04%	15.92%

5. Conclusion

A set of algorithms for preprocessing of data from an impulse radar sensor has been proposed. It consists of three alternative algorithms for sectioning of those data (labelled ME, HE and FE), and an algorithm for estimation of echo parameters in each section. If the sectioning algorithms are concerned:

- The ME algorithm is the simplest (in terms of the numerical complexity), but least reliable. It may be used provided the estimation of echo parameters is preceded by an additional operation aimed at elimination of false echoes.
- The HE and FE algorithms, if correctly implemented, are comparable in terms of numerical complexity, but the second of them is more reliable. The HE algorithm is performing perfect sectioning till the error level $d\eta = 0.01$, while the FE algorithm – till the error level $d\eta = 0.06$.
- The rate of failure for the FE algorithm is relatively low (*ca.* 14%) even for $d\eta = 0.1$; therefore, it may be applied for data subject to such considerable errors, provided a mechanism for elimination of outliers is included into a set of algorithms for data preprocessing.
- The FE algorithm is also most tolerant with respect to the values of its parameters ($y_{th}^{(0)}$, $y_{th}^{(1)}$, and n_{coi}).

If the algorithm for estimation of echo parameters is concerned:

- The estimation of the echo position is very robust with respect to the errors in the data: even for $d\eta = 0.1$, the random errors of estimation do not exceed 2 sampling units. This is an important advantage of the proposed algorithm since the estimates of the position are to be used for evaluation of movements of the target; so, their sequences will be subject to explicit or implicit differentiation, as a rule amplifying random errors.
- The estimates of the echo magnitude are subject to considerable systematic errors due to the piecewise linear approximation of the data resulting in a systematic limitation of the support of their subsequence identified as an echo.
- At the same time, the random error of those estimates is *ca.* 3 times smaller than the errors in the data. This is again an important advantage of the proposed algorithm since the estimates of the magnitude are to be used for evaluation of movements of the target; so, their sequences will be also subject to differentiation eliminating the systematic errors.

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