

# On applicability of impulse-radar sensors 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 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 persons in their home environment is justified. An extensive overview of the literature, concerning existing monitoring techniques, is provided. A technological potential behind impulse-radar sensors is indicated. New systemic and algorithmic solutions are proposed. Preliminary results of its investigation are presented.

## I. INTRODUCTION

Since the share of European people reaching the age of 65 years or more is growing quickly, the problem of organised care over elderly people is getting more and more important. Hence the demand for various sensor systems which could be applied for non-invasive monitoring of the movements of elderly and disabled persons in their home environment. The capability of such systems to detect dangerous events, such as person's fall, is of key 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 [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, attempts to reach high-located objects) and external (damaged roads, crowded places, dangerous steps, poor lighting).

## II. 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 person; 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 after-fall change of the posture; 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 also outdoor. The signals from movement sensors (mainly accelerometers, and gyroscopes), worn by a monitored person, are transmitted via radio to a computer and analysed. This solution makes also possible the acquisition of physiological data (e.g. data representative of blood pressure, ECG signals or EEG signals).

## III. FORMULATION OF THE RESEARCH PROBLEM

Since several years numerous attempts have been made to apply radar technology for monitoring of elderly and disabled 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 a monitoring system whose functioning is based on the analysis of measurement data acquired by means of impulse-radar sensors. A typical sequence of such data from a single sensor, after removing the static background, is shown in Figure 1.

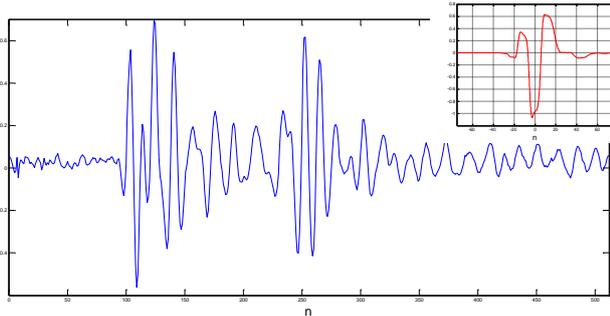


Fig. 1. A typical sequence of measurement data acquired by means of an impulse-radar sensor (blue line) and the shape of the emitted pulse (red line).

The monitoring system under design and investigation is to be composed of two or three Smart Sensors, shown in Figure 2, and an Alarm Controller. The role of Smart Sensors is to provide several time-sequences of parameters characterising the behaviour of a monitored person, extracted from the consecutive sequences of raw radar data. The role of the Alarm Controller is to use those time-sequences of parameters for making the decision about the need, or the lack of the need, to raise alarm, and to communicate the alarm decision to human supervisors of the monitored person.

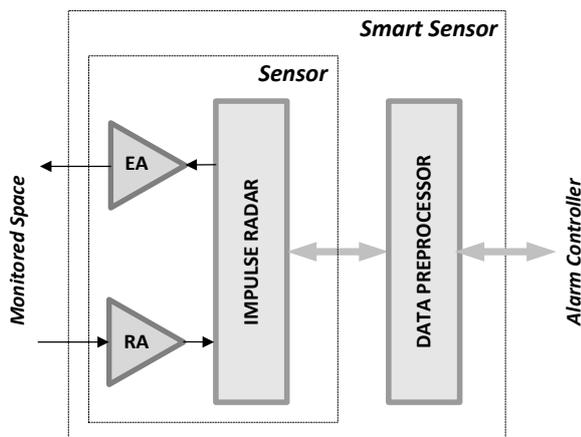


Fig. 2. The functional block diagram of Smart Sensor; EA – emitting antenna, RA – receiving antenna.

#### IV. PROPOSED ALGORITHMIC SOLUTIONS

The algorithms for data preprocessing, to be

implemented in the monitoring system, are based on the transformation of the original sequence of measurement data into an envelope of the low-pass-filtered modulus of that sequence. The envelope is used for identification of sub-sequences of data, each containing information on a single echo whose position and magnitude is then estimated. The piecewise-linear least-squares approximation of the so-called cumulant sequence is used for this purpose, *viz.* the time support of the echo is determined on the basis of the break points of that sequence. Then, an estimate of the echo magnitude is computed as the zero moment of the absolute value of the corresponding subsequence of data, and an estimate of the echo position – as the first moment of that subsequence. The whole procedure is called preprocessing of radar data because the estimates of echo parameters, obtained for a series of emitted pulses, are next processed by decision-making algorithms detecting various kinds of person's abnormal behaviours, falls in particular. The details of the algorithms of radar data preprocessing, as well as the results of study on their numerical properties, are provided in another conference paper, *viz.* [55].

#### V. PROPOSED SYSTEMIC SOLUTIONS

In this Section, the solutions of the functional blocks of the monitoring system under design and investigation are proposed and briefly outlined.

##### A. Sensors

The design of sensors, functionally depicted in Figure 2, is based on impulse-radar sensors NVA series 6000 (manufactured by Novelda AS, <https://www.novelda.no/content/radar-ics>) being fully integrated nanoscale radar transceivers, designed for low-power applications. Those active sensors, generating Gaussian pulses, employ 32-bit digital integration and 512 parallel samplers for maximum frame depth and sensitivity, as well as a fully programmable frame offset for an extensive detection range. The programmable input amplifier ensures the adjustable dynamic range, while the high-speed, high-resolution sampler provides the free space sampling resolution of up to 4 mm. The NVA sensors are available for three frequency ranges, *viz.*: 0.45–3.55 GHz, 6.0–8.5 GHz and 0.85–9.55 GHz. In the first working prototype (R641 module), the NVA6100 sensors are used, but soon they will be replaced with the recently introduced on the market NVA6200 sensors. The latter are offering various functional improvements among which the most important one is tuning of the pulse generator; their user can adjust the centre frequency (from 5.3 GHz to 8.8 GHz) and the bandwidth (from 1.7 GHz to 3.1 GHz) of the pulse to meet local radiation norms. Another change, introduced in the NVA6200 sensors, is the reduction of the number of samples per frame from 512 to 256 or even 128.

### B. Antennas

At the onset of the project, two ultra-wide-band antennas were designed and prototyped, *viz.* for the ranges of 0.45–3.55 GHz and 0.85–9.55 GHz. Their structures were prepared for attaching a screen and a radiator. The measurement tests showed that the main design assumptions had been fulfilled, but the antenna gain was changing with the frequency and with the angle of elevation up to 7.5 dB. Although this could be considered quite acceptable for such a broad operational frequency band, the third antenna for the range of 6.5–8 GHz has been designed and prototyped, taking into account the dimensions of two boxes (120x94x57 mm and 120x120x57 mm) which are to be used for housing the radar module together with a processor and electronics. The construction of the latter antenna enables one to entirely mount it on any of those boxes. The measured characteristics of the antenna prototype are very stable in the whole frequency band; its gain is higher than 7 dBi, the beam width in the H-plane is *ca.* 100°, and in the E-plane – *ca.* 60°. The results of experimental investigation have shown that not only technical specifications and small dimensions of the new antenna fit the purpose, but also that its construction is well adapted to the standard technologies of antenna fabrication.

### C. Computing means

There are two options for implementation of the function of the alarm controller: it may be merged with the preprocessing function of a selected Smart Sensor, or it may be implemented in an external processor. The choice depends on two factors, *viz.* on the number of sensors used for monitoring a predefined living space, and on the complexity of alarm-launching algorithms. Thus, the right choice is possible only when a target application of the monitoring system is defined. In any case, the following operations are to be performed: synchronisation of Smart Sensors deployed in a monitored room, aggregation and analysis of data from those sensors, identification of alarm situations, and alerting the remote supervisors (medical centres, nurses, family, *etc.*). For the time being, it is assumed that both algorithms for preprocessing of measurement data and for decision making will be implemented in the same computing means, *viz.* in a system-on-a-chip ZynQ composed of a dual-core processor Cortex-A9MPCore and programmable logic FPGA. The already developed prototype of a Smart Sensor is, however, using the MIO-2261N-S6A1E single board computer. The motivation behind this solution was to quickly obtain a working device for testing various algorithms – without waiting for a more mature design.

### D. Assemblage

Due to the frequency range used, sensors should be

integrated with antennas on the same printed circuit boards. This will eliminate connectors and possible impedance discontinuities, and consequently – minimise losses of analogue signal power. The Serial Peripheral Interface seems to be sufficient for digital communication within Smart Sensors, although additional control signals and power lines are foreseen. The system ZynQ will be assembled on a standard FR-4 multilayer printed circuit board. The entire device is fitted inside an ABS casing. Appropriate tests have been done to ensure there is little impact of the casing and the way components neighbour each other on the performance of the sensor. Factors such as influence on antenna's characteristics, interference between digital and analogue part have been taken into account to avoid degradation of sensors efficiency.

## VI. CRITERIA FOR EVALUATION OF PROPOSED SOLUTIONS

The proposed solutions need to be evaluated in relation to several needs to be met and challenges to be overcome. Firstly, the assistive technology solutions need to be both as accurate as possible in distinguishing between normal daily activities and healthy body movements and functioning, on the one side, and non-normal activity patterns and body movements and functioning, on the other side. Secondly, the assistive technology need to be based on the identifying key bodily movements: *i.e.* centre of mass, rotations, the dynamic relation between centre of mass and support base. Thirdly, potentially harmful falls need to be detected in the most accurate way possible since falls is a prominent health threat to older people and the prime cause of their hospitalization. Real falls need to be sorted out from non-falls, like when sinking down in a non-dangerous way. False alarms should be avoided, as should non-detection of dangerous falls. This is a real challenge, since even short falls may be harmful or even deadly for frail older people. Potentially dangerous falls need to be detected in a range of situations, when walking, standing still, sitting and lying in bed. Fourthly, prevention is a key issue, where detecting progressive changes in a person's motor behaviour increasing the risk of falling should be a major aim. Fifthly, the need for user involvement should be minimized as the number of older people with cognitive impairment is steadily increasing.

## VII. PRELIMINARY RESULTS

This Section is entirely devoted to the presentation of selected experimental results obtained after the first year of the project development. These are exclusively the results of metrological nature, fitting to the profile of the IMEKO-TC4 Symposium; the issues concerning the decision-making part of the monitoring system under design, will be presented in a separate publication.

The results of measurement data preprocessing have the form of sequences of the estimates: of the echo

positions  $\{eep(i) \mid i=1,2,\dots\}$  and of the echo magnitudes  $\{eem(i) \mid i=1,2,\dots\}$ . In order to evaluate their uncertainty, the following experiment has been staged:

- The sequences of data representative of a typical denoised echo  $\{de(n) \mid n=1,2,\dots\}$  and of  $R=1000$  realisations of the measurement noise  $\{mn(n;r) \mid r=1,\dots,R\}$  have been acquired and recorded.
- The sequences of data representative of two echoes, located at the position  $p$  and  $p+dp$ , have been synthesised using  $\{de(n)\}$  and  $\{mn(n;r)\}$  for several values of  $dp$  and several ratios of their magnitudes.
- For each sequence of those data, the positions and magnitudes of both echoes have been estimated; thus, for each combination of the positions and magnitudes, a subset of  $R$  estimates, corresponding to different realisations of noise, has been obtained.
- Those subsets have been next used for evaluation of the standard deviations of the estimates. Their bias has been neglected since it will be eliminated by differentiation of the sequences of estimates.

The detailed description and complete results of this experiment have been assembled in one of the project reports [56]. Here the most important findings are summarised, the findings corresponding to the following assumptions:

- The ratio of the magnitude of the first (stronger) echo to the level of noise is set to 100, which is imitating the echo reflected from an 'average' person staying *en face* at the distance of *ca.* 1 m from the radar sensor NVA6100.
- The magnitude of the second (weaker) echo is set to the value of 1, 1/2, or 1/3 of the magnitude of the first (stronger) echo. In this way, it is imitating a secondary echo reflected from the person and a near-by staying object.

For the distance between echoes  $dp$  greater than 0.15 m, the following values of the dispersions have been obtained:

- the absolute standard deviation of the position estimation – not greater than  $2 \cdot 10^{-5}$  m;
- the relative standard deviation of the magnitude estimation – not greater than 0.5 %.

For the decision-making algorithms, the changes of the positions and magnitudes in time are more informative than their instant values. Since differentiation of noisy data is an ill-conditioned numerical problem, some attempts have been made to regularise it [57]. For the simplest formula of progressive difference with the step of differentiation, optimised according to the trade-off between error inherited from the data and discretisation error, the following worst-case assessment of the expended uncertainty has been found:

$$2.9 \sqrt{\sup |y''(x)|} \sigma$$

where  $y''(x)$  is the second derivative of the differentiated

function, and  $\sigma$  is the standard deviation of random errors in the data. The worst-case value of  $|y''(x)|$  has been assessed on the basis of data, acquired by means of a wearable accelerometer (*viz.* the OPAL unit manufactured by APDM Co.), showing that the acceleration of a falling person should not exceed  $50 \text{ m/s}^2$ . Consequently, the expended uncertainty of the derivative of the position sequence has been found: 0.01 m/s. Since it may turn out too large for reliable decision making, some more advanced methods of differentiation have been considered, *viz.* the method of central difference and a method based on analytical differentiation of a linear combination of finite-support functions, approximating the data [57].

## VIII. CONCLUSION

The applicability of impulse-radar sensors for monitoring of human movements have been analysed and demonstrated using prototype solutions of the key practical problems related to the design of a monitoring system oriented on the detection of human falls. In particular: the compact integration of the system hardware (sensors, antennas, computing means) has been proposed, as well as an efficient solution for metrological problems related to the generation of informative parameters characterising movements of a monitored person.

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