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Regularised differentiation of measurement data in systems for monitoring of human movements

Jakub Wagner*, Paweł Mazurek, Andrzej Miękina, Roman Z. Morawski

Institute of Radioelectronics and Multimedia Technology, Faculty of Electronics and Information Technology, Warsaw University of Technology, ul. Nowowiejska 15/19, 00-665 Warsaw, Poland

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ABSTRACT

The research reported in this paper is related to assistive technologies that may be used by healthcare institutions for monitoring movements of elderly persons. The corresponding systems, based on impulse-radar sensors and depth sensors are addressed. The reported study is focused on the estimation of the walking velocity of a monitored person, which requires numerical differentiation of data representative of that person's position trajectory. Five methods of numerical differentiation are compared in terms of their applicability in such systems. The comparison is based on both synthetic data and real-world data. The results of experiments indicate the superiority of a differentiation method based on the Tikhonov regularisation. The bias and standard deviation of errors corrupting the velocity estimates, obtained by means of that method, do not exceed 0.10 m/s in the case of the impulse-radar sensors and 0.08 m/s in the case of the depth sensors.

1. Introduction

The number of people with functional deficiencies or ill health, including persons suffering from dementia, has been growing in Europe since the last decade of the XXth century; on the other hand, the recruitment of the healthcare personnel has not been increasing proportionally [1]. Hence the growing importance of research on new technologies that could be employed in monitoring systems supporting care services for elderly persons. The capability of those systems to detect dangerous events, *e.g.* person's falls, is of key importance [2]. However, those systems are expected not only to detect, but also to predict those events on the basis of acquired data. The results of prediction, combined with the results of the analysis of gait, may contribute to the prevention of dangerous events [3]. The relevance of features related to gait analysis in monitoring of elderly persons, and in particular – in fall prevention, has been emphasised in several recent papers [4–9].

There are three main categories of monitoring techniques already applied in care practice: wearable [10], vision-based [11] and environmental [12]. This paper is focused on two emerging families of monitoring techniques: radar-based techniques [13] and depth-sensor-based techniques [14]. The attempts to apply them for monitoring of elderly persons are mainly motivated by the conviction that they 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 (such as pressure sensors installed in the furniture or on the floor). The most attractive feature of the radar-based monitoring techniques is the possibility of the through-the-wall monitoring of human activity, making possible the monitoring in the whole area of the household without the need to install sensors in each room. The applicability potential behind depth-sensor-based monitoring techniques is related to:

– their ability to provide more accurate information about the movement of the monitored person without infringing his/her privacy in the degree the vision-based systems do;
– the low price of depth sensors which are installed in such common gadgets as the Microsoft Kinect devices.

Healthcare-oriented analysis of human gait may comprise the estimation of various gait-related parameters [15]. This paper is devoted to the most important among them – the monitored persons' walking velocity. Even though various factors may affect the value of the walking velocity, healthcare practitioners consider it to be a good indicator of the general health since experimental results – *e.g.* those reported in [16] – suggest that it is correlated with healthcare-informative quantities, such as the risk of falling. The

* Corresponding author.
E-mail address: j.wagner@ire.pw.edu.pl (J. Wagner).

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following observations indicate the informativeness of the walking velocity [17]:

- its values smaller than 0.6 m/s indicate a high risk of fall and hospitalisation of a monitored person;
- its increase of at least 0.1 m/s is a useful predictor of well-being;
- its similar decrease is correlated with deterioration of the health status or decline in overall functioning.

Several techniques have been proposed for estimation of the walking velocity of elderly persons in their home environment, including techniques based on biomechanical models of human gait, on machine-learning procedures, and on estimation of travelled distance and walking time. Those techniques involve the acquisition of data using:

- inertial sensors (triaxial accelerometers combined with gyroscopes and/or magnetometers), attached to the monitored person's waist [18–20], foot [21–24], leg [25,26] or wrist [27,28], as well as embedded in a phone [29–34], watch [35], or glasses [36];
- Doppler-radar sensors [37–40];
- infrared depth sensors [41–43];
- infrared motion detectors [44–46];
- pressure or force sensors, mounted inside the monitored person's shoes [47–49] or under a carpet [50];
- sensors tracking the positions of markers or tags attached to the monitored person's body [51,52];
- sensors of radio-frequency fluctuation [53].

The accuracy of walking-velocity estimates, obtained on the basis of data acquired by means of the above-mentioned techniques, has been reported using different kinds of reference data – obtained using, *e.g.*, the VICON system [54], the GAITRite system [55], or a stopwatch – in different experimental conditions, and using different accuracy indicators; thus, it is difficult to systematically compare those techniques. Roughly speaking, the absolute errors corrupting the velocity estimates, obtained by means of the above-mentioned techniques, are in the range between 0.01 m/s and 0.1 m/s.

This paper is devoted to systems for estimation of walking velocity based on depth sensors and impulse-radar sensors which do not use the Doppler principle (called *radar sensors* hereinafter). The first monitoring system under study, based on radar sensors, has been proposed in an authors' previous paper [56]. It consists of:

- a pair of radar sensors, integrated with the electronic means for preprocessing of digital signals and with the communication means;
- a data processor estimating the position of a monitored person on the basis of data representative of distances between that person and those sensors.

The estimation of the two-dimensional coordinates of the monitored person's position on the basis of data from the radar sensors requires the execution of the following operations [57]:

- suppression of measurement noise and unwanted echoes – the echoes caused by the fact that the emitted impulse is reflected from static objects and/or reflected more than once before reaching the receiver antenna – using bandpass filtering and a procedure based on the analysis of previously acquired data sequences [58];
- estimation of the distances between the monitored person and the sensors on the basis of the parameters of the received signal, determined using a modified version of the CLEAN algorithm [59];
- estimation of the two-dimensional coordinates of the monitored person's position by smoothing the sequences of distance estimates [60] and transforming the coordinate system [61].

The radar sensors, used in this study, operate in a frequency range which conforms to the regulatory framework published by the European Commission [62]. Therefore, they do not interfere with radiocommunication services present in typical households. Furthermore, each radar sensor has been equipped with a high-pass filter, suppressing frequencies below 6.01 GHz, in order to decrease its susceptibility to interference from other wireless systems which may be operating in the monitored area [63]. The vicinity of electronic devices using wireless communication means has not caused any observable disturbances of the monitoring system based on radar sensors.

The second monitoring system, used in the experiments described here, consists of a depth sensor (being part of a Kinect V2 device) and a data processor. The estimation of the two-dimensional coordinates of the monitored person on the basis of data from the depth sensor requires the execution of the following operations [64]:

- elimination of the static background;
- transformation of the coordinate system;
- estimation of the position of the monitored person's centre of mass on the basis of the transformed coordinates of pixels belonging to the image of that person's silhouette.

The data representative of the monitored person's two-dimensional position trajectory, provided by the above-described sensors, have to be differentiated numerically in order to estimate the velocity trajectory. Those data are corrupted with measurement errors, so their numerical differentiation is an ill-posed problem: small errors in the data may contribute to large errors corrupting the derivative estimate. Therefore, regularised methods should be used; throughout this paper, the term "regularised method" means any method aimed at reducing the amplification of random errors by providing a compromise between the fidelity to the data and some kind of "regularity" of the derivative estimate [65]. Several regularised methods for numerical differentiation have been proposed, stemming from various mathematical ideas including: Tikhonov regularisation [66–71], smoothing approximation [72–76], regularisation of finite-difference algorithms [77–82], linear filtering [83–86], mollification [87,88], wavelet transform [89,90], variational calculus [91,92], operational calculus [93,94] and sliding-mode algorithms [95]. The volume of publications devoted to numerical differentiation is quite considerable, and their number per year is growing [96]. Nevertheless, none of the differentiation methods has been proven to provide optimum results for all kinds of data. Furthermore, no systematic strategy for the selection of the optimum differentiation method for a given practical problem has been proposed. Therefore, it is quite common to empirically compare the performance of different methods using real-world data related to a particular application – it has been done recently, *e.g.*, in the context of automation [97–99], political science [100], aircraft diagnostics [101], medical imaging [102], image enhancement [103], oil-well hydraulics [104] and optical metrology [105]. The aim of this paper is to compare five methods for numerical differentiation in terms of their applicability in the systems for estimation of walking velocity using real-world data acquired by means of radar sensors and depth sensors. These are the following methods: