Expert Systems With Applications 62 (2016) 263–272

Contents lists available at ScienceDirect

Expert Systems With Applications

journal homepage: www.elsevier.com/locate/eswa

Benchmark problem for human activity identification using floor vibrations

Ramin Madarshahian[a], Juan M. Caicedo[a,*], Diego Arocha Zambrana[b]

[a] University of South Carolina, 300 Main St. Columbia, 20208, USA
[b] Destek Engineering, 1281 Kennestone Circle, Suite 100 Marietta, GA 30066, USA

ARTICLE INFO

Article history:
Received 27 October 2015
Revised 13 June 2016
Accepted 14 June 2016
Available online 16 June 2016

Keywords:
Benchmark
Human activity identification
Floor vibration
Fall detection
Accelerometers

ABSTRACT

Monitoring and analyzing floor vibrations to determine human activity has major applications in fields such as health care and security. For example, structural vibrations could be used to determine if an elderly person living independently falls, or if a room is occupied or empty. Monitoring human activity using floor vibration promises to have advantages over other methods. For example, it does not have the privacy concerns of other methods such as vision-based techniques, or the compliance challenges of wearable sensors. The analysis of the signals becomes a classification problem determining the type of human activity. Unfortunately only a few research groups are performing research of this subject even though there is a significant number of techniques that could be applied to this field. To date, no systematic study about the challenges and advantages of using different types of algorithms for this problem has been performed. This paper proposes a benchmark problem to: (i) encourage researchers to design new algorithms for monitoring human activity using floor vibrations, (ii) provide a dataset to test new algorithms, and (iii) allow the comparison of proposed methods based on a set of standard metrics. The benchmark consists of seven different cases of increasing difficulty. Each case has a specific number of sensors, calibration signals, and type of floor excitation forces to be considered. The paper also proposes specific metrics that enable the direct comparison of different techniques. Research groups interested in monitoring human activity using floor vibrations are encouraged to use the experimental data and evaluation metrics published in this paper to develop their own methodologies. This will enable the community of researchers to easily compare and contrasts techniques and better understand what type of methods will be appropriate in different applications.

1. Introduction

Structural vibrations analysis is a powerful tool for a variety of purposes including the design and maintenance of infrastructure. Dynamic analyses could be divided into two groups: (i) input output analysis like time history based methods with predefined excitation (for example, for building design) (Madarshahian, Estekanchi, & Mahvashmohammadi, 2011; Yu, Imbimbo, & Betti, 2009), and (ii) output only methods such as operational modal analysis (Azam, Chatzi, & Papadimitriou, 2015; Caicedo & Marulanda, 2011; Jaishi & Ren, 2005; Peeters & De Roeck, 2001). In practice, it is not feasible (or very difficult) to measure the input excitation of in-service structures. However, measurement of ambient structural vibration is easier and has been used for a number of applications such as operational modal analysis (Abdel-Ghaffar & Housner, 1978; Brincker, Zhang, & Andersen, 2000; Brownjohn, 2003; Giraldo, Song, Dyke, & Caicedo, 2009; Siringoringo & Fujino, 2008; Yang, Lei, Lin, & Huang, 2004), model updating (Foti, Diaferio, Giannoccaro, & Mongelli, 2012; Wu & Li, 2004), damage detection (Gentile & Saisi, 2007; Mosavi, Dickey, Seracino, & Rizkalla, 2012), serviceability (Brownjohn, Pan, Middleton, Tan, & Yang, 2014; Chen, Zhang, & Liu, 2015; Salgado, Branco, Cruz, & Ayala, 2014; Van Nimmen, Van den Broeck, Gezels, Lombaert, & De Roeck, 2012), and source identification (Jones, Reynolds, & Pavic, 2011; Kim, Lynch, Lee, & Lee, 2011; Loh, Lynch, Wang, Law, Fraser, & Elgamal, 2007). Low level vibrations have been used for serviceability purposes, where acceptable levels of acceleration are specified depending on the use of the structural system. For instance, Gordon (1992) proposes a generic criterion to limit the floor vibrations in structures containing sensitive equipment (Gordon, 1992; Pan, You, & Lim, 2008). In special circumstances control devices are used to reduce the vibrations in

* Corresponding author: Fax: +18037770670.
E-mail addresses: mdrshhn@email.sc.edu (R. Madarshahian), caicedo@cec.sc.edu (J.M. Caicedo), darocha@destekengineering.com (D. Arocha Zambrana).

http://dx.doi.org/10.1016/j.eswa.2016.06.027
0957-4174/

floors (Allen & Pernica, 1998; Hanagan & Murray, 1997). In some other situations, changing the structural configuration can be effective. For example, studies found that thickening a lower floor in a building was an effective solution at reducing floor vibration due to external excitations (i.e. train induced vibrations) (Hughes, 2008; Hughes, Sanayei, Moore, Zapfe, & White, 2008). The mitigation of vibration in tall buildings due to wind excitation and its effect on their residents is also part of serviceability studies (Kareem, Kijewski, & Tamura, 1999; Wang, Ni, Ko, & Spencer, 2005).

Monitoring small amplitude floor vibrations can also be used to infer human activity (Chaudhuri & Singh, 2015; Davis, Caicedo, Langevin, & Hirth, 2011; Dorvash, Pakzad, Naito, Hodgson, & Yen, 2014; Pereira, Díaz, Hudson, & Reynolds, 2014) and provide an alternative to other methods already used in the medical and security fields (Ciuti, Ricotti, Menciassi, & Dario, 2015; Lowe & ÓLaighin, 2014). For example, fall-induced injuries are one of the most important public health challenges and have a considerable impact on healthcare costs (Korhonen et al., 2012; Stevens, Corso, Finkelstein, & Miller, 2006). Statistics show that fall-related hospital admissions in the Netherlands increased by 137% between 1981 and 2008 (Hartholt et al., 2010). One out of three people over 65 years of age is expected to fall once a year (Rubenstein, Robbins, Josephson, Schulman, & Osterweil, 1990; Vellas, Wayne, Garry, & Baumgartner, 1998). Moreover, people with dementia such as Alzheimer's patients are at higher risk of falling because of their gait patterns (Buchner & Larson, 1987; Sheridan & Hausdorff, 2007). People frequently lay involuntarily on the ground for an extended period of time after falling, developing other complications not directly related to the fall. This is known in the medical community as long lie (Bisson, Peterson, & Finlayson, 2015; Tinetti, Liu, & Claus, 1993). The Personal emergency response system (PERS) is a signaling device that was developed in the '80s and has achieved good acceptance in home healthcare community to help patients get immediate help. PERS is based on a small transmitter that can send a signal to an emergency center when a person pushes a small button (Baldwin, Syverud, & Edlich, 1993; Dibner, 1990; Edlich et al., 1992). Although User-Activated Fall Alarm devices are not expensive and easy to use, people are not always able or willing to press the button (Bradley, 2011; Fleming & Brayne, 2008; Heinbüchner, Hautzinger, Becker, & Pfeiffer, 2010; Simpson & Mandelstam, 1995). Furthermore in Falls, head impact level can reach upwards of 500 g, which is a level that can cause unconsciousness and serious injury, therefore users may not able to press the button after the incident (Hajiaghamemar, Seidi, Ferguson, & Caccese, 2015; Seidi, Hajiaghamemar, & Caccese, 2015; Seidi, Hajiaghamemar, Ferguson, & Caccese, 2015). Wearable sensors using accelerometers and gyroscopes can be put in clothing, watches or cellphones and are an alternative for fall detection (Bassett Jr, Rowlands, & Trost, 2012; Bonato, 2010; Dai, Bai, Yang, Shen, & Xuan, 2010; Maurer, Rowe, Smailagic, & Siewiorek, 2006a; Maurer, Rowe, Smailagic, & Siewiorek, 2006b; Rajendran, Corcoran, Kinosian, & Alwan, 2008; Song, Jang, & Park, 2008; Tay, Nyan, Koh, Seah, & Sitoh, 2005; Yang & Hsu, 2010; Zhang, Wang, Liu, & Hou, 2006). Unlike PERS, these systems do not require the patient to push a button. However, a care giver is usually needed with these systems because the elder and dementia-disabled patient easily forgets to wear the device or charge its batteries (El-Bendary, Tan, Pivot, & Lam, 2016; Lundell, Kimel, Dishongh, Hayes, Pavel & Kaye, 2006; Luo, Liu, Liu, Guo, & Wang, 2012; Mahoney & Mahoney, 2010). Vision-based systems are arguably one of the most autonomous systems for fall detection and human activity monitoring in general (Bosch-Jorge, Sánchez-Salmerón, Valera, & Ricolfe-Viala, 2014; Costa, Castillo, Novais, Fernández-Caballero, & Simoes, 2012; El-Bendary et al., 2016; Shieh and Huang, 2009). Several image and sound processing algorithms have been developed to recognize fall events (Haritaoglu, Harwood, & Davis, 1998; Moeslund & Granum, 2001; Rougier, Auvinet, Rousseau, Mignotte, & Meunier, 2011; Rougier, Meunier, St-Arnaud, & Rousseau, 2011; Töreyin, Dedeoğlu, & Çetin, 2005). However, one of the biggest challenges faced by video systems might not be technological but related to privacy concerns. People generally do not like the feeling of being watched, especially in places like bedrooms and bathrooms (Demiris, Oliver, Giger, Skubic, & Rantz, 2009). Monitoring small amplitude floor vibrations provides an alternative to PERS, vision based and wearable sensors. Vibration based monitoring (VBM) prevents the compliance challenges of wearable sensors and PERS and does not have the privacy concerns of vision systems (Spasova & Iliev, 2014; Zigel, Litvak, & Gannot, 2009). VBM is not limited to fall detection. It has the potential to be implemented for gait analysis to monitor patient's conditions (Chien, Tsai, Guo, & Li, 2009; Gietzelt, Wolf, Kohlmann, Marschollek, & Haux, 2013; Roche et al., 2014; Weiss, Herman, Giladi, & Hausdorff, 2014) or smart surveillance systems (Hampapur et al., 2003) among others uses.

The idea of using floor vibration for human activity monitoring is relatively new. To the best of the authors' knowledge, the first papers on VBM for fall detection were published in 2006 (Alwan et al., 2006; Rajendran et al., 2008) and VBM with the addition of sound in 2008 (Litvak, Gannot, & Zigel, 2008; Litvak, Zigel, & Gannot, 2008). Recent research has incorporated the use of smart wireless sensors (Davis et al., 2011; Tung et al., 2013). Fundamental questions such as sensor density, and appropriate sensors sensitivity are still being investigated. Furthermore, relevant algorithms to determine human activity based on structural vibrations are still in their infancy. Some of the challenges associated with these algorithms include: (i) the amplitude of the signal depends on the distance between the sensor and the location of the event of interest, (ii) two different events could produce similar in signal characteristics (i.e. similar amplitude of frequency content), (iii) changes in the structure's usage and environmental conditions could lead to different floor dynamic characteristics, (iv) every structure has different structural and floor characteristics (e.g. floor type, structural configuration, etc), (v) records could have a high noise to signal ratio.

In disciplines such as structural health monitoring and structural control benchmark problems have proven useful to foster collaboration between researchers and address challenges such as those listed above (Bernal & Gunes, 2004; Caicedo, Dyke, & Johnson, 2003; Dyke, Caicedo, Turan, Bergman, & Hague, 2003; Haselton et al., 2008; Johnson, Lam, Katafygiotis, & Beck, 2001). For example, the IASC-ASCE Benchmark problem in structural health monitoring (Johnson, Lam, Katafygiotis, & Beck, 2003) have been used to illustrate the implementation of artificial neural network (Taha, 2010; Wang, Ni, & Ko, 2011), adaptive recursive least squares filtering theory (Chase, Begoc, & Barroso, 2005; Geoffrey Chase, Leo Hwang, Barroso, & Mander, 2005), Eigen sensitivity-based finite element model (Wu & Li, 2006), Hilbert–Huang transform (Lin, Yang, & Zhou, 2005) in damage detection and system identification using ambient vibration among many other techniques. Similar benchmarks have been proposed in Structural Control (Agrawal, Tan, Nagarajaiah, & Zhang, 2009; Dyke et al., 2003; Nagarajaiah, Narasimhan, Agrawal, & Tan, 2009; Nagarajaiah, Narasimhan, & Johnson, 2008; Narasimhan, Nagarajaiah, Johnson, & Gavin, 2005; Spencer, Dyke, & Deoskar, 1998; Spencer Jr, 2004; Spencer Jr, Christenson, & Dyke, 1998; Tan & Agrawal, 2009; Yang, Agrawal, Samali, & Wu, 2004) to advance the state of the art in that field. This paper proposes a framework to study algorithms for human activity identification using floor vibrations. The problem consists of a set of experimental data created by different human actions such as jumping, bouncing a ball, and dropping a bag full of plastic pieces. Floor vibrations were collected in a two-story steel building with a concrete slab. A total of 16,100 records were collected under con-