Keijo Ruotsalainen, Taneli Rantaharju, Pentti Romppainen & Arto Partanen

Multi-purpose whole-body vibration measurement and evaluation system

Kajaanin ammattikorkeakoulu

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Kajaanin ammattikorkeakoulu
PL 240
87101 KAJAANI
Puh. (08) 6189 9504
Sähköposti: merja.soininen@kajak.fi
http://www.kajak.fi

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ABSTRACT

Ruotsalainen Keijo, M. Sc. (Eng.), project researcher, Centre for Wireless Communications, University of Oulu

Rantaharju Taneli, M. Sc. (Eng.), project planner, Kajaani University of Applied Sciences

Partanen Arto, B. Sc., lecturer (Eng.), Kajaani University of Applied Sciences

Romppainen Pentti, D. Sc. (Eng.), principal lecturer, Kajaani University of Applied Sciences

The minimization of health risks associated with regular and continuous exposure to mechanical vibration has been taken into account in the EU directive 2002/44/EC. Employers are responsible for estimating the daily vibration exposure of an employee based, preferably on measurements. The objective of this article is to describe a comprehensive system designed for long-term whole-body vibration measurements as well as for serving research related needs. The system architecture comprises wireless and wired sensor units, a data acquisition and processing unit and also ubiquitous access to the remote server enabling continuous observation. The execution of calculation algorithms associated with the evaluation of WBV was defined as a priority task. Wireless approaches were applied to enable a practical way to further transfer measured data. To increase the flexibility and versatility of the system, a modular structure equipped with appropriate interfaces such as CAN and Zigbee, was adopted. Long-term measurement also creates certain constraints for the vibration sensing method. Thus, possible substitutes for the uncomfortable standardized method were studied. The architecture was designed keeping in mind an option to modify it for various applications outside WBV research such as health care and wellbeing.

Keywords: whole-body vibration, measurement system, wireless sensor, ISO 2631-1, ISO 2631-5

1 INTRODUCTION

Several occupational groups are exposed daily to substantial amounts of vibration mostly due to normal working routines like operating heavy equipment or driving vehicles on uneven surfaces. Vibration affecting the human body as a whole, and transferred to the body through supporting systems such as the seat or floor, is defined as whole-body vibration (WBV). Studies have shown that long-term exposure to WBV creates adverse health effects, of which lower back pain is the most commonly reported. Such symptoms may lead to a weakened quality of life or even incapacitation. Even though a correlation between health problems and long-term WBV exposure is evident, mechanisms behind the symptoms have remained unexplained.

In Europe, the minimum health and safety requirements regarding the exposure of a worker to risks arising from vibration are defined in the directive 2002/44/EC (The European Parliament and The Council 2002). The objective of the directive is to prevent the exposure of employees to extensive vibration by specifying the limits for daily exposure and defining preventative actions to minimize risks. Employers are responsible for estimating vibration, preferably based on measurements carried out at the workplace. Three dimensional acceleration measured at the seat surface for a seated worker, is used as the quantity describing the severity of vibration. According to the directive, the evaluation and assessment procedures of WBV exposure must be done according to the ISO 2631-1:1997 (International Organization for Standardization 1997). Countries outside Europe also have guidelines concerning exposure to WBV, for instance Australian and North American standards are adopted from ISO 2631-1.

According to the standard, WBV induced adverse health effects are related to energy transferred to the human body and human body sensitivity to vibration which depends on frequency as well as direction. Consequently, the amount of vibration energy can be estimated by combining the frequency-weighted root mean square (r.m.s.) value of acceleration and exposure time. As a result, the level of exposure to vibration can be expressed as a single parameter A(8), called equivalent continuous acceleration over an eight-hour period. If the A(8) exceeds the exposure action value, defined in the standard, the employer is responsible for imposing technical and/or organizational procedures to reduce exposure. The limit value should not be exceeded under any conditions but if this occurs, the exposure to vibration must be reduced immediately.

Vibration containing multiple shocks, occurring in many working environments is generally considered to be more harmful to health than exposure without rapid intermittent variations. As a consequence, an alternative method, based on the calculation of the vibration dose value, has been represented in ISO 2631-1. This method uses the cumulative fourth power of the frequency-weighted time history of acceleration instead of the average of the second power used in the r.m.s. calculation. This approach is also used in the British standard BS 6841. The latest standard ISO 2631-5 (2004) pays special attention to vibration peaks by introducing an acceleration dose, the calculation of which is based on the sixth power of acceleration peaks occurring in the spine. In this standard, the assessment of adverse health effects is based on the daily equivalent static spine compression dose which can be calculated according to acceleration dose values. This evaluation procedure takes into account cumulative vibration history and the age of the worker being assessed.

WBV exposure analysis systems should conform to the applicable standards ISO 2631-1, ISO 2631-5, ISO 8041 and ISO 10326-1. The latter two standards give performance specification and tolerance limits for the data acquisition and processing unit and the accelerometer, respectively. Typically, commercial systems consist of a hand-held analyzer and the standardized semi-rigid seat pad accelerometer placed between the seat pan and the buttocks. Pre-processing, such as the calculation of the frequency-weighted r.m.s value of acceleration, is done in short periods, e.g. one second and the results are stored in a memory. Analyzers are normally equipped with a small display, showing instantaneous or cumulative WBV level information. If necessary, the pre-processed data may be transferred to a PC for future use. Only a few systems have the option of saving raw acceleration data for later use and may also contain the possibility of minor spectral analysis.

Short-term measurements can be used for the approximation of WBV exposure as far as legislation is concerned. Potential health problems emerge in the long run, however. Obviously, this creates a need for the follow-up of continuous and personified WBV data because some persons may be more prone to WBV illness than others. Continuous observation also enables the consideration of working habits. Commercial systems are not intended either for long-term or continuous observation of WBV. In addition, the fairly large semi-rigid seat pad used in commercial systems has been declared uncomfortable and consequently, inappropriate for long-term measurements. The deficiencies of such traditional methods have created a need for the investigation and development of new and alternative approaches. Some studies have been done concerning the capacity of WBV with wireless sensor units for continuous observation, but these systems log the data to a PC or similar data loggers instead of enabling a wireless link to a remote data server (Faiget et al. 2008; Koenig et al. 2008; Morello et al. 2010)

The measurement and analysis system represented in this paper was designed to offer a basis for a cost-effective and easy-to-use solution applicable to the long-term observation of WBV exposure. For continuous measurement purposes, alternative sensor configurations offering improved sitting comfort with respect to the standardized method were investigated both in the wired and wireless form. The system should be able to calculate WBV characteristics such as the r.m.s. value of acceleration or the vibration dose. For the assessment of adverse health effects, continuous transmission of vibration data from a vehicle to a remote server administered by occupational health care organizations, for example, is needed. To enable the system to also operate in remote areas, modern wireless communication technologies were introduced for data transfer. The system should be able to provide instantaneous information about predominant vibration conditions to the machine operator. Real-time data visualized for the operator may be used to help adopt less harmful working methods.

2 SYSTEM DESIGN

Based on the requirements described above, the measurement and analysis system was designed to serve purposes related to the research as well as development of practical applications. The main functionalities such as data acquisition, processing and transmission are handled by an independent unit. To meet both the standardized minimum requirements and other application specific demands, the sensor implementations were carefully specified. The signal processing performance requirements could be derived from the calculation procedures defined in the appropriate standards. As mentioned in the introduction, existing WBV measurement solutions may not offer a practical way to transfer data from a hand-held analyzer. Thus, one of the main issues to be determined was the method for forwarding data conveniently to a remote server. Connectivity was taken into account in the use of modern heavy equipment and vehicle displays showing WBV parameters. All of these design considerations are discussed in the following paragraphs.

The recommended minimum specifications for a vibration transducer intended for WBV measurement applications are defined in the International Standard 8041:2005. The ability to measure acceleration in three orthogonal directions is required whereas the measurement range of the transducer is not specified by the standard. Thus, sufficient range was identified based on extensive WBV measurement data. Resulting from the application requirements, a small-sized and cost-effective triaxial accelerometer is a favorable option. The measured acceleration data must be evaluated according to the procedures defined in standards ISO 2631-1 and ISO 2631-5. As specified by the first-mentioned standard, negative health effects are evaluated in the frequency band up to 80 Hz. Moreover, the calculation algorithms defined in the latter, prefer the use of 160 Hz. As a result, the sampling frequency was chosen to fulfill the requirements of the Nyqvist theorem and both of the standards. The specifications for the measuring system as well as the amount of transferrable data derived from the parameters are depicted in table 1.

Table 1. Specifications for the measuring system

number of channels per accelerometer	3
measurement range	± 2 g
ADC resolution, i.e., accuracy in bits	12 bits
sampling rate of an accelerometer	160 Hz
data rate of a transducer	5760 bits/s

The limitations for minimum data processing performance can be derived from the calculation of parameters used for assessing the health effects of WBV. A simplified presentation of the data processing routine is illustrated in figure 1.

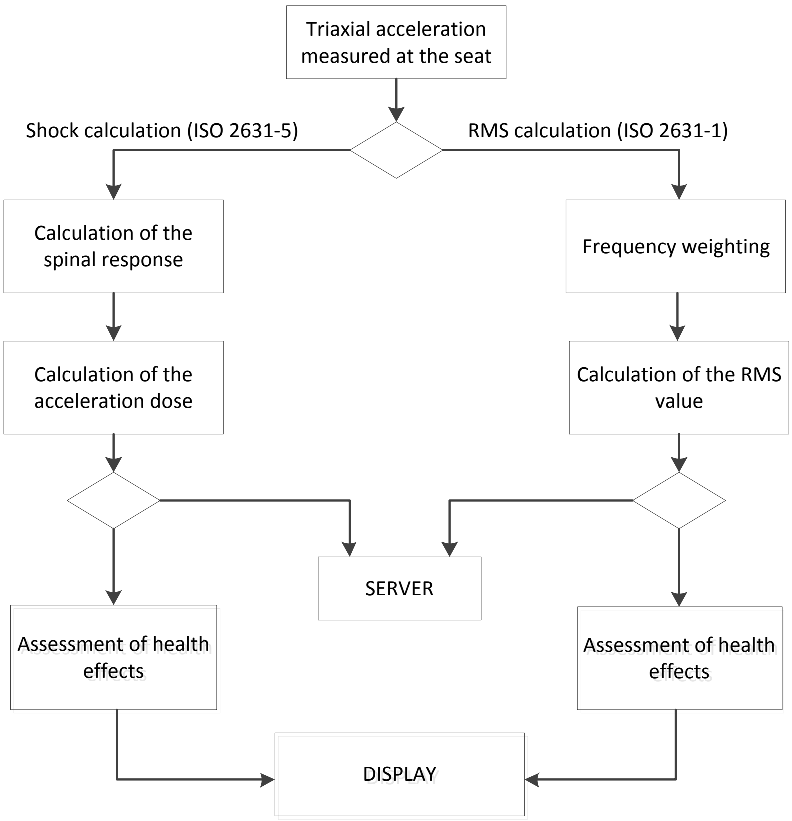

Figure 1. Simplified representation of the WBV data processing routine.

In the r.m.s. method, three dimensional raw acceleration data is frequency-weighted first. In horizontal and vertical directions, filtering is done using three and four second order Butterworth filters, respectively. This is followed by the calculation of the r.m.s. value for each dimension. The steps described above can be performed, e.g., in periods of one second. In the case of the sixth power method of ISO 2631-5, three dimensional acceleration data is first processed to give the spinal response to WBV. In horizontal dimensions, the response of the spine can be modeled with the one degree of freedom (DOF) model that can be realized by a second order Butterworth filter. The calculation of the response in a vertical direction is based on a non-linear approach. It can be represented by a recurrent neural network model. The algorithm contains a total of 99 parameters. The next step is the identification of the magnitude of acceleration peaks in the spinal response. In horizontal directions, both positive and negative peaks are taken into account whereas in a vertical direction only the positive peaks are of importance. After peak detection, the acceleration dose is formed for each direction by raising the peak values to the sixth power, summing them up and calculating the sixth root of the sum. This can be performed e.g., in one-second periods. The calculation of WBV characteristics requires approximately 13 million instructions per second and 3 kilobytes of memory in an 8 bit microcontroller when a sampling frequency of 160 Hz is used.

Data transmission from an occupied vehicle to a remote server must be guaranteed, even if the vehicle is operating in remote areas such as forest, where coverage of the modern communication network is uncertain. Despite the rapid development of data transmission capability of mobile phone networks during the last decade, the system must function using the absolute maximum data rate of the second generation mobile network, usually 9600 bits/s. This is because typical forest work areas are only covered by the second generation mobile network. The real throughput of the network is usually significantly lower than the given value. Thus, it is not reasonable to attempt the transmission of raw sensor data. Instead, a less overloading approach is to calculate WBV characteristics according to the procedures defined in the previous paragraph and to only transmit significant data to the server using the commercial mobile network. The calculation procedure decreases the transmission requirement to six 16 bit parameters per second, excluding any mandatory header data at the application level.

Processed data must be managed both at the vehicle and at the remote server. Typical modern heavy machinery contains an information bus such as the controller area network (CAN) which transfers data between the functional units of a vehicle. The information bus can be used for transferring WBV characteristics to a screen to visualize current WBV exposure for the driver. Accessibility to the vehicle information system may be eased by choosing a microcontroller (MCU) that contains an embedded CAN module. At the remote server, the received data can be organized e.g., by using an SQL-based database.

3 SYSTEM REALIZATION

The measurement system was realized based on the characteristics defined above. The modular architecture of the system is represented in figure 2. The central block of the structure is the data acquisition and processing unit (DAPU). It is responsible for signal processing and controlling the data transmission between the modules of the system. The acceleration data can be acquired from wired or wireless sensor units. The latter units communicate with DAPU via a wireless sensor network (WSN). The processed data can be sent from the DAPU to a remote server and vehicle information system. A ubiquitous connection to the remote server can be established using a commercial mobile network. A modern mobile phone with WLAN functionality or a device with equivalent connectivity must be used to upload the data to the server via the Internet.

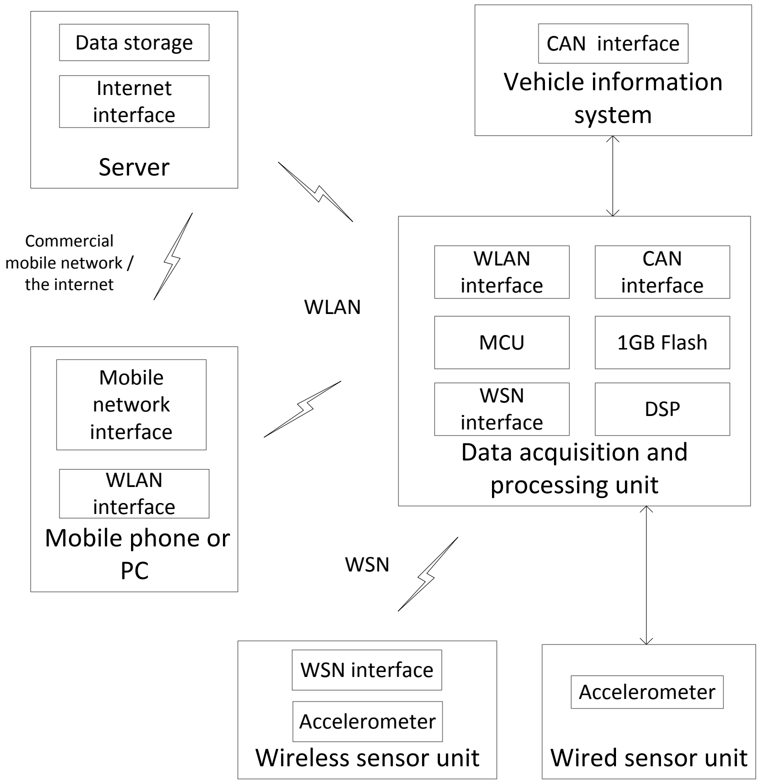

Figure 2. The architecture of the modular measurement system for WBV.

The fundamental element of both sensor solutions is a triaxial accelerometer fulfilling the noise, detection threshold and measurement range requirements detailed above. Other important parameters were the cost-effectiveness and well-known performance characteristics of the accelerometer. Suitable options were available as accelerometers have become common in mass applications, such as the automotive industry. The dimensions and weight of the wireless sensor unit without housing are 47 mm x 20 mm x 7 mm and 6.1 grams, respectively.

The wireless sensor unit, realized mainly for research purposes, comprises the equivalent sensory component as the wired unit, but, it also contains a radio-transceiver, battery and a charging circuit. To allow the sensor unit to operate for a whole working day (8 h) and to minimize the size of the sensor unit and the battery, energy consumption should be minimal. Therefore, the wireless short-range communication technology used for WSN was as simple as possible. The main requirements for the WSN were a sufficiently high data transmission capability and range, which was set to cover the cabin of a vehicle.

The applicability of several standards and known wireless short-range communications technologies for WSN was surveyed. The standardized technologies taken into account were Bluetooth v.4.0, IEEE 802.15.4, ECMA-368, and IEEE 1902.1. The remaining technologies were well-known proprietary technologies applied, e.g., in home automation and sports technology. These technologies use unlicensed industrial, medical or scientific (ISM) frequency bands in data transmission. The summary of the system requirements defined previously as well as the parameters of the considered technologies are summarized in table 2.

Table 2. The results of the wireless short-range communication technology survey.

Technology	**supported data rate**	**range**	**power consumption**	**complexity**
requirement	*5760 bit/s*	*5 m*	*allows 8h measurement*	*low*
IEEE 802.11b/g (WiFi)	54 Mbps	< 100 m	very high	complex
IEEE 802.15.4 (Zigbee)	250 kbps	10-30 m	low	low
Bluetooth high data rate (v 4.0)	3 Mbps	~10 m	high	complex
Bluetooth low energy (v 4.0)	1 Mbps	<10 m	low	average
ECMA-368	53.3....480 Mbps	10 m	-	high
ANT	20 kbps	< 10 m	low	low
Z-Wave	9,6 kbps	< 100 m	high	average
IEEE 1902.1 (Rubee)	9,6 kbps	< 15 m	very low	low
HomeRF	21,6 kbps	20, < 50 m	high	complex

In addition to the main MCU, the DAPU also contains a digital signal processing (DSP) block. It could be argued that the use of an additional DSP is required because the calculation of WBV characteristics is time-consuming and may not enable the MCU to handle communication between different blocks. Sensors and other plug-in modules can be attached to the DAPU via an analog or digital interface. Wireless data acquisition is enabled by establishing a Zigbee based WSN, where wireless sensor units containing the Zigbee interface can connect.

Data transmission between the DAPU and remote server was realized by installing commercial software in a mobile phone. This software converts a modern mobile phone containing WLAN functionality to a WLAN base station. I.e., all traffic from WLAN nodes is switched to the Internet. As stated earlier, only certain predefined WBV characteristics are transferred to the server. If there is need for examining raw measurement data, a PC or any equivalent data logger must be connected directly to the DAPU via WLAN. This option may be required for specific research purposes but is not necessary during normal WBV observation routines. If the ubiquitous connection to the remote server is not available the DAPU can store data in its memory.

The main processor of the DAPU contains an embedded CAN module which enables CAN connectivity easily. This could be used in order to visualize the calculated vibration information for employees. The instrument panel of the vehicle or a separate screen may be used for actual visualization.

4 SYSTEM VERIFICATION

The calculation algorithms for the r.m.s. and acceleration dose values were verified with MATLAB by means of predefined test signals. In order to confirm the functioning of the wired sensor unit, the system was tested against a commercial WBV meter (Svantek 958). The test procedure was performed in the laboratory using an electromagnetic shaker (LDS V850) to generate accurate sine stimuli. Prior to the vibration tests, the noise level of the sensor unit was recorded on a stationary table. The highest of the orthogonal frequency weighted r.m.s. noise values was 0.007 m/s^2, acceptable for an instrument of this type. Next, the wired sensor unit and the triaxial accelerometer of the reference system were tested with sine signals as a function of frequency and magnitude. The frequency weighted r.m.s. values of the vertical direction (z-axis) are depicted in figure 3.

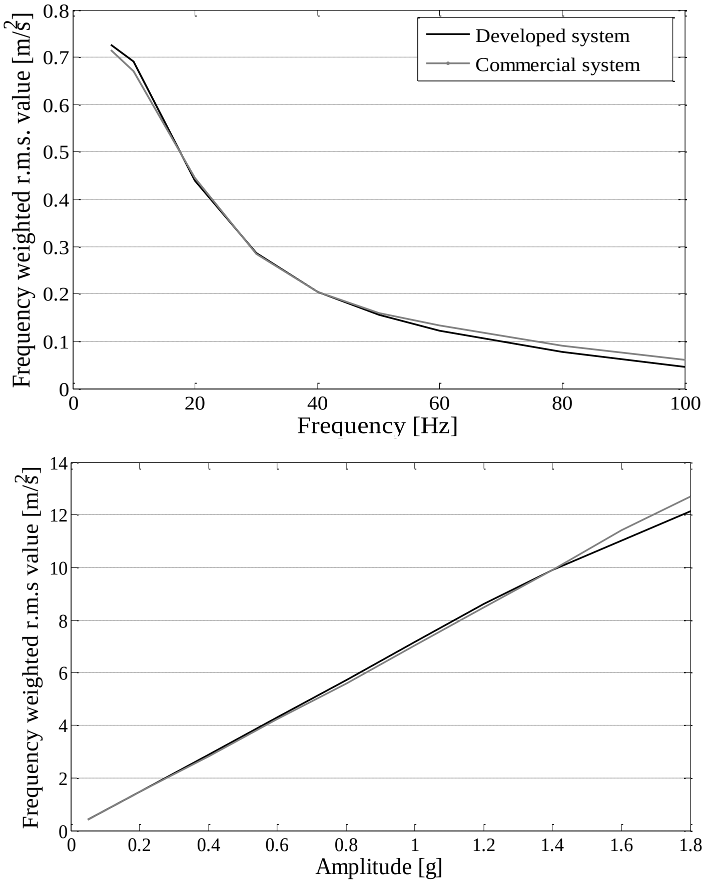

Figure 3. Frequency weighted r.m.s values obtained with the developed and commercial system. (Upper: amplitude 0.1 g, frequency altered stepwise from 6.3 Hz to 100 Hz; Lower: frequency 8 Hz, amplitudes from 0.05 g to 1.8 g)

As can be observed from the upper figure, slight variations occur in the frequency range from 6.3 Hz to 12 Hz as well as at frequencies above 50 Hz. The effect of weighting can be seen as decreasing values as the frequency increases. In the lower figure, the attenuated response of the wired sensor unit above 1.4 g results from its limited measurement range of ± 2 g. Despite these minor deviations, the realized system was proven to function properly. The results depicted in the figure are also representative for the x-axis (fore and aft) and y-axis (lateral). The performance of the wireless unit is consistent with the wired unit since it includes a similar accelerometer element.

Alternative approaches to measuring long-term WBV exposure of a seated human were also investigated. In brief, the studied approach consisted of two triaxial accelerometers secured inside round, plastic mountings 50 mm in diameter. These were buried in the seat cushion in the region of the ischial tuberosities (the sitting bones). Studies were carried out in the laboratory using a group of test subjects, and vibration stimuli were generated by a 6DOF motion system (Moog Inc). To ensure that the results reflected performance in typical vibration environments, exposures were also reproduced based on measurements conducted in heavy machinery. The results obtained with the alternative setup were compared to those of the standard seat pad. Generally, differences between the methods were less than 10 % in terms of frequency weighted r.m.s. values. In conclusion, it could be stated that WBV exposure can be measured via the seat cushion with separate accelerometers, however the uncertainties of this approach must be taken into account.

Wireless data acquisition was studied from the point of view of transmission losses caused by the unwired solution. For recognizing failures in transmission, the wireless sensor unit was configured to send packets in which the first byte was the packet number. PC software was set to detect if packets were lost. The test was carried out in three separate environments a) narrow corridor b) large process hall and c) in the cabin of a harvester. The test included transferring 10 000 packets under three different circumstances: line-of-sight (LOS) path, non-line-of-sight (NLOS) path and varying path, in which moving obstacles could have been in the LOS path. Very few lost packets were detected and only for the varying signal path. The result was identical in all three environments, although the radio channel is slightly different in environments a) and c) (Taparugssanagorn et al. 2009).

Data transmission between a vehicle and server is mostly dependent on the coverage of the commercial mobile network. Without performing very large scale testing with various commercial networks available it is difficult to make any conclusions about data transmission behavior. If coverage in a certain environment is good enough, a connection between the vehicle and server can be established. By default, the established TCP/IP connection is reliable, if it can be established from the point of view of the network coverage. For example, some operators announce the coverage of their network to be about 99% of the area of certain countries.

5 DISCUSSION

The majority of commercially available measuring systems lack the functionality to enable long-term WBV observation. Additionally, sensors used in these systems are quite expensive. The represented modular approach is a promising solution for implementing a cost-effective system for the continuous measurement and observation of WBV. The most significant difference with respect to conventional WBV measuring systems was the establishment of a wireless link for transferring pre-processed parameters to a remote server. Due to low price and sufficient performance characteristics for WBV applications, capacitive accelerometers were utilized. Moreover, to increase the flexibility and versatility of the system as well as its suitability for research purposes, a wireless sensor unit was implemented.

The wireless sensor approach may offer additional benefits by enabling continuous WBV data acquisition concerning employees whose job includes alternative work postures in addition to a typical seated posture. In these cases, irreplaceable freedom may be achieved by utilizing a wireless sensor unit. Another remarkable advantage of wireless sensors is that impractical cables also susceptible to mechanical faults can be discarded.

When considering data transmission between a vehicle and server, the use of a commercial mobile network is the only reasonable option. This may cause additional periodic costs, but excluding the complex satellite based systems or the construction of a very large scale private network, ubiquitous access to the server may not be realizable by any other means. Even though some areas are beyond the coverage of the latest high data rate networks, sufficient data transmission capacity is available most of the time.

By post-analyzing collected data, work tasks with a health risk could be noticed or at best, eliminated. Additionally, data stored in a specific server administered by occupational health care authorities, for instance, could be used in the study of long-term effects of WBV. The other option is to visualize real-time data for the operator who can use it to adopt less harmful working methods.

Most of the recently developed ubiquitous measurement systems are mobile phone-centric, i.e., the sensor nodes are directly connected to the mobile phone e.g., via Bluetooth. Using a mobile phone as the central unit of the WBV measurement system would create an excessive data processing capacity requirement for the mobile phone. Furthermore, Bluetooth as a WSN solution could be impractical due to large-scale power consumption. Additionally, attaching wired sensor units to the mobile phone may be complex.

Even though the represented system was targeted at WBV measurement and evaluation, it could be transformed to be applicable, e.g., to various health care applications with just minor modifications. Basically, it only requires the modification of the signal processing system and the transfer of data to a dedicated server to enable e.g., the remote detection of falls in the elderly. Additionally, if alternative sensor units are realized, this system could allow the remote monitoring of various quantities related to human health or wellbeing. The system could also provide position-independency for both the overseer and people under observation by extending server functionalities. Ubiquitous access may become beneficial if the system with modified signal processing were to be placed, in an ambulance, for example. In this case, high data transmission rates may be achieved in most cases because of the wide coverage of the 3rd generation mobile network in residential areas. Alternative sensor units must naturally be built to acquire required life critical data.

6 CONCLUSION

Based on the recognized need for the continuous observation of WBV, a measurement and analysis system fulfilling the specific requirements of this application was designed and realized. The created ubiquitous system enables the use of novel methods for WBV research and observation. The main components are the wired and wireless sensor units, data acquisition and processing unit and a ubiquitous connection to the remote server. An approach utilizing modern communication networks enables the continuous collection of particular WBV characteristics to a remote server from various environments. The collected data may be taken advantage of when estimating the impacts of long-term vibration exposure, for example.

Wireless sensor units can be used for establishing wide-ranging, innovative sensor setups. For example, a seat cushion equipped with buried accelerometers was proven to be a promising option in the discrete measurement of long-term WBV. With necessary modifications, the system structure could also be altered to serve purposes other than vibration measurement.

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