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Safety Optimized Shift-Scheduling System based on Wireless Vibration Monitoring for Mechanical Harvesting Operations

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Traditional approaches to vibration risk assessment are often carried out manually on the basis of reference data, whereas an automated approach, can yield more valuable information that can be beneficial for improving the health and safety conditions of the workers. In particular, the exposure to prolonged vibration is a potential cause of pathologies such as the hand-arm vibration syndrome (HAVS), therefore national and international regulations establish recommended limits to the workers' exposure to vibration within an allowable daily limit. However, evaluating the maximum allowable operating time is not straightforward, therefore reference vibration values are provided by the manufacturer. These values are frequently unreliable, since the effective vibration intensity generated by mechanical machines largely depends upon several specific factors such as maintenance, operating conditions, etc. A more effective approach would rather involve equipping the worker with suitable instruments to monitor and analyse in real time the vibration exposure. This is particularly difficult in open-field operations as mechanical harvesting, where wireless sensing and communicating technologies can be effectively employed in general framework of the Internet of Things (IoT) to develop small monitoring devices at affordable cost. In such context, the present research proposes an innovative system aimed at estimating the hand-arm exposure to vibration according to the Standard EN ISO 5349-1:2004. In particular, the proposed system is based on a referenced monitoring system, based on the employment of a compact wearable unit to be attached to the waist of the operator and a fixed station for data storage and analysis. The paper describes how this information can be exploited in a decision context to effectively schedule the working shifts for a team of workers in high exposure operations such as olive harvesting with mechanical shakers. .

1. Introduction

The execution of repetitive and physically demanding activities by workers can strain their body parts and can result in fatigue, injuries or in severe cases permanent disabilities. This topic is generally addressed in the context of ergonomics, which involves the assessment of job tasks to identify ergonomic risk factors and appropriate engineering or work practice controls to reduce or eliminate the identified risk factors. Ergonomic risk factors are characteristics of a job that contribute to the creation of ergonomic stress on the body. Generally, the greater the exposure to a single risk factor or combination of risk factors, the greater the probability of an ergonomic injury or illness, also called Work-Related Musculoskeletal Disorders (WMSD). Potential ergonomic risk factors include vibration, contact stress, sustained exertions, and cold temperatures. The basic premise of ergonomics is that job demands should not exceed workers' capabilities and limitations to ensure that they would not be exposed to work stresses that can adversely affect safety and health as well as the company's productivity.
According to such considerations, it is essential to monitor the exposure of workers to risk factors, in order to prevent potential injuries. In many cases, however, traditional worker monitoring methods are inefficient and are carried out manually whereas, an automated approach, apart from monitoring, can yield valuable information concerning work-related behavior of worker that can be beneficial for worker training in a virtual reality world. In particular, vibrations are a well known potential cause of health diseases and therefore constitute a main concern for the safety of workers in a large number of activities. In order to prevent health

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hazards, national and international institutions have issued laws and directives which establish recommended limits to the workers' exposure to vibrations during operations. Consequently, if the amount of adsorbed vibration exceeds the allowable daily limits the worker has to stop his job. In Europe, the Directive 2002/44/EC states that employers are required to take action to control vibration exposures that exceed a prescribed level of vibration (the action value) and state the maximum vibration exposure (exposure limit) that a worker can be exposed to (Table 1). Exposures above these limits are considered to pose unacceptable risks to worker health.

Table 1. EU daily exposure action values and daily exposure limit values

Average daily vibration exposure A(8)	Hand-arm vibration	Whole body vibration
Action value	2.5ms^{-2}	0.5ms^{-2} or 9.1ms$^{-1.75}$ (VDV) $^{(2)}$
Exposure limit	5ms^{-2}	1.15ms^{-2} or 21ms$^{-1.75}$ (VDV) $^{(2)}$

(1) Standardized to eight-hour energy equivalent frequency weighted acceleration magnitude - (2) Vibration dose value

The maximum allowable operating time is commonly calculated on the reference vibration values provided by the manufacturer. This approach is however questionable as in fact the effective vibration intensity generated by mechanical machines largely depends upon several specific factors such as maintenance, operating conditions, etc. A more effective approach would rather involve equipping the worker with suitable instruments to monitor and analyse the vibration exposure, thus providing a valuable information to prevent health hazards. Recent wireless sensing and communicating technologies can effectively be employed for such purpose, allowing to develop small monitoring customized devices at affordable cost that can also be integrated in the workers' clothes. This topic is nowadays emerging as a fundamental topic of Industry 4.0 and the Internet of Things, where Cloud Computing and Big Data management provide the technological basis for the management of data. Ubiquitous tracking and monitoring technologies are now routinely used in industrial environments, but very rarely with the goal to improve occupational health and safety (Kortuem et al. 2007). Nevertheless a wide range of examples of smart materials, smart personal protective equipment and other Ambient Intelligence applications can be found in the Literature, that have been developed to improve workers' safety and health. The use of these solutions modifies work methods, increases complexity of production processes and introduces high dynamism into thus created smart working environments (SWE) which ultimately lead to a new conceptual framework for dynamic OSH management (Podgórski et al, 2017). In such context, the present research proposes an innovative system aimed at estimating the hand-arm exposure to vibration according to the Standard EN ISO 5349-1:2004. In particular, the system employed (Catania et al., 2012) is based on Micro Electro-Mechanical Systems (MEMS) technology and involves the design of a compact wearable unit to be attached to the waist of the operator and a fixed station for data storage and analysis. Due to such advantages, they are spreading today in many industrial applications for sensing and measurement such as automotive electronics, medical equipment, computer peripherals, wireless devices and portable electronics. MEMS accelerometers are also well known for being employed in many safety systems to prevent and reduce health hazards. Mathie et al. (2004) and Chen et al. (2005), for example, applied MEMS accelerometers to study human movements for fall detection purposes. Additionally, due to the versatility of MEMS sensors and their small size, they have been efficiently employed for monitoring vibrations in engines, mechanical equipment and facilities (Vogl et al., 2009) and in civil structures (Lynch et al., 2002). The possibility of employing such systems in vibration risk assessment is also a field of application recently approached and investigated by researchers (Koenig et al, 2008, Morello et al., 2010). The system here proposed involves the collection of acceleration data by means of a MEMS axial accelerometer during the operator's activity and their transmission via wireless network to a station where they are stored and analysed. The device employed is based on the ZigBee network which is the industrial standard most suitable for short-distance communications with low-data-rate. ZigBee networks are in fact self configuring and self healing, maximizing reliability and minimizing the cost of network deployment and maintenance. They provide transmission speeds of 20, 40 and 250 Kb/s over a range of 10–100 m and can be configured in star, mesh or peer-to-peer topologies. In addition ZigBee networks use considerably less power than all other networking technologies (Gutierrez et al., 2001). The proposed systems, presents some crucial differences compared with common configurations of current low power sensor networks. In real-time wireless vibration monitoring of multiple devices however bandwidth limitation may become a critical issue. It has been shown (Kohvakka et al., 2006) that the actual bandwidth for a ZigBee network is 157 kbps after taking into account acknowledgements time, headers and inter-frame delays. Consequently, in order to monitor simultaneously a set of vibration sensing devices, the polling rate and data transmission features must be determined coherently with the available bandwidth. By properly regulating such parameters, the proposed architecture permits to manage a distributed sensor network, thus allowing to remotely control the status of several workers simultaneously.

2. The vibration monitoring system

The measurement system has been designed on the basis of the preliminary vibration analysis and taking into account the requirement of measuring the vibration levels affecting the hand–arm system of a workman in real operating conditions. Such conditions involve possible exposure to water, elevated temperatures, electrical interference, hazardous-area classifications, obstructions, physical location and distance. The MEMS accelerometer is a device that converts a physical acceleration into a voltage output. The signal processor performs signal conditioning and pre-buffering for data transmission, and a workstation is finally used to display sensor data for real time monitoring and processing. The measuring chain contains the digital xyz axis capacitive accelerometer, the I2C converter for converting I2C to UART and the XBee module for wireless transmission. The described components are arranged in two separate assemblies: a wearable remote unit involving main device (for data storage & pre-processing), the cable connected sensor probes, the battery, and the transmitter (Zigbee) unit, and a fixed station constituted by a computer and a zigbee communication module for receiving data. The wearable unit is attached to the operator's waist during its working activity, while the fixed station is placed nearby within the range of the zigbee communication modules. The effectiveness of such system setup in vibration measurements has been tested in the past (Catania et al., 2012). With such features, a single fixed station can monitor several workers until the bandwidth of the ZigBee network is full. By implementing proper threshold values, as suggested by the current international regulations, hence the system presented can be the underlying technological infrastructure of a broader worksite safety management system, including decision support methodologies for crew scheduling with a beneficial effect on workers well-being and company productivity. By means of the proposed system, in fact, the site manager could keep under control the vibration levels of an entire team, and schedule changes before vibration thresholds are reached.

Figure 1: Team monitoring system.

2.1 Hardware features

The wearable sensor unit has been designed taking into account that the unit must be lightweight, small and compact as possible in order not to hamper the operations and the movements of the worker. According to such specifications, the Freescale MMA7455 triaxial accelerometer device based on Microelectromechanical systems (MEMS) technology, has been selected. The main feature that makes the freescale accelerometer suitable for in-field vibration testing is its extremely flexible performance/power consumption options through user-configurable sample rates. The rates can be adjusted to provide the performance needed for specific functions, with adequate current consumption. The maximum sampling rate (120 Hz) is probably the most significant performance limit of the device selected, which is however appropriate for the application considered where the main harmonics are below 50 Hz. The acceleration data collected by means of the previously described sensor are fed into a microcontroller and sampled via an analog digital converter (ADC). We selected the CUBLOC SC830 microcontroller, based on the Atmel ATmega128 processor for such purpose. The Atmel ATmega 128 is one of the most powerful 8 bit micro controllers running at a frequency up to 16 Mhz. The microcontroller does simple pre-processing on the data and sets the working mode of the accelerometer accordingly. Pre-processed data are fed into an IEEE 802.15.4 wireless transceiver and sent to the data logger unit. For our design, the XBee 802.15.4 radio modem from MaxStream has been chosen as the wireless transceiver. It operates with a chip antenna up to 30 meters indoor, under transparent mode with a simple connection with a microcontroller. The transmission range can be further increased to 90 meters by using a whip antenna. The XBee module has a low maximum transmit power of 1mW and a high receiver sensitivity of -92 dBm. Finally the device involves a Card reader/writer interfaced with CUBLOC SC830 via the Serial Port Interface. Finallly, the data logger unit is a wireless XBee transceiver which upon receiving the measurement data from the wireless interface, forwards the data directly to the workstation for processing according to the procedure described below.

2.2 Data analysis

Acceleration data are processed in real time in order to evaluate the health risk the worker is exposed to, according to the guidelines for measuring and evaluating human exposure given in ISO 5349-1 and ISO 5349-2. In the ISO 5349 standard recommendations, the quantity used to describe the magnitude of the vibrations transmitted to the operator's hands is the root-mean square (rms) frequency-weighted acceleration. According to such guidelines, the vibration spectrum must be extracted from the raw acceleration data by means of Fast Fourier Transformation (FFT), and analyzed in 1/3 octave bands. Subsequently, the rms intensity in each band must be multiplied by its weighting factor. Human response to the hand-transmitted vibration, in fact, varies with frequency, and in particular, it is high at low frequency (Giacomin et al., 2004; Morioka and Griffin, 2006). ISO 5349 standard, in particular, recommends a specific weighting curve, which shows a peak value for the weighting factor in the range between 8 and 16 Hz, and a rapidly decreasing curve reaching values below 0.1 for frequencies above 150 Hz. According to such curve, values from one-third-octave band allow the calculation of the frequency-weighted acceleration:

$$a_{hw(x,y,z)}=\left[\sum_{j=1}^{n}\left(W_j \cdot a_{w,j(x,y,z)}\right)^2\right]^{1/2} \tag{1}$$

where $a_{w,j}$ is the acceleration measured in the one-third octave band in m/s², and W_j is the weighting factor for the one-third-octave band. The evaluation of vibration exposure in accordance with ISO 5349 is finally based on a quantity that combines all the three axes. This is the vibration total value a_{hw} or weighted acceleration sum (WAS) and it is defined as the root-mean-square of the three component values:

$$a_{hw}=\sqrt{a_{hw(x)}^2+a_{hw(y)}^2+a_{hw(z)}^2} \tag{2}$$

where $a_{hw(x)}$, $a_{hw(y)}$, $a_{hw(z)}$ are frequency-weighted acceleration values for the single axes. The vibration exposure depends on the magnitude of the vibration total value and on the duration of the exposure. Daily exposure duration is the total time for which the hands are exposed to vibrations during the working day. The daily vibration exposure shall be expressed in terms of the 8-hour energy-equivalent acceleration or frequency-weighted vibration total value:

$$A(8)=a_{hw}\sqrt{\frac{T}{T_0}} \tag{3}$$

where T is the total daily duration of the exposure in seconds, and T_0 is the reference duration of 8 h.

3. Experimental results

Experimental tests have been carried out on the hand held shaker for olive harvesting and involved the real time acquisition and processing of the acceleration data gathered by means of the monitoring device. Each test consisted in 3 trials of 40 seconds with a polling frequency of 120 Hz. Such measurement is repeated in X, Y and Z axis in each hand thus generating 6 data streams with an overall 30 kbit/sec bandwidth approximately required. Additionally, before each test, a calibration step was carried out by placing the MMA7455 sensor flat with the z axis pointing up so that the X and Y axis will initially read zero and the Z axis will read 1g.

The acceleration values from one-third-octave band analysis can thus be calculated and weighted according to the ISO weighing curve. According to Eq(1). The system developed can execute such calculations in real time for each axis x, y, z, as given in Figure 2. The weighted acceleration sum (WAS) can thus be calculated as the root-mean-square of the three component values, and the frequency-weighted vibration total value A(8) can be calculated by means of Eq(3). Warning and alert thresholds can finally be established according to the EU regulations and the exposure limit can be determined as given in the following Figure 3.

The warning and alert thresholds can be employed to determine if the worker has reached the allowable vibration level and decide whether the worker must be substituted or stopped, according to the following decision scheme:

1. Measure the vibration magnitude and the corresponding exposure time for each worker.
2. Find the value in the above figure that lines up with the magnitude and time.
3. Compare the points value with the exposure action and limit values

4. schedule workers shifts

In particular, in the experimental monitoring tests the values obtained are close to 19 m/s^2, as given in the following Figure 4, which means that each working shift should not exceed 15 minutes.

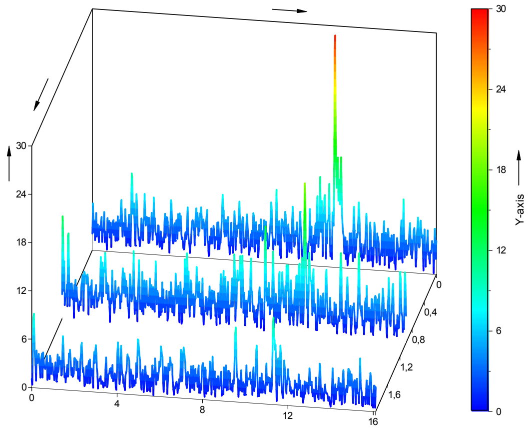

Figure 2: Tri-axial vibration FFT

Vibration Magnitude m/s^2	5 min	15min	30 min	1hr	1hr 30 min	2hr	3hr	4hr	5hr	6hr
40	265	500								
30	150	450	900							
25	105	316	825	1250						
20	67	200	400	800	1200					
19	60	180	360	720	1100	1450				
18	54	160	325	650	970	1360				
17	48	145	290	580	855	1150				
16	43	130	255	510	770	1000				
15	38	115	225	450	675	900	1350			
14	33	98	195	390	590	765	1260			
13	28	85	170	340	505	875	1000	1350		
12	24	72	145	290	480	575	865	1150	1450	
11	20	61	120	240	385	485	725	970	1200	1450
10	17	50	100	200	300	400	600	800	1000	1200
9	14	41	81	160	245	325	485	650	810	970
8	11	32	64	130	190	255	385	500	640	770
7	8	25	49	98	145	195	295	390	490	590
6	6	18	36	72	110	145	215	290	360	430
5.5	5	15	31	61	91	120	180	240	305	385
5	4	13	25	50	75	100	150	200	250	300

Exposure Time, T

(red)	Above exposure limit value
(orange)	Likely to be at or above limit
(yellow)	Above exposure action value
(light grey)	Likely to be at or above action value
(green)	Below exposure action value

Figure 3: Warning and alert thresholds

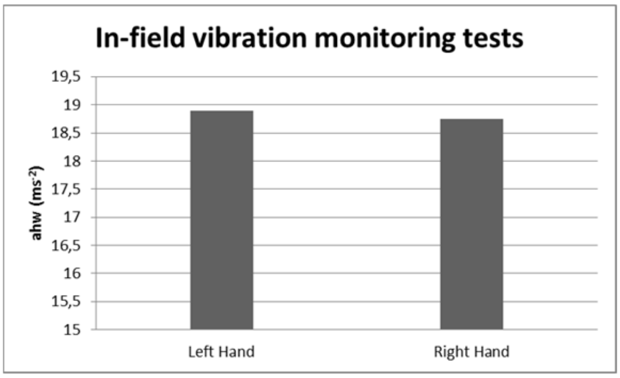

Figure 4: Results of the in-field monitoring tests

4. Conclusions

In the era of Industry 4.0, smart technologies are considered the drivers of a new industrial revolution where mechanical equipment seems the main beneficiary of the technological improvements. However there is a wide range of situations where new technologies can originate significant benefits in increasing the safety and healthiness of the workspace. In this view paper aims promoting the employment of new technologies such as cloud computing, IoT, and big data management to improve the working conditions of human resources with the ultimate goal of increasing worker's productivity. This research demonstrates that the key-technologies in industry 4.0 are mature enough to allow a real-time monitoring of vibration levels, thus promoting a disruptive change in the way vibration risks are currently managed. In particular, the research involved the development of a novel device for assessing the health risk caused by hand-harm vibrations in real worker operating conditions. The device developed can easily be integrated into workers' standard equipment employed in outdoor operations, since it is involves a lightweight wearable device with on board power supply and wireless communication module. Surprisingly enough, the development of wireless vibration monitoring seems more addressed towards machine condition monitoring rather than reducing the risk of pathologies for the workers. The results show how a cheap hardware can lead to a fairly precise assessment of the vibration levels, thus providing significant information to the management in defining safe work-shifts and improving the resource scheduling and allocation. The study allows for methodological considerations, susceptible to be integrated by further investigations, and proposes new sceneries in "smart" worker safety management systems. It is hence possible to foresee future developments which might significantly modify the current approach to ergonomics, including for example intelligent protection devices, integrated with workers' equipment and clothing.

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