Health & Safety 4.0: a digital twin reference model to support the smart operator at the workplace

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Abstract: In the Industry 4.0 era, Cyber-Physical Systems (CPS) and the Internet of Things are the enabling technologies for a new tool, the Digital Twin, that allows a streamlined communication, automation and interoperability among all the production assets. Even if there has been a great deal of efforts toward digital twin engineering, little attention has been paid to the correct integration of humans in the emerging context of smart factories and, in particular, to the potential contribution of digital twins for supporting a health and safety 4.0 at the workplace. This paper sets the stage for a discussion over health and safety aspects for the Smart Operator and proposes a renewed approach to the theme in the context of industry 4.0, aimed at exploiting the value of digital information in improving the wellness and safety conditions of workers. A digital twin reference model has been developed that illustrates how to extract and analyze real-time safety information, to detect potential hazardous situations and to send out alerts to the smart operators that are using Augmented Reality devices, such as smartphones or tablets, at the workplace. Insights about digital twin-based operator's health and safety are reported on the basis of preliminary experimental tests carried out on a hand held shaker for olives harvesting to assess the hand-arm exposure to vibration.

Keywords: Industry 4.0, digital twin, smart operator, safety, ergonomics

1. Introduction

The Industry 4.0 era envisions a new interconnected and smart working environment where machines and human operators are supposed to cooperate. Distributed computing power, Internet of Things (IoT), Virtual (VR) and Augmented Reality (AR) are among the enabling tools of the Industry 4.0 that preaches a hybrid automation in manufacturing driven by human-machine collaboration (Malik et al., 2020). Digitalization and automation technologies are changing not only the way to work (Murawski & Bick, 2017) but the workplace itself (Cohen et al., 2018). Nowadays most workers use digital tools at work and therefore workers are required to possess digital competencies (Oberländer et al., 2020). Even if there has been a great deal of work toward smart factory concepts, such efforts are mostly related to automation systems, plant solutions, communication infrastructures, systems connectivity and interoperability and data flows management (Saucedo-Martínez et al., 2018). This idyllic view of smart production systems arises some fundamental questions about the role of the human operator in the workplace of the future, and how this interaction with smart cyber-physical systems (CPS) will take place. Little attention has been paid to the correct integration of humans in the emerging context of smart factories and, in particular, to safety aspects at workplace (Pacaux-Lemoine et al., 2017). The risk of underestimating such issues, leaving the man in the background of an industrial revolution focused on technology, actually exists and it would eventually lead towards a general deterioration of the worker's physical and psychological condition.

In the very last years, the Operator 4.0, also referred to as Smart Operator, came up as a new concept in the Industry 4.0 framework. In this stream of research, automation and ICT technologies are treated as an enhancement of the human's physical, sensorial and cognitive capabilities and are expected:

- to support operators performing tasks within a process/workflow;
- to support understanding and decision-making;
- to learn from the activity of operators to predict specific situations, optimize the process and better organize the smart factory.

However, the body of knowledge around the Smart Operator is still very limited and the physical and cognitive interaction of workers with robots, machines and the smart factory as a whole, poses serious safety issues. Therefore, it is essential to monitor the exposure of workers to risk factors in order to prevent potential injuries and design new efficient methodologies to yield valuable information concerning work-related behavior of the Smart Operator. In the I4.0 scenario, innovative approaches for a health and safety 4.0 are then required.

This paper sets the stage for a discussion over health and safety aspects for the Smart Operator (Section 2) and proposes a renewed approach to the theme of worker's safety and ergonomics in the context of industry 4.0, aimed at exploiting the value of digital information in improving the wellness and safety conditions of industrial workers. In particular, the proposed approach aims at demonstrating how a digital twin-based approach, through gathering and analyzing real-time information about the worker and the working environment, can be effectively exploited for improving the wellness and safety conditions in industrial contexts (Section 3). A digital twin reference model has been developed that illustrates how to extract and analyze real-time safety information, to detect potential hazardous situations and to send out alerts to the smart operators that are using Augmented Reality devices, such as smartphones or tablets, at the workplace. (Section 4). Preliminary results from experimental tests with a hand-held shaker for olives harvesting are presented in Section 5 to assess the hand-arm exposure to vibration and discuss the potential implications of using a digital twin to prevent injuries and to pave the way for an operator's health and safety in a 4.0 perspective.

2. Health and Safety in the Smart Factory: a focus on Work-related Musculoskeletal Disorders

Recognizing the existence of a relationship between working conditions and the development of diseases triggered by biomechanical overstrain, the World Health Organization has made Work-related Musculoskeletal Disorders (WMSDs) an international health concern. The literature review and epidemiological studies have shown that in the genesis of the WMSD three sets of risk factors can be considered (Bernard, 1997; Devereux et al., 1999): physical factors, psychosocial factors and individual factors. Almost 40 million workers in Europe suffer from WMSDs. According to Eurostat (2010), these disorders account for almost 60% of work-related health problems, and are therefore the most common occupational disease in the European Union. WMSDs are a major health issue, affecting almost 50% of industrial workers in developed countries, and represent an important cost for companies and society as a whole (Schneider & Irastorza, 2010). Hence, new approaches to assess such factors at the workplace and to prevent injuries are needed. In many cases, 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. Indeed, ergonomics is currently evaluated with standard pen-and-paper worksheets filled by experts observing the workers doing their job. Digital human modelling software provide automatic filling of these ergonomic worksheets, but only based on a digital simulation of the activity to evaluate. These systems are intended for workstation design: they do not work in real-time, and the identification and tracking of actions performed by the operator is done manually by the analyst. This approach clearly appears outdated and somewhat inadequate when referred to the cliché of the smart factory promoted by industry 4.0. A more effective approach would rather involve equipping the worker with suitable instruments to monitor and analyze health data, 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 (Marcon et al., 2019). 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. The use of these solutions modifies work methods, increases complexity of production processes and introduces high dynamism, thus creating smart working environments, which ultimately lead to a new conceptual framework for dynamic occupational health and safety management (Podgórski et al., 2017).

3. Towards a digital twin for Health and Safety 4.0: open challenges and design considerations

From 2005 onwards, digital twin theory has evolved enormously. 2010 marks the turning point in the use and application of digital twin tools fed by real data acquired by sensors (Shafto et al., 2010). In the manufacturing sector, the digital twin was initially defined as a simulation model powered by real data that aims at predicting future states of the system under analysis (Gabor et al., 2016; Rosen et al., 2015). More recently, the digital twin has already showed relevant benefits for the Smart Factory in terms of production time, costs and process quality (Longo et al., 2019). The digital twin could also be a considerable tool that could help companies in safety management and risk assessment. However, there is a very low number of works on safety management topic through the use of digital twin, so we claim that the future of research could further develop this topic. A search in the Scopus scientific database using "digital AND twin AND safety" combination keywords, returns only 120 documents until 2019. By analyzing the documents, most are conference papers (68.3%) and the majority of them have been published in the last 3 years, demonstrating the novelty of this research field. By extracting the documents from Scopus, only 50 were pertinent and the full-text fully available while only 14 apply to the manufacturing domain. The diffusion of Industry 4.0 tools has favored the development of a human-robot collaboration, where human safety represents an important challenge (Savur et al., 2019). Lee, Cameron, & Hassall (2019) affirms that the rate of accident is not diminished over the last years, so they propose a digital twin used as a simulator to train the operator during emergency condition.

Based on the above considerations, a relevant literature gap emerges in the context of the design of digital twins, since the approaches proposed rarely involve all the features and functionalities that characterize the digital twin concept. In such situation several scientific contributions can hardly be differentiated from more traditional approaches like simulation or predictive modeling, thus failing in catching the real novelty of the digital twin technology. In such contest, this research aims at contributing to the scientific debate about the conceptualization and the employment of digital twins in safety management, by promoting a novel framework focused on the employment of two types of input data:

a) sensor data for real-time monitoring or for training purpose that could be used to prevent accidents as well as correct wrong processes or procedures carried out by the smart operator;
b) data simulated by predictive systems that could be used to prevent the forthcoming faulty behavior of a machine, process or material.

The digital twin is prospectively crucial to support safety, but its efficiency mainly depends from data quality. Therefore, data gathering, processing and visualization represent critical steps whose issues and challenges are described in the next paragraphs.

3.1. Data Gathering from Human Operators

In order to provide a real time assessment of the safety conditions of the working environment, the digital twin must be directly connected to the human operators and physical assets present in the real world, through a sensor network. In this regard, the introduction of CPS in smart production systems will promote the spread of next-generation operating machines replacing the current production resources. CPS will allow to easily gather relevant information about their operational state through pre-installed sensing devices. In addition, their unprecedented characteristics of interoperability and interconnection will allow a seamless integration with the digital layer, thus ensuring their participation in the virtual factory ecosystem. While it is true that manufacturers are investing on the implementation of such features in operating machines, the possibility of achieving the same level of interoperability for human operators is largely demanded to the advances in wearable sensing devices. The initial investigation on wearable sensing devices date back to the late '90s when the technology of Micro Electro Mechanical Systems (MEMS) allowed the realization of miniaturized and low-energy demanding sensing devices. Most of the pioneering researches on human sensing has been thus conducted using wired or wireless accelerometers attached to different parts of a subject's body (Aiello et al., 2012). During the last decade, with the advancement of smartphones, a major paradigm shift occurred in the data collection approach for human operators, and several researchers focused on the employment of commercial devices for human activity recognition. Although suffering from some significant technical limitations, however, such devices are gaining popularity in monitoring human activities because of their portability (small size and light weight), substantial computing power, embedding various sensors, ability to send and receive data, and their nearly ubiquitous use in today's life. Finally, recent researches focus on the employment of body sensors to collect raw data of physiological signals, with the objective of linking the information related to the activity performed, to the psychophysical conditions of the workers. The diffusion of such miniaturized wearable sensing devices integrated into work suits, would allow the assessment of the worker's wellbeing condition through the monitoring of the presence of specific biomarkers in biological fluids. Such approach is less futuristic than it may seem, since the recent development of nanostructured biosensors, with unprecedented performance and miniaturization possibilities actually opens new application sceneries in such regard. Finally, the last element of the data gathering system is the IoT layer which directly connects the digital information to its physical counterpart, thus completing the "twinning" process, i.e. the process through which the virtual twin is created and connected to the real world.

3.2. Data Processing

Raw data gathered by the sensors network need several actions to turn into valuable information, for supporting the digital twin's decision support and predictive analysis functions. Indeed, real datasets tend to be imperfect, contain errors, outliers, missing data, extra noise, and other forms of inconsistencies. A pre-processing stage is hence required in order to clean the data and ensure the consistency of information. Once the consistency of data is ensured, the relevant information must be extracted through adequate data processing techniques. Recently, artificial intelligence (AI)-driven big data processing technologies are intensively applied to deal with the large-scale heterogeneous data. Segmentation refers to extracting a sequence of continuous measurements or the pre-processed data that are likely to contain relevant information. Such approach is generally employed in conjunction with windowing techniques, which consist of dividing sensor signals into small time segments to allow real-time analytics. A further subsection of AI, is machine learning which consists in the creation of algorithms that can analyze data autonomously with the ability to learn without being directly programmed. For more general analysis, machine learning can be further classified into Supervised Learning and Unsupervised Learning. In the first case, the algorithms are trained on given test data, while in in the second case algorithms implement own learning methods for categorizing and highlighting patterns within data.

3.3. Data Visualization

The final fundamental function of the digital twin framework is the data visualization, which concerns the establishment of an appropriate graphical representation of the results. An appropriate visualization function should provide the worker(s) with relevant information about the safety issues related to its task or working environment. An effective technology for such purpose is to implement advanced HMI involving AR technologies. Augmented Reality has strong potential to provide both powerful contextual, on-site learning experiences and serendipitous exploration and discovery of the natural connected information in the real world. The application of AR in order to support an industrial process can be traced back to the 1960s, when Ivan Sutherland (1968) performed his visionary experiments. The concept of AR actually emerged in the early 1990s, when Caudell & Mizell (1992), from Boeing, presented a head-up see-through display used to augment the visual field of an operator with information related to the task she/he was carrying out. There are various types of hardware that can deliver Augmented Reality to users, such as: Head-Mounted Displays (HMDs), Hand-Held Displays (HHDs), monitors, projectors and 2D smart glasses. This articulated landscape of emerging technologies opens several possibilities for research applications. A review of the current state of the art in industrial systems has been recently proposed by Damiani et al. (2018) while Segura et al. (2020) analyzed Visual Computing technologies as a critical role in operators' empowering process.

4. Developing a digital twin reference model

This paragraph describes the main features of a digital twin reference model (Figure 1) that illustrates how to extract and analyze real-time health and safety information and to send out alerts to the smart operators that are using Augmented Reality devices, such as smartphones or tablets, at the workplace, with the ultimate goal of predicting and preventing the occurrence of unhealthy or hazardous situations. This reference model represents not only a conceptual HW/SW architecture for a digital twin system, but also shows the main data flows between the system components (white arrows). Starting from the bottom-left angle of the picture, data are collected from production resources (e.g. equipment, machines, the workplace environment and the workers) through an IoT layer constituted of sensor devices and edge data processing devices that communicate and exchange messages over the enterprise network with each other, thus enabling also M2M communication.

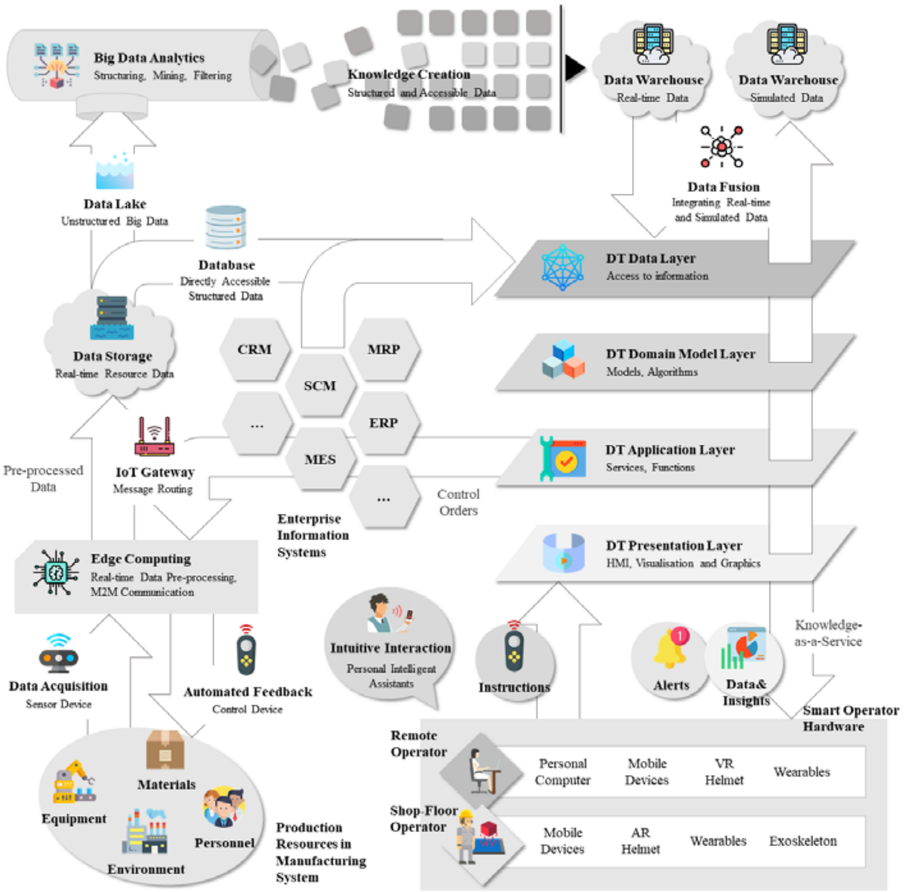


Figure 1. Reference model of a digital twin prototype for an Health & Safety 4.0

Production assets or resources (i.e. machinery, individual products, software installations and the production environment in general) are represented as entities in the information realm according to the models proposed by Tao, Zhang, & Nee (2019). This approach is Industry 4.0-compliant as an Asset Administration Shell (AAS) is assigned to each production resources and maximizes interoperability. This architecture also focuses the attention on the need to define a proper AAS also for human resources. The Smart Operator must be properly represented in the "digital realm" as a virtual entity that meaningfully interact with the other IT systems in a streamlined fashion. Given the huge amount of information that may be collected, big data analytics, management and visualization tools have to be integrated to structure, mine and filter relevant information from raw data. In the top section of the picture, real-time collected data are fused with data simulated by the digital twin application that forecasts the future states of the smart production environment. The application is based on a 4-layer structure, characterized by:

- a data layer, that receives and manages the real-time data coming from sensor devices (i.e. structured information from big data), simulated data returned by the digital twin application and data exchanged with legacy enterprise information systems) including MES, ERP, CRM, etc.);
- a domain model layer, that contains all the models required to build the digital twin of the production resources (equipment, materials, workplace environment and operators);
- an application layer that provides a set of functionalities to the users in the form of web services that allow them to diagnose or manage a specific asset, to carry out simulations and forecast models or to assist the operator during the execution of tasks
- the visualization layer, which includes all those elements which are necessary to access the system functionalities, visualize and synthetize information for operator fruition on dedicated hardware, such as computers, mobile devices, wearables, etc.

Augmented knowledge is then provided to the smart operator “as-a-service”: the system can send out alerts if potential hazardous situations are forecasted or display synthetized data to support decision making or to support the execution of tasks. Office or remote operators and shop-floor operators will use the digital twin application on dedicated hardware. Office/remote operators use computers, mobile devices, VR helmets or wearable devices, whereas shop-floor operators should use hardware tools that do not interfere with their tasks, such as mobile devices, wearables, AR helmets or even exoskeletons, even interfaced with intelligent personal digital assistants. Through these HMIs, and the digital twin application, the smart operator will be able to send back to the production resources control orders and instructions, and therefore control the factory floor.

5. Case study and preliminary results

Experimental and validation tests of a first stage digital twin application prototype for the operator’s health have been carried out on a hand held shaker for olives harvesting to assess the hand-arm exposure to vibration and the potential implications to the operator’s health and safety. Vibrations are indeed 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. National and international institutions have issued laws and directives which establish recommended limits to the workers’ exposure to vibrations during operations (e.g. the EU Directive 2002/44/EC). Consequently, if the amount of absorbed vibration exceeds the allowable daily limits the worker is informed and has to stop his job. Verification and validation activities have been also extensively carried out both prior and during the deployment of the system in the reported case study.

4.1. First prototype of the digital twin front-end

AR-based data visualization features have been developed in an early-stage prototype of the digital twin front-end. In order to maximize the usability and portability of this tool for the Smart Operator within the Smart Factory, a Java-based application has been developed for Android-based smartphones. The system has been developed using the free and open-source PHP web framework Laravel and retrieves enterprise assets’ data (i.e. data about machinery, products, the production environment and operators themselves) through API calls to the system data warehouse. The AR features of the digital twin application prototype have been tested and validated in a real world environment with traditional machines that have been equipped with external sensors and connectivity features to send data over the enterprise network and share it with the digital twin application. Figure 2 shows one of the most interesting functionalities of the digital twin application that places a virtual representation of the machine in an open environment and the smart operator can get closer or move around it. This AR-based representation is generated starting from the real-time data flow coming from the machine, therefore the smart operator can see and monitor the machine even if he/she is not nearby the real machine.

Figure 1. Using AR features of the Digital Twin App Front-End

The developed application is therefore intended to demonstrate the advantages and potential of the proposed safety-oriented digital twin and to visualize the data during the process by using AR. 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 were calculated and weighted according to the ISO weighing curve. The weighted acceleration sum, a_{hw}, was calculated as the root-mean-square of the three component values for the single axes. Such value can finally be employed to evaluate frequency-weighted vibration total value, A(8), which is the daily vibration exposure over a 8-hour shift. The system developed can execute such calculations in real time for each axis x, y, z, as given in Figure 3.

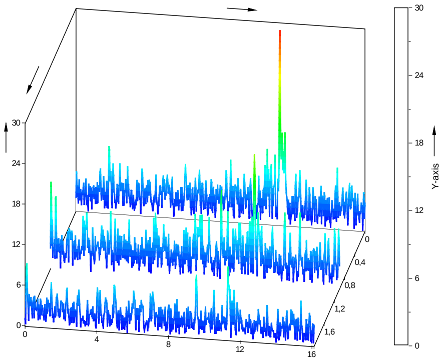
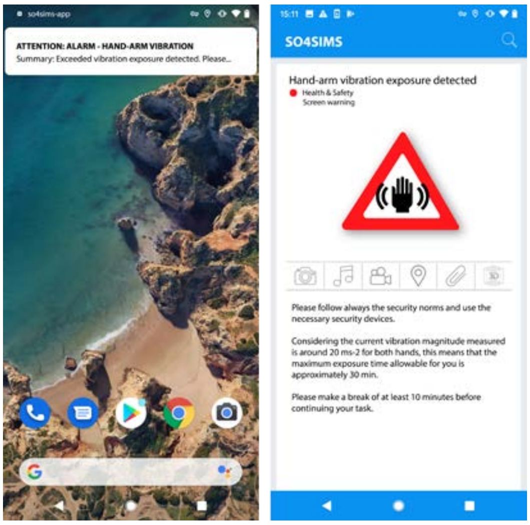


Figure 3. Tri-axial Vibration Fast Fourier Transformation

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.

No statistically significant differences were found among the three tests, both in the right and in the left hand of the operator. Taking into account the thresholds prescribed by the regulations, the criticality of a vibration dose in terms of time of exposure and vibration magnitude can be effectively represented in a “risk matrix”. This information can be accessed easily from the app and is used to send out alerts and notifications to the smart operator using the app. Considering the vibration magnitude measured during the field tests is around 20 ms^{-2} for both hands, this means that the maximum exposure time allowable for the operator is approximately 30 min. Data regarding the potential health hazards that may derive from a longer exposure to the vibration of the machine were sent immediately to the operator that receives an alert on his/her smartphone (see Figure 4), but also on a tablet or smartwatch. He/she can consequently adjust real-time his/her behavior and way to work with benefits for the health and the company too (because the operators may work for a longer time).



ATTENTION: ALARM - HAND-ARM VIBRATION
Summary: Exceeded vibration exposure detected. Please...

Hand-arm vibration exposure detected
Health & Safety
Screen warning

Please follow always the security norms and use the necessary security devices.

Considering the current vibration magnitude measured is around 20 ms-2 for both hands, this means that the maximum exposure time allowable for you is approximately 30 min.

Please make a break of at least 10 minutes before continuing your task.

Figure 4. Notification alerts in the digital twin application for smartphones

6. Conclusions

Ensuring a safe and comfortable environment for workers in the smart factory should be an integral part of workplace management policy. Digital twin system has proved to be an important tool to promote safety measures and prevent health hazards in the workplace. This paper proposes a new reference model for a health and safety oriented digital twin to support the smart operator at the workplace. The main contribution of this paper is to show how a safety oriented digital twin can extract and analyze real-time safety information coming from different data sources to detect potential hazardous situations and send out alerts to the smart operators that are using Augmented Reality devices of mobile devices, such as smartphones or tablets at the workplace. Future research activities will be devoted to investigate further the potential application of digital twin technology to support safety and ergonomics considerations for the smart operator.

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