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Designing the Operator of the Future: The Architecture of Human Digital Twin Systems

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Abstract: The central role that the human operator assumed in industrial design and development processes, driven by Industry 5.0 principles, has paved the way for the creation of new human-centric system architectures. This paper discusses the practical implications regarding the deployment of a Human Digital Twin-based system in the manufacturing environment. It provides a proof-of-concept of the architecture for the implementation of the twinning process, starting from the investigation of the most suitable hardware selection based on the desired outcomes to build up the human monitoring phase. We analyze three management decision-making levels to determine the scalability of the proposed architecture for strategical, technical, and operational managerial strategies. This research aims to propose some technological selection criteria, based on the main characteristics of the available technological acquisition devices, to determine the most suitable sensors for the creation of the physical twinning monitoring process.

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Keywords: Digital Twin; HDT Architecture; Industry 5.0; Operator 4.0, Human-centered design

1. INTRODUCTION

All the industrial achievements that preceded the fourth revolution, also known as Industry 4.0, were characterized by radical advances in mechanics and automation. The centrality of the human worker, who is still recognized as one of the most fragile but highly valuable resources for creating a flexible and resilient work environment in the recent fifth industrial revolution, disrupts all previous trends by centralizing innovations on the workforce instead of focusing the attention on a technology-driven transformation (Breque et al., 2021, Xu et al., 2021). The development of operator's health and wellness monitoring systems through the creation of an architecture based on the Human Digital Twin (HDT) concept is the concrete representation of the digital transformation towards human-centered working systems (Berti et al., 2023). Consequently, manufacturing companies started to purchase and adopt smart sensors, often without properly analyzing and determining the suitability of new devices with their current operating working system, nor with their expected business goals (Löcklin et al., 2021). For this reason, most of the system architectures proposed in literature often include a wide range of wearable sensors and garment types to monitor user's wellness and safety risk level, without debating the usefulness of the generated information for the strategical, technical, or operational decisions that company management must undertake.

This paper proposes an HDT architecture for practical on-site data monitoring in manufacturing working environments. We investigated the suitability of wearable sensors and technological devices that are adopted to build HDT-based systems according to the expected impact time horizon for three management decision-making levels:

1. Strategic level (e.g., Pre-deployment workplace design)
2. Technical level (e.g., Workstation balancing strategies)
3. Operational level (e.g., Job scheduling strategies)

This study aims to determine which sensors are best suited to pursue the objectives of each management decision area according to the end users of the expected results from the HDT simulation analysis. As we want to provide practical knowledge on this research topic, we propose a proof-of-concept of an HDT-based system, where technology selection was made according to the working environment conditions and to the managerial decision level. This research aims to investigate the intersection between the technologies used to monitor worker's physical and mental health in industrial applications and the impact that generated outcomes can have on short, medium, and long-term decisions.

The paper is structured as follows: Section 2 summarizes the current literature on HDT-based system architectures,

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highlighting the novelty of this research topic. Section 3 describes the HDT proof-of-concept while Section 4 mainly focuses on the software requirements to build up the proposed system architecture. Section 5 discusses the impact of HDT system deployment on different managerial decision levels while Section 6 finalizes this research describing the current limitations and proposing some future perspectives.

2. LITERATURE REVIEW

The Digital Twin (DT) represents one of the most characterizing enabling technologies of company digital transformation (Negri et al., 2017). Its development and deployment in industrial settings can foster the digital transition of manufacturing companies through the fourth digital industrial transition. Although the DT-based systems started to be developed in 2012 (Glaessgen & Stargel, 2012), recent advancements in this research topic have been triggered when Industry 5.0 shifted the spotlights on workforce safety and well-being toward more human-oriented workplaces and human-centered management strategies (Xu et al., 2021). The development of a work environment that actively involves the workforce in the prevention of occupational risks, injuries, or accidents was initially included in the concept of Operator 4.0 (Romero et al., 2016) and subsequently extended with the adoption of the principles of Industry 5.0. Therefore, a novel declination of DT-based systems took place to describe the new profile that characterizes workers' role in digital transition process, leading to the definition of a new human-oriented DT sub-system, also referred to as HDT (Sparrow et al., 2019). Research interest in this topic has started to gain attention since 2019, as reported in Figure 1 (i.e., Data collected on Scopus database, until December 2023 on Article title, Abstract and Keywords for "Human Digital Twin").

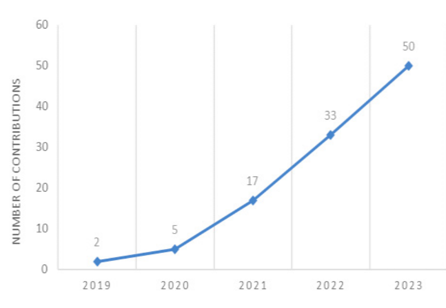

Figure 1: HDT-based contributions to the Scopus database

The application sectors where HDT systems have been investigated in the literature range from sport, healthcare, construction, and recently also included the manufacturing applications (Wang et al., 2024). Prior research on the suitability of hardware devices based on the characteristics of sensors, such as the internal memory, sensor weight, Wi-fi connection, and data streaming protocols has been already addressed (Montini et al., 2022); however, the suitability of sensors based on the managerial decision-level has not been fully investigated yet. Although real-time data capture platforms are available to directly monitor safety-related parameters in workers (Battini et al., 2022), HDT-based systems must implement structured hardware architectures and software protocols to convey data and generate concrete outcomes to help managers make decisions.

3. HUMAN DIGITAL TWIN ARCHITECTURE

In smart manufacturing systems, the availability of real-time data has given new connotations to the design phase and production job scheduling. Productivity, resilience, and flexibility remain the main targets for companies, and they can be achieved by applying strategical, tactical, and operational decisions on workplace design or job assignment to enhance the resilience of the production system to any unpredictable events. The continuous exchange of data between the physical working environment and its digital counterpart allows companies to forecast and prevent hazardous working scenarios using the captured data as input for simulation approaches to adjust working conditions. The adoption of data live streaming to feed software that can simulate future outcomes falls within the definition of DT (i.e., when physical systems transfer data to their digital counterparts and vice versa and bidirectional data exchange happens in real-time at a high capture frequency (Kritzinger et al., 2018)). Upon successful development and testing of the initial architecture, our objective is to meticulously define all conceivable parameters to build an HDT architecture, each serving a primary purpose, as reported in Figure 2.

The proposed architecture aims to assess the impact on three levels of analysis, which require distinct volume and precision of data; therefore, the type and characteristics of the technology must be modulated according to the final objective of the assessment. The strategic analysis of the production layout requires greater precision and a huge volume of data that allows evaluating different alternative scenarios aiming to design safe workplaces. Nevertheless, moving towards operational analyses, a progressive level of simplification in data collection can be established due to operational and privacy constraints, but mainly due to time constraints. In fact, in tactical and operational analysis, the speed of the choices to be made increases, and it becomes not always feasible to carry out a complete analysis, but it is more strategical to focus on measuring the most impactful decision variables (i.e., those linked to the well-being of the workers, or the ones related to the workforce learning rate). In these last phases, the use of Artificial Intelligence (AI) and machine learning (ML) algorithms become crucial since they can predict human behavior and the level of occupational risk of a task despite the incomplete data availability.

3.1 Postural ergonomics

Full-body poses are integrated into HDT to ease real-time and post-processed analyses of body posture, shift coverage, automated detection of keypoints and prediction of workers' future intentions. Motion capture systems (Mocap) are widely adopted manufacturing applications to acquire workers' movements during job execution (Slama et al., 2023). Three distinct technologies are currently available:

- Optoelectronic motion capture
- Inertial motion capture
- Markerless motion capture

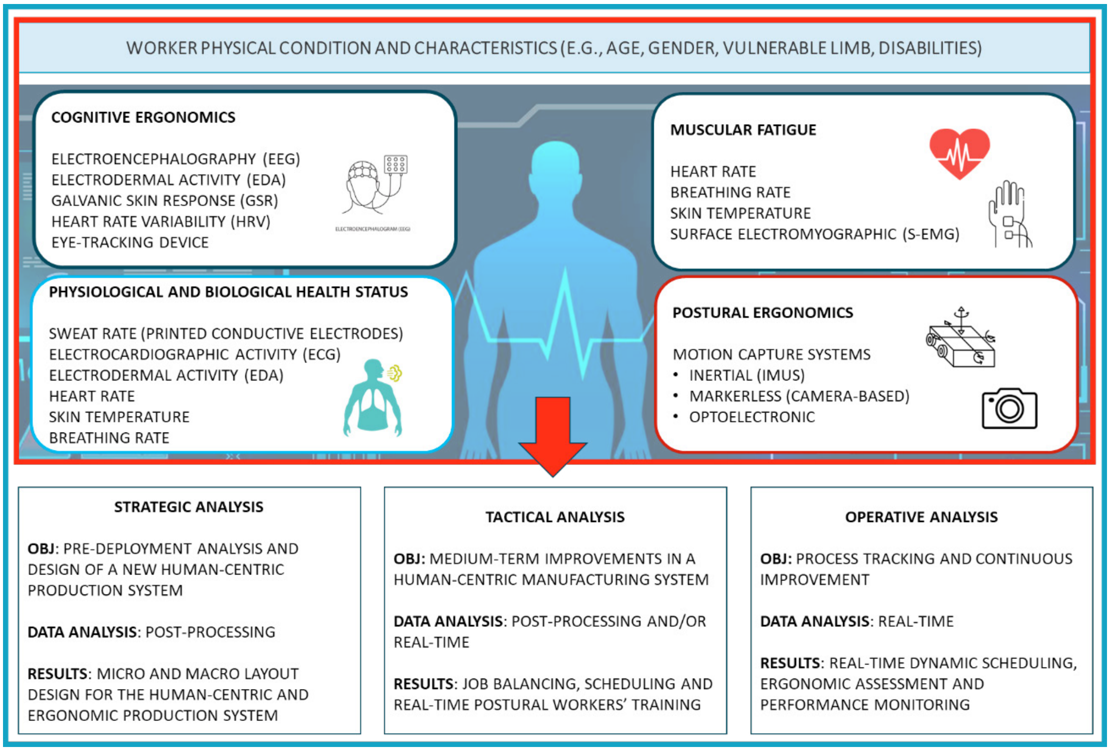

Figure 2: Human Digital Twin architecture deployed on three management decision-making levels

Optoelectronic motion capture faces challenges in industrial settings due to its intricate setup requirements and the necessity for physical retroreflective markers applied to the operator's skin. Markerless motion capture, while minimally intrusive, as it does not require sensors or markers on the human body, provides relatively lower quality information about human pose. Inertial motion capture, on the other hand, furnishes accurate motion estimates but demands the use of Inertial Measurement Units (IMUs) worn on the person's clothing. For the proposed HDT architecture, we evaluated the suitability of managerial decisions with the adoption of a full body inertial motion capture system (Xsens MTw Awinda) and a pair of inertial gloves to precisely monitor human body and fingers movements (Quantum Mocap Metagloves). Furthermore, in applications where cameras outperform inertial sensors to capture human movements (e.g., in working contexts where wearables and garments are not allowed due to magnetic noises, vibration transmission from tools, or protected environments), we also consider the possibility of integrating a set of RGB-D cameras (e.g., Microsoft Azure Kinect) to progress real-time data capturing.

3.2 Physiological and biological health status

Recent advances in the field of printed electronics are enabling the integration of smart and wearable sensors within garments and personal protective equipment (PPE) to track workers' movements and health status (Sardini et al., 2020). Combined with proper customized telemetric techniques for data acquisition and transmission, this represents a promising approach to move forward truly embedded, multi-sensing, and integrated smart PPE (e.g., helmets, gloves, pads) and smart garments (e.g., T-shirts) (Tonello et al., 2022). In smart helmets, embedded temperature and pressure sensors used to monitor wearability conditions can be integrated together with conductive electrodes that could estimate sweat rate or possibly, in more static working environments, a single ECG lead for heart rate estimation. In smart gloves, flexion sensors integrated with conductive electrodes printed on each finger could monitor workers' gestures and simultaneously evaluate their stress level through electrodermal activity monitoring (EDA). Finally, integrated temperature and pressure sensors within joint pads could improve the monitoring of wearability and eventual impacts or falls. T-shirts that integrate customized conductive paths could perform either position monitoring or breath rate monitoring, possibly correlated with stress or overload conditions.

Combining the main needs targeted by the HDT architecture with a careful literature analysis of the most recent technologies for physiological signal parameters, the device we propose exploits printed electronics advantages to target a comfortable, minimally invasive, fully printed and strongly customizable multi-sensing platform for the simultaneous monitoring of a single lead Electrocardiographic activity (ECG), Electrodermal Activity (EDA, also known as Galvanic Skin Response, GSR or skin conductance) and sweat rate. The main novelty aspects related to the design of the devices included in this architecture are the following:

- The proposal of a device that could act as a multi-sensing system for ECG, EDA, and sweat rate signal, without the need for multiple different electrodes.
- The combination of printed conductive electrodes with suitable and sustainable cellulose-based microfluidics for quantifying sweat rate, realized with a printing technique exploiting novel cellulose-based inks to enable the realization of more complex geometries.
- The study and optimization of electrode geometries specifically designed to act on stretchable substrates,

limiting the variability induced by sensor strain on the targeted physiological signals measure.
- A proper choice of electrode materials and conditioning electronics to minimize contact impedance and maximize signal-to-noise ratio even in real work scenarios, where motion artifacts will be strongly present.

3.3 Cognitive ergonomics

Work environments can be perceived as unsafe or risky by workers, which affects their well-being and the quality of their work. Consequently, effective processes are needed to highlight negative feelings, such as cognitive workload or high level of stress during working activities. Cognitive load is a multifaceted concept that takes its origins from the educational domain and involves processes of memory, perception, attention, and decision making (Brolin et al., 2017). Traditionally, subjective cognitive load was measured using questionnaires, self-reporting, and interviews (Rubio et al., 2004). The diffusion of cost-effective wearable devices increased the investigation of solutions based on the acquisition and monitoring of physiological data (Morton et al., 2022) and facial expressions. In an industrial setting, the usage of certain productive tools for quality inspection and the imperative adoption of PPEs often do not allow facial emotion recognition. For this reason, alternative methods can be adopted to assess the cognitive workload using natural language, conversational data, and physiological parameters with alternative solutions, such as:

- Electroencephalography (EEG)
- Electrodermal Activity (EDA)
- Galvanic Skin Response (GSR)
- Heart rate/heart rate variability (HR/HRV)
- Breathing rate
- Body temperature

Wearable devices can be used to collect both physical and physiological data. Finally, several machine learning algorithms and statistical approaches can be explored to analyze the collected data (Wang et al., 2024). Natural Language Processing (NLP) models are emerged as a novel and effective method for dealing with sentiment analysis and human well-being assessment. In the proposed framework, NLP models will be used to assess users' sentiments, including the sense of unsafe or risky situations.

4. SOFTWARE DESIGN

Following the definition of Digital Twin (DT) proposed by Kritzinger et al. (2018), data collection needs to be streamed in real-time to a digital representation of the physical reality, which is constantly monitored by the architecture depicted above. Once a real-time data collection stream is established, simulation of several scenarios can be computed, starting from the input data received from the digital platform.

To achieve these objectives, a seamless integration of hardware and software is essential. To this end, we propose to exploit ROS (Quigley et al., 2009), specifically leveraging its latest long-term support version, ROS2 Humble. ROS serves as the de facto standard architecture for highly complex distributed applications in robotics. It is designed to facilitate efficient real-time communication among various entities, such as sensors, computers, and robots. Providing tools and APIs in both C++ and Python, ROS enables high efficiency and flexibility simultaneously. Coupled with the specific APIs of the sensors intended for use, it allows to establish an abstraction level between gathered data (e.g., human body poses, health parameters) and the underlying technology or sensor, facilitating seamless support for different technologies and enabling a plug-and-play approach for diverse sensors and technological devices.

ROS2 introduces improvements over the original ROS architecture, focusing on usability in the industry, beyond the confines of a test laboratory. Unlike ROS1, it avoids a master-slave architecture, mitigating potential single-point failures. In addition, ROS2 uses the Data Distribution Service (DDS) for distributed communication, ensuring high efficiency, reliability, low latency, and scalability. Configurable Quality of Service (QoS) parameters further adapt the proposed network to diverse hardware configurations, encompassing sensor types, processing power, and network performance. ROS2 relies on different message types for communication among devices. As an example, data from an Inertial Measurement Unit (IMU) is transmitted as an IMU Message, including readings of angular velocity, linear acceleration, and sensor orientation. Heart rate data from a sensor is conveyed through a Heart Rate Message, providing instantaneous heart rate readings. These messages are data-specific rather than hardware-specific, allowing the use of any brand of sensor, provided its readings can be converted into the corresponding message type through the producer's APIs. Streaming frequencies can also be freely adjusted to meet each sensor and application's specifications.

Leveraging ROS2 efficiency and capabilities enables the integration of a wide variety of hardware for real-time monitoring of an operator, facilitating the creation of a detailed and complex HDT. Moreover, the system can be easily extended to monitor multiple operators by exploiting the same interfaces used in the single-person scenario (Berti et al., 2022). The initial step towards this goal involves defining the interfaces for each sensor and determining the message types to describe their readings or estimations. Although this choice might seem trivial for specific typologies of sensors (e.g., an IMU will likely exploit IMU messages), this is not true in general. For instance, the human pose can be described in multiple ways: it can be represented as a set of keypoints, or using anatomical joint angles possibly coupled with a set of offsets. Additionally, different sets of keypoints and angles can be used, depending on the underlying model describing the human. Then, successive analyses might require just a subset of data (i.e., only a few key points/angles or perhaps no key point/angles at all). Another critical factor to consider is the possibility of having delayed or even missing information (e.g., many markerless systems do not provide joint angle data). Finally, the whole HDT cannot be described simply by its pose, but a possibly large amount of data obtained by heterogeneous sensors might be integrated, depending on the specific application.

5. DISCUSSION

The flexibility of solid architectures of HDT facilitate their adoption on multiple deployment levels. Strategic decisions target long-time-horizon goals, and they can have a huge impact on the safety and well-being of the workforce due to their implications on workplace design and environmental working conditions. The international regulatory system sets some gold standards for the industrial design process; however, the heterogeneity of the individual characteristics conflicts with the adoption of the international standard, as it suggests a tailored approach for workplace design process. Collaborative workplace design represents one of the most challenging process phases that is currently dealing with human diversity. The adoption of collaborative robots (cobots) in working areas can increase the safety risk of workers, as well as affect cognitive workload due to safety threats that robots can create on workers' perception (Zanchettin et al., 2013). The adoption of digital technologies such as mocap systems to monitor worker movements and EEG to assess the cognitive load in collaborative task execution allows inclusion into the design process of collaborative workspace the individual perception of the worker, leading to more ergo-friendly and human-oriented design phase (Cella et al., 2023).

Technical decisions impact medium-term strategies. They can affect workload balance between workstations, workforce turnover scheme, skill development, and workers' training. In such a context, none of the abovementioned sensors is excluded from the analysis, but the frequency of data capturing can change according to the required precision, or to the urgency of the assessment. The suitability of motion tracking systems, biosensors, and cognitive sensors depends on the flexibility of capture frequency modulation technology to favor data processing speed rather than capture sensitivity at high frequencies. As a result of emergency situations due to shortage of personnel or lack of knowledge to operate machines, the use of untrained workers for certain tasks can pose very high risk to the company. In such cases, the process of simulating risk scenarios through the adoption of HDT data and information loop must take precedence over the precise capture of high-frequency data, thus encouraging the generation of alternative scenarios that can be relied upon to maintain a high level of safety in the work environment.

Operational strategies have a short-term impact on workforce management because they can be immediately deployed in the work field. Adopting biosensors (e.g., sweat level, heart rate, breathing rate, skin temperature) to monitor the biological parameters can help to immediately intervene whenever hazardous working behaviors occur. However, the continuous monitoring process may lead to the generation of cognitive stress and working bias; thus, the capturing frequency in these cases can be reduced to trigger alarms only on awkward peaks of ergonomic risk scores (Berti et al., 2023) or biological risk levels to simulate working scenario through the adoption of the HDT twinning loop and propose alternative task assignment, or job rotation strategies, to cope with potentially dangerous consequences. The adoption of HDT-based systems and machine learning algorithms in human-robot collaborative applications represents nowadays one of the most investigated research topics due to the multiple quantifiable benefits exploitable from real-time dynamic robot control based on workers' health status monitored using smart devices (Lorenzini et al., 2023).

6. CONCLUSIONS

The deployment of smart wearable sensors in the manufacturing sector to monitor vital parameters has broadened the horizons in the management of workers' safety and well-being in real time. Various industrial applications can benefit from constant health monitoring (e.g., logistics, operations, warehouse); however, the correct choice of sensors depends on the applications and the nature of managerial decisions the company must undertake. Therefore, decision makers must wisely select the right technology, the correct data capture frequency, proper algorithms to process data and the suitable outcome format to convey their decisions to the workplace based on the real-time information received from the simulated scenarios generated in the twinning process.

The main limitations of the present work concern the targeted research performed on the existing HDT-based architectures, without extending the search to Digital Twin systems that are not classified as HDT, but still include ergonomic assessment and human factors. Therefore, research must be further expanded on DT-based architectures and frameworks that provide guidelines and methodologies on technology implementation to support managerial decision making. Additionally, the adoption of biosensors that stream real-time data to HDT systems can lead to privacy-related issues concerning personal data storage and legal concerns in compliance with the General Data Protection Regulation 2016 (Regulation EU on GDPR, 2016). However, the expected benefit of skillful use of such technologies on workers' safety and well-being in a manufacturing context, in accordance with the security of the monitored data, can facilitate the parties' meeting to find a breakeven point for HDT system adoption. The adoption of biosensors to monitor the driver's attention and level of tiredness to avoid accidents in warehouse activities, or the acquisition of real-time data on the physiological parameters of workers to avoid repetitions of dangerous tasks are a couple of examples to create safer working environments by leveraging the same perspective achieved by Industry 4.0 with machine failure detection, now moved to monitoring the health of the human workforce to prevent possible harmful behaviors.

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