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Architecture of a Human-Digital Twin as Common Interface for Operator 4.0 Applications

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Abstract

At collaborative workspaces, humans and robots share the shop floor and work closely together. Operator 4.0 is a wide research topic and its solutions aim at the creation of Human-centered Cyber-Physical Systems that improve operators' capabilities. Such applications require a bi-directional flow of information and need data, models and simulations of machines as well as humans. To realize a common interface for information, the concept of Digital Twin is promising. This paper therefore discusses the adaption of conventional Digital Twin architectures and presents a derived Human-centered Digital Twin (H-DT) architecture designed for operators in production and intralogistics.

Keywords: Digital Twin; Operator 4.0; Human-centered Cyber-Physical System

1. Introduction

In manufacturing, humans are often indispensable due to their great flexibility and dexterity, especially in the area of final assembly [1–3]. For many companies, partial automation with a focus on the ideal use of human capabilities is more advantageous than full automation [1]. Smart Manufacturing, Intralogistics 4.0 and Cyber-Physical Production Systems research often ignores the human factor and solutions address the ideal interaction of technical systems solely [4, 5]. In order to achieve the optimum in partially automated production processes, the humans involved must also be ideally integrated.

This paper discusses the Human-Digital Twin approach. In the field of utilization and management of machines and robots, great success has already been achieved by the introduction of Digital Twins, which allow uniform interfaces, life cycle-spanning management of models and improvement of simulation capabilities [6–8]. A Digital Twin facilitates the planning of new production processes and the investigation of potential optimization measures. And by providing monitoring and cross-validation capabilities, it can help ensure the safe operation of plants.

Research in the field of Digital Twins mainly addresses technical assets. However, why should only the robot be virtually represented by a Digital Twin in a human-robot collaboration scenario? A Human-Digital Twin, as illustrated in Figure 1, represents humans in the virtual world. It can provide centralized access to various simulations from the field of workplace ergonomics and thus support the production planning process. Similarly, predictive models of human behavior in human-robot collaboration can ensure safe and efficient cooperation. The manifold results of the research areas Human-centered Cyber Physical System and Operator 4.0 show the wide spectrum of possible approaches to better integrate the humans in production and intralogistics by using wearable or peripheral sensors and applying wireless data transmission via WLAN, UWB or 5G. The centralization of all models and data concerning humans by a Human-Digital Twin facilitates the development and reuse of human-centric solutions and has the potential to prevent data misuse.

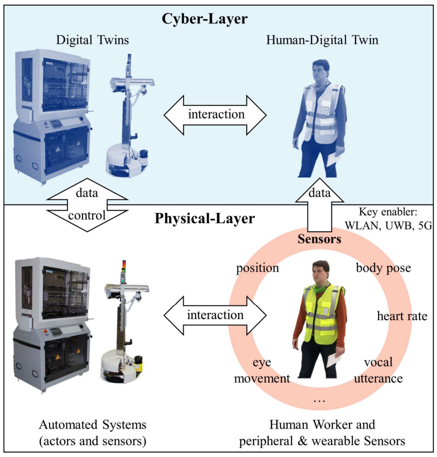

Figure 1: Human-Digital Twin (H-DT) represents humans

The remainder of this paper is structured as follows: Section 2 is dedicated to the discussion of Human-Digital Twin (H-DT) approaches. In Section 3 a generalizable H-DT architecture is proposed. Differences to Digital Twins of machines are discussed in Section 4.

2. Basics and Related Work

2.1. Definition of (Human-)Digital Twin

A Digital Twin contains all models and data of its physical counterpart and is always in sync with the physical world [7]. Therefore, a Digital Twin can be seen as a digital replica of a physical system and can mirror its static and dynamic characteristics. Systems are understood as the interplay of a physical and a virtual part. The connection of physical artifacts with models can be used for various applications [9, 10]. Therefore, the concept of Digital Twin is based on the paradigm of modularization and object orientation. What exists in the physical world is represented in the virtual world by its own individual entity, and the concept of types and instances is applied. Research in the field of Digital Twins is very manifold as Digital Twin is a blurred term [6, 8].

Digital twins typically address technical assets. In order to fully implement the Digital Twin concept for production systems, humans involved in the production process must also be taken into account [11]. Two implementation options can be distinguished. Either corresponding models and data of humans are stored with the respective Digital Twin of the technical asset. This contradicts the object-oriented approach underlying the Digital Twin concept but allows straight-forward integration of human models where necessary. However, in contrast to technical assets, personal data is particularly sensitive due to its high potential for misuse [12]. Human models and data can be stored in a separate Human-Digital Twin (H-DT), which represents a special form of Digital Twins [13]. By implementing separate H-DT, humans are managed as a virtual entity whereby data and models can be specially secured and anonymized. By processing all personal data in one place, access rights to data and models can be managed at a central location. H-DT thus enables data sovereignty [14]. Its explicit focus on sensitive data and models distinguishes H-DT from Digital Twins of technical assets.

2.2. Application purposes of H-DT and link to Operator 4.0

Research into the "Human-Digital Twin" (H-DT) or "Digital Twin of the Person" is considered to have considerable potential, and its implementation is seen as the missing piece of the puzzle for fully implementing the concept of the Digital Twin [11]. As per [13], benefits of H-DT in manufacturing are:

- Gather data for lean manufacturing measures.
- Enable real-time anomaly detection of manual work.
- Gamification of manual tasks for higher motivation.
- Feedback mechanism for human workers.
- Analyzing dangers and help resolving labor disputes.
- Speed up worker integration; offer customized training.
- N-dimensional safety monitoring.

Existing approaches realize H-DT for very specific applications but generalizable reference architectures are lacking, which is the research gap addressed in this paper. Publications that address Human-Digital Twin, Digital Twin of a person or individual and Operator 4.0 indicate that Digital Twins of humans or persons are being considered especially in the medical and manufacturing sectors. An H-DT is used to treat physical [15] or psychological [16] ailments better as well as to control athletes training intensity [17]. There is an overlap between the medical and manufacturing sectors in the research area of work ergonomics. Here, models of an H-DT are used for ergonomics evaluation [18, 19] and real-time monitoring [12, 20] of manual tasks. Ergonomics and fatigue factors can also be taken into account in production planning [21] and job scheduling [22] using H-DT. Furthermore, capability models of humans are useful for job scheduling [23, 24]. H-DT also addresses worker safety by improving the path planning of robots [25] and by considering human errors [26]. An H-DT can also be used for monitoring of manual assembly tasks [9, 27, 28]. The transition between H-DT and Digital Twins of machines represents the use of Digital Twins for human-machine interaction. Either to engineer interfaces [29] or to improve human-machine interaction [18, 30–34], Digital Twins provide models of human behavior. Another application of H-DT is in the field of product design, where customers are modelled [35]. Research on the Human-Digital Twin (H-DT) is not aimed at replicating a person's complete personality in order to make him or her obsolete. Rather, it is about harnessing the possibilities of advancing digitization for the benefit of humans.

The concept of the H-DT is versatile. In the production area, the research areas H-DT and Operator 4.0 partially overlap. Operator 4.0 addresses the realization of human-centered cyber-physical production systems [36]. Research in Operator 4.0 is multifaceted and revolves around the better integration of humans into the production process [37], with application areas [38] that match those of H-DT research. Although this empowering of workers often raises concerns amongst workers if they are not kept involved in development as discussed in [39], research on Operator 4.0 aims to improve the cognitive, sensory, physical or interactional abilities of humans in a production environment [40]. This requires a bi-directional information flow between operator and the automated system [41], and the H-DT can be this interface.

Therefore, the H-DT supports the implementation of Operator 4.0 through its features of data sovereignty [14] and lifecycle management of human-related applications. In addition to Operator 4.0, the H-DT also addresses applications that aim to optimize production by taking better account of human workers and the human factor.

The H-DT facilitates the use, adaptation and reuse of Operator 4.0 and other human-aware technologies through the central availability of always up-to-date models and data. At the same time, the H-DT approaches and applications presented in the discussed publications serve a single, clearly defined purpose. The efficiency and usefulness of Digital Twins are, however, all the greater, the more applications profit from models of the Digital Twin [7]. For this purpose, a H-DT reference architecture is presented in Section 3.

3. Proposed Human-Digital Twin Architecture

The Operator 4.0 research area is manifold and comprises many approaches. As shown in Section 2.2, the required technologies, models and data are so far very strongly adapted to the application, which makes reuse difficult. Here a Human-Digital Twin can help, if it has a generalizable structure. Very abstract architectures are discussed in [14, 42], in [14] it includes sensors for collecting user information, observations as well as functional units for deriving objectives whereas in [42] focus is on data collection from birth till death for health management. The architecture presented in the following is strongly oriented on already established architectures for Digital Twins of technical assets used for manufacturing that are discussed in [7]. The authors believe that a similar structure leads to improved usability of Human-Digital Twins (H-DT).

Figure 2 shows the proposed architecture of an H-DT. It includes the following components: a unique ID, data of the represented human, models of the represented human, relations to other Digital Twins and relations between models. Besides, the H-DT requires different interfaces, in particular, a co-simulation interface, an interface for data acquisition and an interface to access the models and data of the H-DT. The individual components are described below.

Unique ID: With the H-DT it must be distinguished whether the H-DT can or should be assigned to a single individual or whether the H-DT represents only a certain type of human beings and their specific role as operator. Here it always depends on the intended use. During the development phase, it is usually sufficient to use an H-DT of a certain type of human, which has characteristics that apply well to a large number of operators (height, weight, qualification, etc.). During operation, however, it can be quite useful to use the H-DT of a specific individual, for example if individual characteristics such as access authorizations or workplace preferences are required. Thus, the unique ID is used to assign the H-DT either to an individual or a type of human beings respectively operator role. This ID can be used to access the models and data of the H-DT and to define relations.

Data of the represented individual or role: Here, all collected data of the represented person is stored. The H-DT can be both a short-term memory that deletes sensitive data in a systematic procedure after a limited period of time, or it can

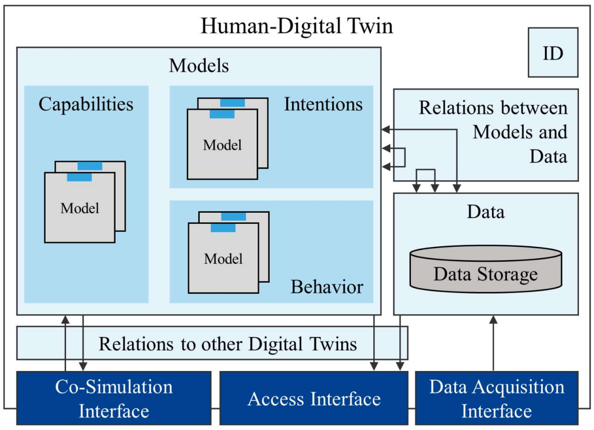

Figure 2: Reference Architecture of a Human-Digital Twin (H-DT)

be a long-term memory and store data over the entire life cycle. Stored data can be vital data collected via sensors, such as blood pressure, location data about the current position, work data, such as which order is currently being processed, but also "organizational" data such as access rights, admin rights and salary group. This data can be used by the models of the H-DT or by other applications of the automated system. From outside the H-DT, however, person-related data is encapsulated by the access interface.

Models: The H-DT represents and has various models of a human being or alternatively, if more anonymity is required, of an operator role or type. These can be categorized into *behavior*, *intentions* and *capabilities* models. The behavioral models depict different behavior of the human being, such as future movement. The intention models are more abstract and describe objectives of a human. Current objectives can be derived from past activities or activities planned for the future. The capability models show the abilities and skills as well as physical characteristics of humans, like for example qualifications or information about ergonomic properties. A model categorization regarding abstract intention and concrete behavioral models is common in the modeling of humans and dates back to the theory of planned behavior [43]. A further subdivision of the intention category into motivation, possibilities and desires is possible. In the field of production, the modeling of capabilities is also essential and is therefore proposed as a separate category. Depending on the application, models are either used to improve a technical process or to improve the well-being of the person. Some of these models are executable and can therefore be used for simulations. These models are created and maintained in different tools. Therefore, it is additionally necessary to have an interface to the respective tools to execute or adapt them. Besides, versioning of the models must be done, i.e. changes to models must be stored in new versions to enable traceability. The access interface also encapsulates the access to or adaption of models.

Relation to other Digital Twins: Here relations to other Digital Twins and H-DTs are stored. These relations are not static over the complete life cycle of the H-DT but can change constantly. For example, a relation between an H-DT and a Digital Twin of a machine exists as long as the worker is working on this machine or is in its immediate vicinity. A relationship between two H-DTs would be, for example, a hierarchical structure like that of the shift leader and operator.

Here, however, not only the current relations are stored, but also historical relations, to enable traceability. Making relations transparent allows data sovereignty, as discussed later.

Relations between models and data: In addition to the relations to other Digital Twins, the relations between models and data must be defined. There are relations between different models as well as between models and data. An example of a relation between models is if a behavior model needs to access a capability model to predict behavior as exact as possible. For such a prediction by a behavioral model also collected data is needed, for example, the current position in a trajectory prediction, which is an example for a relation between models and data. Stored relations show dependencies between components and help to estimate the effort for planned changes better.

Co-simulation interface: A co-simulation interface is required to determine the behavior of an H-DT in interaction with other Digital Twins or the behavior of a Digital Twin in interaction with an H-DT. This provides more than just a static image of reality and can be used to determine the interaction of components and humans, for example, for movement prediction in a workshop with moving components and humans. A possible realization of such a co-simulation interface is given in [44].

Interface for data acquisition: The data acquisition interface is used to acquire a wide variety of data and must therefore be manifold. It must be able to collect vital data measured by sensors as well as to determine the current position and collect data resulting from the interaction with machines. All these data must be collected automatically, but it must also be possible to enter "organizational" data manually if necessary. Thus, a multitude of interfaces is bundled here, which serves to collect different data.

Access interface: Confidentiality and integrity are a very relevant issues for H-DT, access rights and security measures must be considered as data and models are person-related and therefore sensitive. For this purpose, all data and models are encapsulated in the H-DT via suitable mechanisms, e.g. encryption, and can only be read via the specified interfaces. Thus, only authorized applications can access data or models of the H-DT of an individual. Blockchain technology can be used to document every data access with non-breakable transparency as for example demonstrated in [45]. The adaption of models of the H-DT also has to be done via secured interfaces by authorized administrators.

4. Human-Digital Twin vs. Digital Twin of machines

Comparing the architecture of a Human-Digital Twin (H-DT) with the architecture of a Digital Twin of a technical component, there are some essential differences, which are discussed in the following. The most significant difference is that in the considered technical environment of an H-DT, a benefit is only created if it is linked to Digital Twins of technical components. Then both the technical process and the working environment of the represented individual can be improved.

Also, the issue of privacy must be given much greater consideration in H-DT. Once the H-DT can be assigned to an individual, it contains sensitive data. This data must be protected in compliance with legal requirements. Therefore, any access to data, models or other information of the H-DT must be encapsulated and may only take place with the appropriate authorization. Responsible for this is the access interface presented above. With a Digital Twin of a technical component, most of the information contained is much less sensitive, which is why it is not necessary to invest that much in data protection and access control.

The synchronization of the models as well as the data acquisition also make a difference. With a Digital Twin of a technical component, both data collection and synchronization of the models must be completely automated. With the H-DT, however, this is not always possible. On the one hand, the models change much less frequently, and on the other hand, such changes are much more difficult to detect, for example, when an individual's skills change due to training. Not all data can be recorded automatically without further effort either, for example if organizational data changes.

Another difference is that with the Digital Twin of a technical component, the actually added value is only achieved when it is the Digital Twin of a specific component. In the H-DT, however, even representations of a general type can offer added value if they are linked to Digital Twins of technical components. This is especially true when improving the technical process. If the working environment is to be improved, the H-DT of the respective individual is usually required, for example to customize a workstation.

Version management in the Digital Twin of a technical component and the H-DT also differs. In H-DT, the models have to be adapted much less frequently, since a person changes less frequently. However, the relations to other Digital Twins have to be adapted more frequently, since a person is much more mobile. However, relations are easier to adapt than models, which is why this article does not propose central version management for H-DT. Instead, for an H-DT, individual version management for the models and relations is recommended.

Overall, it can be stated that the basic idea and some components of Digital Twin and H-DT are the same, but as shown in this section, there are also significant differences between the two in some aspects.

5. Evaluation of the Human-Digital Twin reference architecture

To evaluate the proposed reference architecture, a Human-Digital Twin (H-DT) is implemented for the application area of position-based automation and improved human-AGV-interaction. Automated Guided Vehicles (AGV) are used to realize flexible intralogistics solutions. AGVs and operators share the same traffic space on the shop floor. To further optimize the performance of AGVs, models can be used to predict human movements [46]. This enables AGVs to act with greater foresight, for example by rolling out in case of a temporarily blocked route rather than going fast and braking hard. The prediction of human motion can be used for other applications as well. In the evaluation scenario, a production machine starts its maintenance routines in advance so that a maintenance technician can start work as soon as he reaches the machine as the boot-up process is already finished.

The realized H-DT is representing the maintenance technician in the virtual world, as shown in Figure 3. The PLC-controlled workstation communicates via Profinet, whereas the robot requires WLAN and the position of the human is determined by an ultra-wideband-based real-time locating system [46] that also uses the ultra-wideband infrastructure for secure wireless data transmission [47]. For better real-time performance, 5G technology could be deployed. The data acquisition interface of the H-DT is used to store the position data of the human. Besides data, the H-DT also provides models. In the evaluation scenario, models predict the future movement trajectories of the technician by analyzing his/her past positions.

Using this intention information, a behavioral prediction model is then executed, which predicts the specific movement of the technician in the near future. A time-dependent motion trajectory is calculated for all possible targets using an A^* pathfinding algorithm. These future predicted position data are then made available to other applications via the access interface of the H-DT. Behavioral prediction benefits from intention prediction since it narrows the list of possible targets. The interaction between the two models is stored in the model relations section. A capability model has not yet been implemented. By including further context-based information, motion prediction can be improved.

To prevent misuse of person-related position data, the H-DT is implemented as short-term memory and deletes position data that is no longer required. Via the access interface, future position data is made available. To protect this interface, further measures can be applied to ensure that only authorized applications can use it. In the relations to other Digital Twins section, all access rights of applications are specified. Thus, transparency and data sovereignty are achieved. Besides, relations between digital twins and models help to identify technical dependencies, which is especially useful when implementing updates.

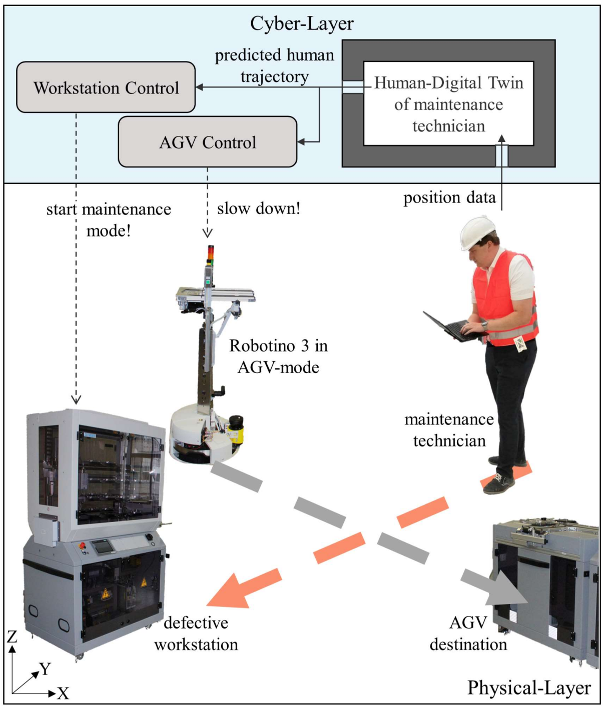

Figure 3: Trajectory prediction model used for two applications

The predicted future positions of the maintenance technician are used by the "AGV Control" and "Workstation Control" as shown in Figure 3. These can be the AGV's or workstation's own digital twins, but in the present scenario, these are only control applications. The AGV control anticipates a collision with the maintenance technician who is on his way to the workstation and will cross the path of the AGV. The AGV, therefore, reduces its speed to avoid energy-inefficient hard braking. Workstation control recognizes that the maintenance technician is about to arrive and starts the maintenance mode in advance. As an alternative to the H-DT, both applications could have implemented appropriate models and use operator position data themselves. The human-centered storage and processing of person-related data in the H-DT allow for transparency of the purposes for which position data is used. Furthermore, position prediction models are provided at a central location, and they only need to be developed and maintained once. Any freed-up development capacities can be used to enhance the models instead of developing similar solutions twice.

6. Conclusion

The Human-Digital Twin (H-DT) represents humans in cyberspace and is the missing piece of the puzzle for the complete implementation of the Digital Twin concept. The Operator 4.0 research area develops solutions for better integrating humans in production processes. This requires up-to-date data and models, which are provided by the H-DT. Previous Operator 4.0 and H-DT approaches are tailored to a single application. In order to exploit symbiosis effects and enable reuse, a common interface for all person-related data and models is needed, a generally applicable H-DT.

For this purpose, the reference architecture presented in Section 3 serves as a guideline which components an H-DT can comprise. Applications require various models and data. In practice, only the required components are implemented. H-DT manages sensitive person-related data and models in a common location and enable data sovereignty through access control and transparency. To further increase anonymity, a Human-Digital Twin can also virtually represent only a specific operator role instead of an individual.

The more applications that benefit from the Digital Twin, the greater its utility. An advanced Digital Twin provides many different models and data. This increases the probability that models can be reused. Furthermore, the presence of other models and data can trigger symbiosis effects, as already existing components interact and provide higher-value information. For example, context information can be derived and used. Thereby the digital twin stimulates the development of sophisticated solutions.

Operator 4.0 is the future and is becoming within reach. In addition to researching new Operator 4.0 approaches, it is also important to make them accessible to companies with the best possible practical benefits. The core technology for this is the

H-DT, which can be used to offer a wide variety of Operator 4.0 applications in bundled form. The prerequisite for building a suitable H-DT for this purpose is alignment with reference architectures, such as the architecture proposed in this paper for the production and intralogistics sector.

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References

[1] Malik A, Bilberg A. Human centered Lean automation in assembly. 52nd CIRP Conference on Manufacturing Systems 2019; 659–64.
[2] Segura Á et al. Visual computing technologies to support the Operator 4.0. Computers & Industrial Engineering 2020; p. 105550.
[3] Hanna A, Bengtsson K, Gotvall P-L, Ekstrom M. Towards safe human robot collaboration - Risk assessment of intelligent automation. 25th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA), Vienna, Austria; 2020; 424–31.
[4] Nunes D, Zhang P, Sa Silva J. A Survey on Human-in-the-Loop Applications Towards an Internet of All. IEEE Commun. Surv. Tutorials 2015; 2:944–65.
[5] Peruzzini M, Pellicciari M. A framework to design a human-centred adaptive manufacturing system for aging workers. Advanced Engineering Informatics 2017; 330–49.
[6] Sjarov M et al. The Digital Twin Concept in Industry – A Review and Systematization. 25th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA), Vienna, Austria; 2020; 1789–96.
[7] Ashtari Talkhestani B et al. An architecture of an Intelligent Digital Twin in a Cyber-Physical Production System. at - Automatisierungstechnik 2019; 9:762–82.
[8] Löcklin A et al. Digital Twin for Verification and Validation of Industrial Automation Systems – a Survey. 25th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA), Vienna, Austria; 2020; 851–8.
[9] Bilberg A, Malik A. Digital twin driven human–robot collaborative assembly. CIRP Annals 2019; 1:499–502.
[10] Schleich B, Anwer N, Mathieu L, Wartzack S. Shaping the digital twin for design and production engineering. CIRP Annals 2017; 1:141–4.
[11] Samir K, Maffei A, Onori M. Real-Time asset tracking; a starting point for Digital Twin implementation in Manufacturing. Procedia CIRP 2019; 719–23.
[12] Assadi A et al. User-friendly, requirement based assistance for production workforce using an asset administration shell design. Procedia CIRP 2020; 402–6.
[13] Sparrow D, Kruger K, Basson A. Human Digital Twin for integrating human workers in Industry 4.0. International Conference on Competitive Manufacturing (COMA '19) 2019.
[14] Zibuschka J, Ruff C, Horch A, Roßnagel H. A Human Digital Twin as Building Block of Open Identity Management for the Internet of Things2020.
[15] Barbiero P, Torné R, Lió P. Graph representation forecasting of patient's medical conditions: towards a digital twin2020.
[16] Angulo Cecilio, Ortega Juan Antonio, Gonzalez-Abril Luis. Towards a Healthcare Digital Twin. Frontiers in Artificial Intelligence and Applications 2019; 312–5.
[17] Barricelli B et al. Human Digital Twin for Fitness Management. IEEE Access 2020; 26637–64.
[18] Malik A, Brem A. Digital twins for collaborative robots: A case study in human-robot interaction. Robotics and Computer-Integrated Manufacturing 2021; p. 102092.
[19] Nikolakis N, Alexopoulos K, Xanthakis E, Chryssolouris G. The digital twin implementation for linking the virtual representation of human-based production tasks to their physical counterpart in the factory-floor. International Journal of Computer Integrated Manufacturing 2019; 1:1–12.
[20] Greco A, Caterino M, Fera M, Gerbino S. Digital Twin for Monitoring Ergonomics during Manufacturing Production. Applied Sciences 2020; 21:p. 7758.
[21] Latif H, Starly B. A Simulation Algorithm of a Digital Twin for Manual Assembly Process. Procedia Manufacturing 2020; 932–9.
[22] Ariansyah D et al. Towards a Digital Human Representation in an Industrial Digital Twin. 9th International Conference on Through-life Engineering Service 2020.
[23] Graessler I, Poehler A. Integration of a digital twin as human representation in a scheduling procedure of a cyber-physical production system. IEEE International Conference on Industrial Engineering and Engineering Management, Singapore; 2017; 289–93.
[24] Fang Y et al. Digital-Twin-Based Job Shop Scheduling Toward Smart Manufacturing. IEEE Trans. Ind. Inf. 2019; 12:6425–35.
[25] Dröder K et al. A Machine Learning-Enhanced Digital Twin Approach for Human-Robot-Collaboration. Procedia CIRP 2018; 187–92.
[26] Askarpour M, Mandrioli D, Rossi M, Vicentini F. Formal model of human erroneous behavior for safety analysis in collaborative robotics. Robotics and Computer-Integrated Manufacturing 2019; 465–76.
[27] Sun X et al. A digital twin-driven approach for the assembly-commissioning of high precision products. Robotics and Computer-Integrated Manufacturing 2020; p. 101839.
[28] Fera M et al. Towards Digital Twin Implementation for Assessing Production Line Performance and Balancing. Sensors (Basel, Switzerland) 2019; 1:
[29] Fass D, Bastien J, Gechter F. Human Systems Design Towards an Integrative Conceptual Framework. In Conference on Applied Human Factors and Ergonomics. Cham: Springer; 2020; 283–8.
[30] Lv Q et al. A digital twin-driven human-robot collaborative assembly approach in the wake of COVID-19. Journal of Manufacturing Systems 2021.
[31] Marcon P et al. The Asset Administration Shell of Operator in the Platform of Industry 4.02018; 18th International Conference on Mechatronics - Mechatronika (ME).
[32] Ma X et al. Digital twin enhanced human-machine interaction in product lifecycle. Procedia CIRP 2019; 789–93.
[33] Pairet E et al. A Digital Twin for Human-Robot Interaction. Proceedings of the 14th ACM/IEEE International Conference on Human-Robot Interaction, Daegu, Korea (South); 2019; p. 372.
[34] Wilhelm J, Beinke T, Freitag M. Improving Human-Machine Interaction with a Digital Twin. In Dynamics in Logistics. Cham: Springer; 2020; 527–40.
[35] Cheng Z, Kuzmichev V. Digital twin and men's underwear design. IOP Conf. Ser.: Mater. Sci. Eng. 2018; p. 12075.
[36] Ruppert T, Jaskó S, Holczinger T, Abonyi J. Enabling Technologies for Operator 4.0: A Survey. Applied Sciences 2018; 9:p. 1650.
[37] Romero D et al. Towards an Operator 4.0 Typology: A Human-Centric Perspective on the Fourth Industrial Revolution Technologies. In International Conference on Computers and Industrial Engineering. Tianjin, China: 2016;
[38] Peruzzini M, Grandi F, Pellicciari M. Exploring the potential of Operator 4.0 interface and monitoring. Computers & Industrial Engineering 2020; p. 105600.
[39] Kaasinen E et al. Empowering and engaging industrial workers with Operator 4.0 solutions. Computers & Industrial Engineering 2020; p. 105678.
[40] Gazzaneo L, Padovano A, Umbrello S. Designing Smart Operator 4.0 for Human Values: A Value Sensitive Design Approach. Procedia Manufacturing 2020; 219–26.
[41] Harriott C, Garver S, Cunha M. A Motivation for Co-adaptive Human-Robot Interaction. In International Conference on Applied Human Factors and Ergonomics. Cham: Springer; 2017; 148–60.
[42] Shengli W. Is Human Digital Twin Possible? Computer Methods and Programs in Biomedicine Update 2021; p. 100014.
[43] Ajzen I. The Theory of Planned Behavior. Organizational Behavior and Human Decision Processes 1991; 50:179–211.
[44] Jung T, Shah P, Weyrich M. Dynamic Co-Simulation of Internet-of-Things-Components using a Multi-Agent-System. Procedia CIRP 2018; 874–9.
[45] Choudhury O, Sylla I, Fairoza N, Das A. A Blockchain Framework for Ensuring Data Quality in Multi-Organizational Clinical Trials. IEEE International Conference on Healthcare Informatics (ICHI)2019; 1–9.
[46] Löcklin A et al. Trajectory Prediction of Humans in Factories and Warehouses with Real-Time Locating Systems. 25th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA), Vienna, Austria; 2020; 1317–20.
[47] Löcklin A et al. Tailored digitization with real-time locating systems. atp 2021; 03:76–83.