2025 Design, Automation & Test in Europe Conference (DATE 2025)

Human-Centered Digital Twin for Industry 5.0

Francesco Biondani, Luigi Capogrosso, Nicola Dall'Ora, Enrico Fraccaroli, Marco Cristani, Franco Fummi
Department of Engineering for Innovation Medicine, University of Verona, Italy
{francesco.biondani_02, name.surname}@univr.it

***Abstract*—Moving beyond the automation-driven paradigm of Industry 4.0, Industry 5.0 emphasizes human-centric industrial systems where human creativity and instincts complement precise and advanced machines. With this new paradigm, there is a growing need for resource-efficient and user-preferred manufacturing solutions that integrate humans into industrial processes. Unfortunately, methodologies for incorporating human elements into industrial processes remain underdeveloped. In this work, we present the first pipeline for the creation of a human-centered Digital Twin (DT), leveraging Unreal Engine's MetaHuman technology to track worker alertness in real-time. Our findings demonstrate the potential of integrating Artificial Intelligence (AI) and human-centered design within Industry 5.0 to enhance both worker safety and industrial efficiency.**

***Index Terms*—Artificial Intelligence, Digital Twin, Human-Centered Digital Twin, Industry 5.0, Metaverse.**

I. Introduction

The transition from Industry 4.0 to *Industry 5.0* represents a shift in industrial practices, moving from automation and efficiency to human-centered systems [1], [2]. While Industry 4.0 emphasizes Cyber-Physical Systems (CPSs), Industry 5.0 redefines these systems by prioritizing human integration [3], [4]. Specifically, Industry 5.0 emphasizes human-machine collaboration, where technology enhances productivity and ensures adaptability, resilience, and sustainability in industrial operations. This shift introduces unique challenges, particularly in integrating the human element within digital data-driven industrial ecosystems. One of the key technologies enabling this integration is the concept of *Digital Twins (DTs)*. By mirroring the real-time state of its physical counterpart, DTs enable continuous data collection, analysis, and simulation [5]. The ultimate goal of using DTs is to provide insights into system behaviors, enabling more informed decisions and optimizing performance.

Motivations: While extensive research exists on creating DTs of machines and factories [6], incorporating a human replica into these digital worlds remains a challenge. A potential solution to this problem is the concept of the *Industrial Metaverse*, *i.e.*, a digital space where human and machine interactions occur in real-time [7]. However, the Industrial Metaverse is still a new concept in the context of Industry 5.0 [8]. Most current developments focus on machines and automation, ignoring how humans fit into these systems. As a result, there are no clear methodologies yet for developing human-centered DTs within the Industrial Metaverse. These considerations form the basis of the proposed pipeline in Figure 1 for the creation of a *human-based DT*.

This study was conducted within the MICS (Made in Italy – Circular and Sustainable) Extended Partnership and received funding from Next-Generation EU (Italian PNRR – M4 C2, Invest 1.3 – D.D. 1551.11-10-2022, PE00000004). CUP MICS D43C22003120001 - Cascade funding project CollaborICE, and by the European Union's Horizon Europe research and innovation programme under the Marie Sklodowska-Curie grant agreement No. 101109243.

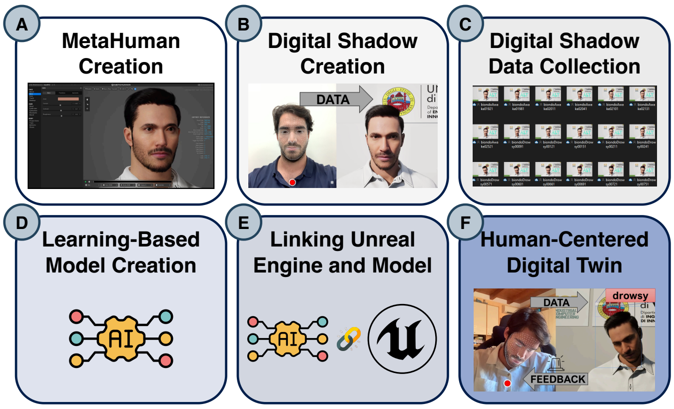

Figure 1. (A) The process starts by creating a MetaHuman, *i.e.*, a virtual replica of the real human. (B) The connection between the real human and the virtual replica is established using the LiveLink plugin, forming the Digital Shadow that allows real-time data acquisition. (C) Then, images were acquired and labeled to capture the operator's real-time movements under awake and drowsy conditions. (D) A state-of-the-art deep learning model, *i.e.*, the YOLOv8, is trained to detect the operator's state. (E) A client-server architecture is set up to facilitate the communication between YOLOv8 and Unreal Engine. (F) Finally, the DT reflects the operator's state (in our case, awake or drowsy) and provides alerts based on real-time conditions.

Innovations: To address this gap, we propose a pipeline that utilizes Unreal Engine's MetaHuman technology [9] and Artificial Intelligence (AI) to create human-centered DTs for real-time monitoring and decision-making in Industry 5.0 environments, basing our work on wakefulness and drowsiness detection task. This solution aims to enhance safety, adaptability, and performance in Industry 5.0 scenarios by connecting the physical human with its virtual counterpart. To the best of our knowledge, this is the first real proposal that shows how to create and integrate human DTs in the context of Industry 5.0, addressing the critical gap in human-machine collaboration.

Contributions: In summary, the main contributions of this paper are: *i)* a concrete proposal for creating and integrating human DTs in the context of Industry 5.0; *ii)* the application of game engine technology, *i.e.*, Unreal Engine, for real-time human DT creation, opening new possibilities for Industrial Metaverse development; and finally *iii)* an effective pipeline for real-time tracking of human states, like drowsiness, that enhances safety and adaptive decision-making in industrial environments.

978-3-9826741-0-0/DATE25/© 2025 EDAA

II. Methodology and Implementation

Our human-centered DT pipeline involves six stages depicted in Figure 1.

A) MetaHuman Creation: The first stage involves creating a highly accurate digital replica of the human operator using Unreal Engine's MetaHuman Creator, the state-of-the-art tool for generating hyper-realistic virtual humans. The web interface allows the creation of a detailed virtual replica by customizing facial features and general appearance, ensuring that even individuals with minimal computer graphics expertise can generate highly realistic digital humans.

B) Digital Shadow Creation: The second stage involves creating the Digital Shadow, *i.e.*, a continuously synchronized virtual representation of the operator's real-world movements. In this phase, we used the LiveLink Face application developed by Epic Games. Unlike full-body motion capture systems that require specialized suits, LiveLink uses a simple smartphone or tablet, eliminating the need for complex hardware or sensors and making it easier to adopt and scale.

C) Digital Shadow Data Collection: In this stage, data was gathered to capture the operator's real-time movements under both awake and drowsy conditions. A Python script was used to automatically capture screenshots from Unreal Engine, ensuring diverse and high-quality data by acquiring images from various angles and positions.

Moreover, the Industrial Metaverse allows data collection to be conducted remotely, enabling operators to work from the office or even from home. This capability not only provides flexibility but also ensures that the factory's operations remain uninterrupted.

D) Learning-Based Model Creation: Our wakefulness and drowsiness detection model, based on the YOLOv8 architecture [10], classifies each detected object as awake or drowsy. The model achieved high evaluation metrics, with an accuracy of 99.5%, precision of 1.000 (wakefulness) and 0.965 (drowsiness), and recall of 0.998 (wakefulness) and 1.000 (drowsiness). These results demonstrate highly accurate and reliable wakefulness and drowsiness detection on our acquired data with minimal false positives or missed detections.

E) Linking Unreal Engine and the AI Model: After training, the model was integrated into Unreal Engine using a client-server architecture. This setup ensures that any changes in the operator's state are instantly reflected in the DT, facilitating immediate feedback and interaction.

F) Human-Centered Digital Twin: The DT system continuously monitors the operator's state, updating the virtual replica in real-time based on the model's predictions. In the final phase, the fully functional DT was evaluated for both its real-time interaction capabilities and the quality of its output.

Finally, the developed human-centered DT was validated into a real manufacturing plant's DT of the Industrial Computing Engineering Laboratory of the University of Verona[1]. This validation demonstrates how our pipeline allowed easy integration of the human-centered DT into a new existing machine-oriented DT ecosystem, which was previously focused only on CPS and machine-centric applications.

[1]https://www.icelab.di.univr.it/.

III. Concluding Remarks and Outlook

The proposed human-centered DT pipeline demonstrates a practical and cost-effective approach to real-time worker monitoring and interaction within industrial environments.

While there has been extensive research on DT technologies and their role in Industry 4.0 and 5.0, practical implementations remain limited. Many existing works are theoretical, and fully operational systems that integrate human DTs into industrial settings are scarce. This pipeline marks the initial effort to address this gap, offering the first working solution.

Nonetheless, this system presents some limitations. The reliance on camera-based facial tracking restricts the operator's movement to the camera's field of view, which can be a constraint in dynamic industrial environments. Therefore, our solution is better suited for operators working in fixed production cells or vehicles rather than for workers who need to move throughout the factory. Moreover, although MetaHuman Creator offers realistic digital replicas, it lacks customization options for representing diverse body types and individuals with disabilities. Addressing these limitations will make the solution more inclusive and versatile. Finally, relying on camera-based tracking alone presents inherent limitations in dynamic and large-scale industrial environments.

Despite these considerations, the pipeline represents a fundamental step toward the creation of human digital twins, establishing a foundation for future advancements and practical applications across diverse industries. Moreover, it highlights that the Industrial Metaverse is not merely a futuristic concept but a tangible and viable solution for addressing real-world challenges.

References

[1] S. Nahavandi, "Industry 5.0—A Human-Centric Solution," *Sustainability*, vol. 11, no. 16, p. 4371, 2019.

[2] X. Xu *et al.*, "Industry 4.0 and Industry 5.0—Inception, conception and perception," *Journal of Manufacturing Systems*, vol. 61, pp. 530–535, 2021.

[3] M. Hermann *et al.*, "Design Principles for Industrie 4.0 Scenarios," in *49th Hawaii International Conference on System Sciences (HICSS)*, 2016.

[4] P. K. R. Maddikunta *et al.*, "Industry 5.0: A survey on enabling technologies and potential applications," *Journal of Industrial Information Integration*, vol. 26, p. 100257, 2022.

[5] F. Tao *et al.*, "Digital twin modeling," *Journal of Manufacturing Systems*, vol. 64, pp. 372–389, 2022.

[6] J. Leng *et al.*, "Digital twins-based smart manufacturing system design in Industry 4.0: A review," *Journal of Manufacturing Systems*, vol. 60, pp. 119–137, 2021.

[7] J. Guo *et al.*, "Industrial metaverse towards Industry 5.0: Connotation, architecture, enablers, and challenges," *Journal of Manufacturing Systems*, vol. 76, pp. 25–42, 2024.

[8] S. Zhang *et al.*, "Industrial Metaverse: Enabling Technologies, Open Problems, and Future Trends," *arXiv preprint arXiv:2405.08542*, 2024.

[9] E. Games, "Unreal Engine," https://www.unrealengine.com, accessed: 2024-09-16.

[10] R. Varghese *et al.*, "YOLOv8: A Novel Object Detection Algorithm with Enhanced Performance and Robustness," in *International Conference on Advances in Data Engineering and Intelligent Computing Systems (ADICS)*, 2024.