Enhancing Human-Machine Interactions: A Novel Framework for AR-Based Digital Twin Systems in Industrial Environments

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ABSTRACT

Industry 5.0 represents a paradigm shift initiated by the European Commission, which emphasizes human-centricity, sustainability, and resilience in industrial settings. This novel paradigm underscores the importance of giving a central role to humans in every process entailed in the implementation of advanced technologies into work and industrial scenarios. By following this view, in this work, we present a novel human-centric framework integrating Digital Twins (DTs) and Augmented Reality (AR) within a manufacturing setting, focusing on a design and evaluation process that facilitates seamless interaction between humans and machines. This work contributes to the ongoing discourse on Industry 5.0 by offering a twofold yet integrated perspective on humans and novel industrial technologies, providing insights into the transformative potential of integrating AR and DT technologies within industrial settings. From a technical perspective, the framework's hardware and software specifications, design principles, and technical implementation are elucidated, followed by an evaluation of its responsiveness and spatial accuracy. Results demonstrate the framework's efficacy in providing real-time monitoring and control of robotic systems. Parallely, the potential impacts of our AR-based digital twin systems on human labor and work routines are discussed, providing a more human-based perspective to complement the technical one.

CCS CONCEPTS

• **General and reference** → **Measurement**; • **Applied computing** → *Industry and manufacturing*.

KEYWORDS

Human-Computer Interaction, Digital Twin, Extended Reality, Manufacturing, Pervasive Devices, Robotics

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1 INTRODUCTION

Industry 5.0 is a conceptual framework initiated by the European Commission, which was introduced through its 2021 Policy Brief titled "Industry 5.0-towards a sustainable, human-centric and resilient European industry" [3]. This transition entails a significant deviation from the preceding Industry 4.0, which was predominantly technology-centric and mainly brought significant advancements focusing on the Internet of Things (IoT), big data analytics, cloud computing, Artificial Intelligence (AI), and automation. In contrast, Industry 5.0 places paramount importance on human-centricity, sustainability, and resilience as its fundamental pillars [3].

As Industry 5.0 advances, greater attention is directed toward the interfaces within manufacturing systems, particularly those involving human interaction. A clear consensus has emerged emphasizing that an intelligent manufacturing system goes beyond just AI; it also includes a hybrid approach integrating human participation into the manufacturing process [21], [12]. Particularly in the context of industrial and manufacturing robotics, collaborative robots, or "cobots," represent key technologies designed to collaborate with human workers safely, hence emphasizing the human-centric vision of Industry 5.0 and fostering symbiotic relationships between humans and robots [11]. As such, concepts like cyber-physical systems (CPSs), characterized by the integration of computational and physical capabilities facilitating interaction with humans through diverse modalities, have gained prominence [2]. CPSs serve as a key mechanism for bridging the gap between human operators and industrial technologies, thereby supporting humans within complex and highly flexible industrial environments. This support extends beyond mere performance enhancement and skill augmentation, encompassing novel Digital Twins (DTs) and Extended Reality (XR) systems that allow safer working conditions and training environments [1, 9].

In the present work, we present our novel human-centered AR-based DT framework. Remarkably, intending to advance technological development with special attention to the human, we provide a twofold yet integrated perspective on our system, delving both into the engineering of the technical framework and the human-related implications relative to the actual implementation of our system. More specifically, we aim to achieve three primary objectives:

(1) introducing the architecture, functionalities, and implementation details of our framework;

(2) evaluating its performance and responsiveness in a highly realistic lab-based scenario;
(3) discussing the practical applications of our framework in a human-centered view, reviewing possible impacts on human factors, labor dynamics, and work routines within industrial settings.

The paper is organized as follows: after a brief definition of the technologies involved in our framework (i.e., cobots, DT, XR), Section 2 provides an overview of related works in the field of DT frameworks, highlighting existing approaches and their limitations. Section 3 delves into the design principles and technical aspects of our AR-based DT framework, fulfilling the first objective of this paper (1). Related to the papers' second objective (2), Section 4 discusses the evaluation methodology and presents empirical results regarding the framework's performance and responsiveness. Finally, in Section 5, we address the third objective (3) by discussing potential applications and implications of our novel framework on human factors, labor dynamics, and industrial work routines. Conclusions and future outlines are presented in Section 6.

Cobots. Robots designed to work alongside human workers in industrial settings, aim to improve productivity, efficiency, and safety [11]. They feature advanced safety measures and sensing capabilities, enabling safe human-robot interaction without physical barriers. Cobots contribute to various manufacturing stages, with research focusing on optimizing design parameters and enhancing human-robot interaction [6]. In the context of cyber-physical systems, cobots integrate computational intelligence and physical robotics, enabling real-time monitoring, adaptive control, and collaborative decision-making. Studies on cobot applications typically address design, programming, and operation aspects, aiming to refine hardware, develop algorithms, and integrate systems effectively [6].

Additionally, human factors studies have also reported how cobots promote a human-centric approach in manufacturing by prioritizing safety, enhancing capabilities, and boosting job satisfaction, eventually increasing operators' well-being [19].

Digital Twin (DT). DT technologies are essential components of smart manufacturing [20]. They integrate physical and virtual spaces by connecting physical and virtual data, allowing for modeling of various production system parameters across different levels, from assembly processes to entire production lines [7, 20]. DTs facilitate dynamic updates, enabling real-time synchronization with the physical system by synthesizing data from multiple 2D–3D sensors [10]. This capability empowers manufacturers to make informed decisions and optimize operations based on up-to-date information about the production process. Consequently, DTs play a crucial role in smart manufacturing by bridging the gap between physical and virtual realms, enabling enhanced monitoring, analysis, and control of manufacturing operations [20].

DTs offer significant benefits from a worker-centered perspective as well. Specifically, they enhance workplace safety by enabling predictive maintenance and hazard identification. Additionally, DTs foster collaboration between humans and machines, creating a more integrated work environment, and they empower workers with data-driven recommendations, improving decision-making and efficiency [20].

Extended Reality (XR). A particularly promising scenario involving industrial cobots and DT sees XR technologies as valuable interfaces allowing users to easily interact with both the physical and virtual elements of industrial systems. For instance, Augmented Reality (AR) overlays virtual information onto the real environment, revolutionizing how we interact with our surroundings, blurring the lines between the physical and digital worlds, and therefore representing a powerful technology to be integrated with DTs [8] [23]. This integration enhances production flexibility, worker safety, and performance, while immersive AR systems help operators comprehend and manage complex systems more effectively, driving productivity and advancing smart manufacturing practices [10, 24]. Overall, AR-based DTs place humans at the center of industrial processes, supporting workers in highly flexible environments and augmenting their abilities to meet the demands of Industry 5.0 [8, 10, 23, 24].

2 RELATED WORKS

Various technical frameworks and models have been developed to facilitate the integration of cobots, DTs, and, oftentimes, XR technologies. For instance, Xu and colleagues [22] demonstrated a notable framework focused on cloud-based communication and control in industrial robotics. Remarkably, they effectively tackled the obstacles associated with real-time data exchange and control in distributed robotic systems [22]. Similarly, an example of DT frameworks developed to facilitate the deployment of robots in challenging environments is unfolded by Mo and colleagues [13]. They assessed the framework through a navigation task utilizing a robotic machine, and they employed agent-centered representations to streamline relevant information and optimize deployment strategies, enabling robust and adaptable robot deployment in various industrial settings. Moreover, DTs have been utilized to monitor and adapt robots' behavior in flexible assembly lines, enabling seamless production line changes and optimizing operational efficiency. These frameworks empower manufacturers to make informed decisions and adapt quickly to changing production demands [7].

However, studies detailing the engineering of industrial DT involving cobots and XR are scarce. In the realm of on-site robotic construction processes, one example was provided by Ravi and colleagues [17], who developed an XR interface to provide real-time feedback on construction progress. By integrating DT representations with immersive visualization in XR environments, this interface enables stakeholders to visualize and interact with virtual models of construction processes [17]. Similarly, AR-assisted robot programming systems have been developed to simplify task definition and interaction for users with limited programming knowledge. By transforming the robot work cell into an augmented reality environment, these systems enable users to define 3D points and paths for real robots to follow, enhancing user interaction and programming efficiency in industrial applications [10]. While this literature represents crucial advancements from a technical standpoint, it seems to lack a human-focused discussion, resulting in mainly robot-centric outcomes.

Overall, the versatility of DT technology spans various domains, yet the existing literature overlooks significant aspects such as: (a) documenting practical models within these domains; (b) providing detailed descriptions of DT implementations for complex systems involving XR technologies; and (c) discussing human-centered applications and impacts.

To bridge these gaps, our study aims to offer comprehensive technical insights and details essential for understanding and implementing DT frameworks effectively in practical settings, with a keen focus on human-centric considerations.

3 TECHNICAL PRESENTATION OF OUR AR-BASED DT FRAMEWORK

This section presents our framework designed and developed for integrating DT and AR in industrial settings. Figure 1 illustrates the physical setup of the framework, comprising three main components: the Cobot (client A), the DT (Server), and the Head-Mounted Display (HMD) (client B).

3.1 Hardware and Software Specifications

The framework comprises four hardware components: the server, cobot (client A), HMD (client B), and haptic gloves for the AR environment. The hardware specifications are detailed as follows: **Server:** MSI GP76 Leop ard with Ubuntu 22.04.3 LTS, equipped with an 11th Gen Intel(R) Core(TM) i7-11800H processor, 32.0 GB of RAM, and NVIDIA® GeForce RTX 3070 GPU 8GB GDDR6. The server runs Unity LTS 2022.3.16f1. **Cobot (client A):** Universal Robot UR10e with polyscope version 5.11. **HMD (client B):** Oculus Quest 3 with firmware MetaQuest build version 63.0, running Unity LTS 2022.3.16f1. **Haptic Gloves:** bHaptics TactGlove DK1.

3.2 Framework Design

The framework comprises three entities: one server and two clients, as depicted in Figure 2.

3.2.1 Server - DT. The server, operating on Ubuntu, utilizes Python for code implementation. It functions as a TCP/IP server, facilitating information exchange between the two clients. Utilizing the RTDE communication protocol, the server communicates with the cobot UR10e, obtaining its joint positions to update the DT's state in real time. Furthermore, the server checks the target position defined by client B and commands the cobot to move the Tool Center Point (TCP) accordingly.

3.2.2 Client A - Cobot. Client A, representing the cobot, does not require specific code as it is controlled remotely by the server. Safety regulations, including spatial limits and speed and acceleration constraints, are defined during the cobot's installation phase and managed automatically by polyscope.

3.2.3 Client B - HMD. Client B, running on the Oculus Quest 3, is developed using Unity C#. It establishes a TCP/IP communication socket with the server, receiving actual joint positions of the cobot from the server. Client B updates the representation of the cobot in the AR space and manages user inputs and interactions with the UI. Furthermore, it sends control commands to the server for execution by client A. Client B provides multimodal feedback to the user, including audio, visual, and haptic feedback, enhancing user experience and interaction. Additionally, it leverages HMD functionalities for spatial awareness and scene understanding in the augmented space. Figure 3 presents a high-level UML representation of the framework's main blocks, summarizing the explanation above.

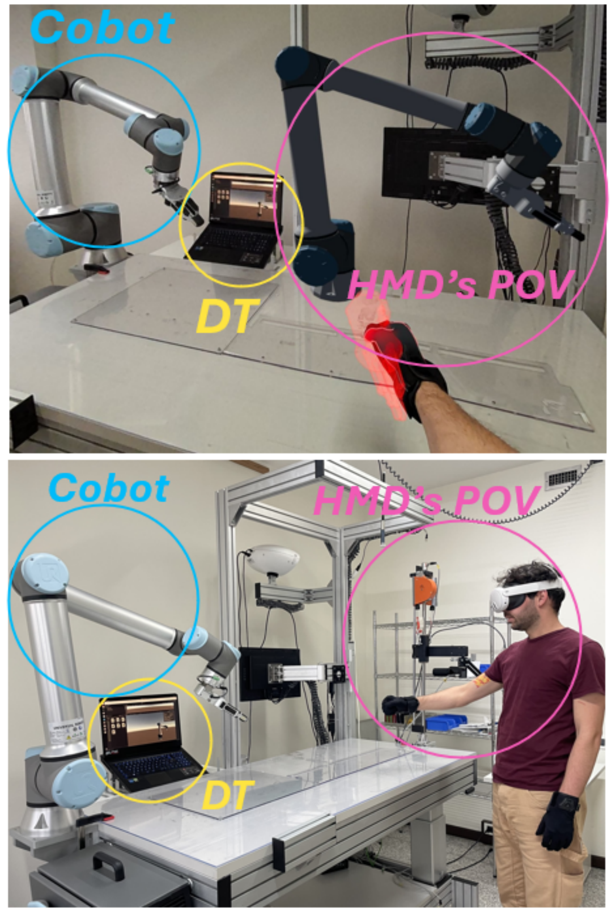

Figure 1: The physical configuration of the framework, depicting the three primary components: the Cobot (client A), the DT (Server), and the HMD (Oculus Quest 3, client B). The server oversees the status of the DT and facilitates the exchange of information between the two clients to replicate the physical cobot and issue commands from the virtual subspace.

4 FRAMEWORK EVALUATION

4.1 Evaluation Metrics

Our assessment of the framework primarily focuses on two key metrics: responsiveness and spatial accuracy. These metrics are pivotal in gauging the system's performance and effectiveness.

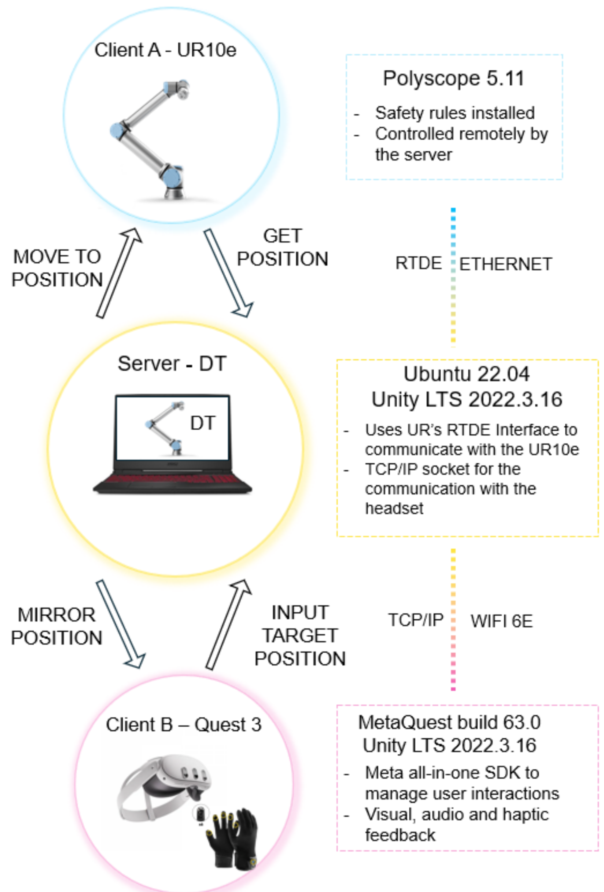

Figure 2: High-level graphical depiction of the framework's design, delineating the communication flow between the server and clients. The server orchestrates communication between the clients, retrieving real-time joint positions from the cobot (client A), updating the DT model, and projecting the DT into the AR space of the HMD (client B).

Responsiveness. Responsiveness is assessed in terms of time delays incurred during various stages of operation. The total time delay encompasses several components, namely:

- *HMD processing time* (T_H): The duration required by the Oculus Quest 3 to process the input command pose and provide visual feedback once the cobot initiates movement.
- *HMD-server round-trip time* (RTT_{HS}): The time taken for a TCP/IP packet to travel from the Oculus Quest 3 to the server and back, facilitated through the wifi 6e physical layer.
- *Server processing time* (T_S): The time expended by the server to interpret messages from clients and forward them accordingly.
- *Server-cobot round-trip time* (RTT_{SC}): The duration for a TCP/IP packet to transit from the server to the cobot and return, facilitated via the Ethernet physical layer.

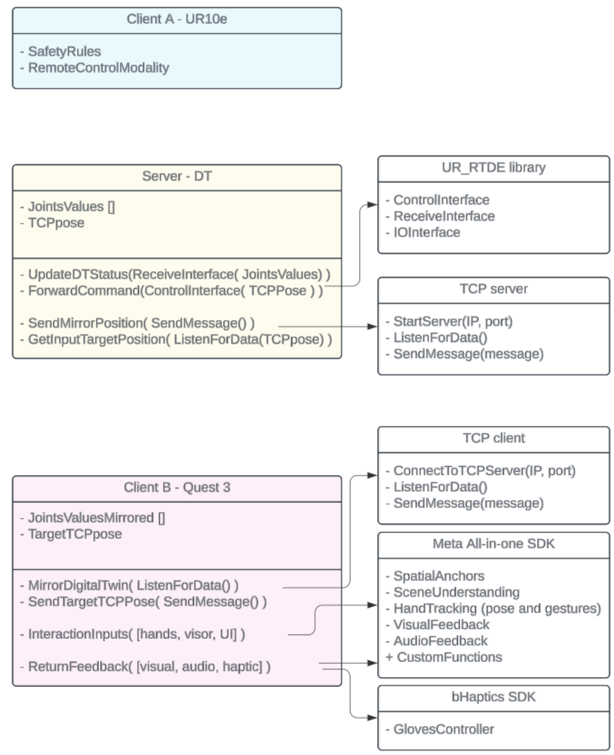

Figure 3: High-level UML representation illustrating the framework's design, encapsulating the primary components of the system. The server employs the UR_RTDE library for cobot control and utilizes TCP/IP libraries for communication with the HMD. Client B utilizes TCP/IP libraries for server communication, along with bHaptics and Meta SDKs to facilitate user interactions and feedback.

- *Cobot processing time* (T_C): The time required by the cobot to process the command, commence the action, and communicate successful initiation.

The representation of these delays and the methodologies employed to measure them are depicted in Figure 4. Profiling of code segments (P_n) within the HMD and server, as detailed in the figure, facilitated computation of processing times (T_H, T_S, and T_C), wherein communication delays were subtracted to yield precise processing times. Moreover, round-trip times (RTT_{HS} and RTT_{SC}) were measured by utilizing the ping function within Ubuntu's command line, exchanging 100 packets of 64 bytes each, and subsequently calculating average RTT and standard deviation.

Spatial Accuracy. To evaluate spatial accuracy, we computed the position accuracy of the DT representation's end-point in AR relative to the input pose received from the HMD. This assessment involved measuring the Euclidean distance and angle between the target TCP pose from the input and the actual TCP pose in AR. Unity's built-in functions facilitated this computation, with 100 poses provided as input to the system, followed by calculation of average and standard deviation of the measurements.

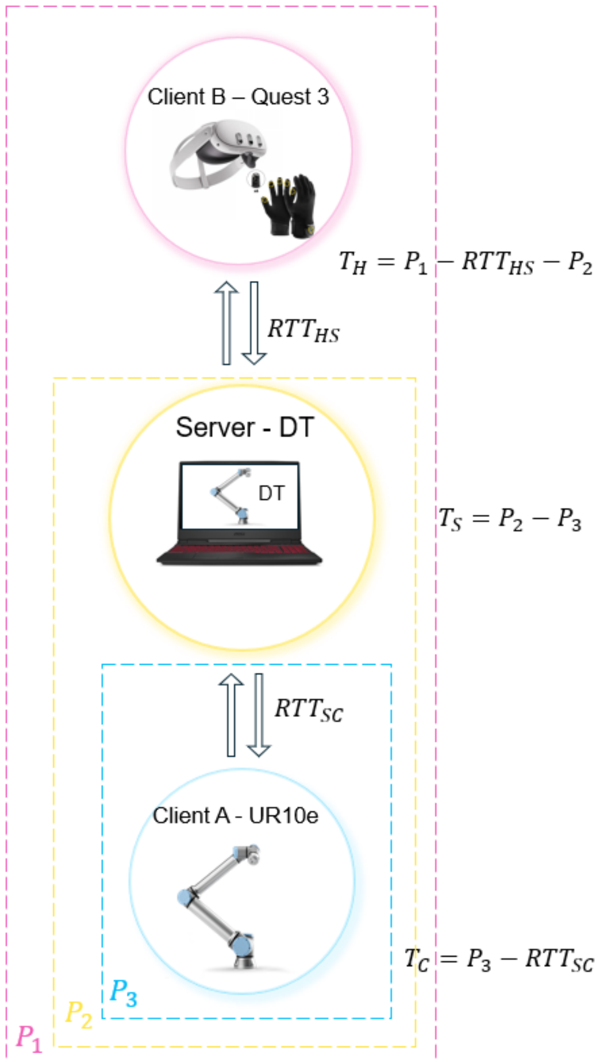

Figure 4: The figure illustrates the various delays within the system, accompanied by the methodologies utilized for their assessment. Denoted as P_1, P_2, and P_3, these profiles represent the analyses conducted on specific code segments. Specifically, P_1 quantifies the interval from user command input to the updating of the DT representation in the augmented subspace. P_2 evaluates the duration from server receipt of command from client B to the initiation of position transmission to client B. Conversely, P_3 is determined by measuring the time from server initiation of command transmission to the cobot's receipt of a successful flag. Additionally, round-trip times ($RTTs$) are calculated using Ubuntu's ping function, while T_H, T_S, and T_C are deduced from differences between P_n and $RTTs$.

	AverageTime [ms]	StandardDeviation [ms]
P_1	27.68	6.56
RTT_{HS}	10.34	4.12
RTT_{SC}	0.11	0.015
P_2	8.12	3.15
P_3	3.29	0.16
T_H	9.22	-
T_S	4.83	-
T_C	3.18	-

Table 1: This table presents the results of measuring various performance metrics for system interaction. P_1 represents the total delay perceived by the user, with an average time of 27.68 milliseconds and a standard deviation of 6.56 milliseconds. Additionally, the table includes, RTT_{HS},RTT_{SC}, P_2, P_3 along with their respective average times and standard deviations. Finally it presents the average times for the computed T_H, T_S, T_C.

4.2 Results

Responsiveness. Of paramount importance is P_1, representing the total delay perceived by the user during system interaction. For P_1, the average time recorded was 27.68 milliseconds, with a standard deviation of 6.56 milliseconds. Additional statistical data is presented in Table 1.

Position Accuracy. Regarding the pose, the average Euclidean distance measured 5.32 millimeters, with a standard deviation of 2.30 millimeters. Additionally, the average angle of difference amounted to 0.20 radians, with a standard deviation of 0.011 radians.

4.3 Technical discussion of our AR-based DT framework

4.3.1 Measures. Delay times provide significant insights into system behavior and are utilized in this study as a metric for responsiveness. P_1, representing the total delay, remains well below 100 milliseconds, a threshold typically considered instantaneous from a human perspective [18]. Both the average RTT_{SC} and its standard deviation are notably smaller than RTT_{HS}, primarily due to the wired physical layer employed in the former case and the wireless layer in the latter. The wired layer not only ensures faster communication but also enhances stability and robustness. Meanwhile, T_H accounts for the majority of processing time, as most functionalities are provided by the HMD.

The minor discrepancies in spatial accuracy stem from inaccuracies in the dimensions of the cobot's arms within the DT. The server retrieves joint angle values from the cobot and the target TCP pose from the HMD. Inaccuracies in arm dimensions result in erroneous computation of direct and inverse kinematics, leading to slight differences in positions. Although these differences are negligible in most use cases, further refinement of the internal model could improve accuracy.

4.3.2 Technical Choices. The selection of the Oculus Quest 3 HMD was based on its unique features, particularly its advanced pass-through capabilities, distance sensor, and scene understanding capability, making it ideal for AR applications. Additionally, its support for wifi 6e facilitates smooth interactions with the system by leveraging the fastest wireless communication available in the market. The robust hand-tracking capability enables natural and intuitive interaction in AR, even when wearing haptic gloves. Moreover, integration with the Meta all-in-one SDK provides advanced interaction capabilities. The choice of the PC for the server and the UR10e cobot reflects their state-of-the-art status in their respective fields.

The fundamental concept of the framework revolves around leveraging existing SDKs and libraries. Components such as the Meta All-in-one SDK for Oculus Quest interactions, bHaptics SDK for managing haptic gloves, UR_RTDE library for cobot communication, and TCP/IP libraries for socket instantiation are readily available in the market and freely accessible. This approach makes the framework accessible to everyone without requiring additional components. As a result, technical choices were influenced by the compatibility of components. Notably, the UR_RTDE library's lack of compatibility with Android-based embedded or Windows-based systems necessitates server-based communication management. Additionally, the haptic gloves' SDK is currently only programmable on Windows systems, necessitating the deployment of the client from Windows.

5 HUMAN-CENTERED IMPACTS AND DISCUSSION

5.1 XR-based DTs' impacts on human labor and work routines

Looking ahead, our AR-based DT framework opens up several possibilities for human workers. Among those, it can potentially revolutionize training and onboarding processes by providing immersive learning experiences, possibly improving task performance, decision-making, and operators' safety. AR-based DT can also make remote collaboration seamless, and it can provide real-time assistance and guidance through AR overlays. For instance, it can enable experts to support workers from afar, shortening the perceived distance between operators and maintainers and assisting the operators with visual aids and audio assistance that can significantly speed up maintenance, repair, and quality control tasks. By leveraging visual aids, also data visualization and analytics can be made more accessible, empowering workers with actionable insights throughout the workflows. As only a few studies have started to explore such application cases with DTs and XR technologies (e.g., [4, 16]), further user studies involving our AR-based DT framework could provide practical insights in this direction.

5.2 Psychological and cognitive perspectives on the human factors involved in XR-based DTs' adoption

Besides the impacts that our AR-based DT may have on human workflows and work routines, a more subtle psychological and cognitive impact is worth further discussion. Indeed, while the whole design and development of our framework have been conducted in compliance with a human-centered perspective, human-centered tests and detailed assessments including behavioral and psychological aspects of the workers using such technology can better inform levels of User eXperience (UX), perceptions, psychologically and cognitive dynamics. These factors are known to be of high importance for ensuring workers' well-being [5], and become particularly relevant when regarding the usage of new technologies like our AR-based DT. Indeed, integrating novel devices into traditionally physical and hand-based workflow may impact users' mental and physical loads, also depending on UX aspects, on their dispositional trust, eventually affecting the overall technology acceptance. Similar studies were conducted on users interacting with immersive XR simulations of cobots (e.g., [14, 15]), but more rarely on fully running DTs. Yet, understanding human factors related to the practical usage of AR-based DTs holds promise for various reasons, including ensuring high levels of workers' acceptance of the new systems and low levels of workers' cognitive demand, and enhancing the overall system's ergonomics, creating personalized and adaptive interfaces that enhance user satisfaction and task performance in industrial environments. In the end, only by considering the unique needs and preferences of end-users such advanced DTs can streamline workflows and promote a more harmonious human-technology interaction.

6 CONCLUSION AND FUTURE WORKS

This study has showcased the potential of AR-based DT systems in facilitating human-machine interaction, laying the groundwork for future research in this domain. The framework's evaluation demonstrates its effectiveness in monitoring and controlling robotic systems within industrial settings. Additionally, the technical discussion sheds light on the framework's design and implementation, emphasizing its adaptability to modern industrial challenges. While a human-centered approach has guided the design process, a further discussion of the practical applications, and psychological and cognitive impacts of these technologies has augmented the technical presentation of our framework, providing a truly human-centric perspective.

Future research may focus on optimizing interaction modalities and feedback mechanisms for AR models of cobots to enhance UX and system effectiveness. Exploring multimodal feedback, incorporating visual, auditory, and haptic cues, or investigating singular modalities, could provide valuable insights. Prioritizing the measurement of human factors, performance metrics, and cognitive dimensions related to our framework is also crucial, requiring user studies, surveys, and experiments to understand behavior, performance, and subjective experiences. Further assessing the impact of our framework on human productivity, safety, and well-being in industrial contexts, including measures of task efficiency, error rates, user satisfaction, and cognitive workload, can also provide practical insights. Finally, examining cognitive and psychological effects, such as cognitive load and user trust, associated with interacting with AR models of cobots, has the power to deepen our understanding of human-centric aspects, thereby further advancing human-machine interaction in a human-centric fashion. In doing so, we aim to advance the state of the art both from a technical and engineering perspective and from a human-centered one, fostering a more seamless and symbiotic relationship between humans and machines in industrial environments.

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