Multi-platform interactive digital twins for better data intelligibility and collaborative decision support

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Short abstract:

This thesis aims to design and evaluate ergonomic and interactive interfaces for Digital Twins (DT) to enhance the intelligibility of the complex data they provide and facilitate decision-making, particularly in a collaborative context. Building on the advancements of the CNRS@CREATE DesCartes project on urban digital twins (DesCartes Program - Francisco Chinesta: "Nous débutons les démonstrateurs du programme DesCartes" - CNRS@CREATE) and integrating into the ITTAI [1] alliance for resilient territories, this research project will examine the contribution of interactivity compared to static visualizations and will compare the impact of different media (virtual reality, augmented reality, traditional screens, etc.) on the understanding of the information provided by a digital twin. A particular focus will be placed on user collaboration around the digital twin, assessing how a shared virtual environment can support collective decision-making. Finally, a specific innovative feature aimed at increasing the effectiveness of the digital twin will be defined and integrated during the thesis (e.g., an intelligent analysis assistant or an additional interactive simulation tool). The candidate, with a background in cognitive psychology, will be based at LAMPA in Laval and co-supervised by experts in numerical modeling (CNRS, PIMM) and virtual reality (LAMPA), ensuring an interdisciplinary approach. This project is positioned at the heart of the PEPR eNSEMBLE program (Future of Digital Collaboration), exploring new forms of immersive digital collaboration to improve the understanding and use of complex data, thereby contributing to the redefinition of tomorrow's collaborative tools, notably in augmented engineering applications.

[1] L'alliance ITTAI a la mission d'apporter une contribution majeure au plan de planification écologique national par Le développement d'une méthodologie novatrice de conception et développement de solutions et de systèmes pour l'environnement et la société.

Short description of hosting research group / lab:

The LAMPA laboratory (UMR Arts et Métiers), and more specifically its Presence & Innovation team on the Laval campus, specializes in the study of immersive technologies (virtual reality, augmented reality, 3D interfaces) and their impact on user experience and human performance. Located at the Laval Virtual Center, LAMPA-Laval is recognized for its work in cognitive ergonomics applied to virtual environments, particularly through the iPerform Research Chair dedicated to collaborative performance via immersive technologies (Chaire iPerform : la Performance Collaborative via les technologies immersives et les mondes virtuels | Arts et métiers). The researchers at LAMPA combine expertise in engineering, virtual reality, and human factors to innovate in the design of user interfaces tailored to the needs of industry and society. The PhD candidate will benefit from a cutting-edge research environment, with access to immersive platforms (VR/AR systems, simulators) and experienced supervision in UX for virtual worlds. In parallel, the co-supervisor at the PIMM laboratory (Processes and Engineering in Mechanics and Materials, Arts et Métiers Paris, UMR CNRS) will provide expertise in mathematical modeling and industrial digital twins, while collaboration with Beatriz Moya and Francisco Chinesta will offer a direct connection to large-scale digital twin developments. This synergy between human sciences (cognitive psychology, ergonomics) and engineering sciences (numerical simulation, VR) within the project will ensure a holistic approach to the research topic.

Description of the PhD proposal (3 pages max)

Digital twins are dynamic representations of physical systems that allow for the simulation, prediction, and optimization of their operation. According to the most recent official definition offered by the AAAIA (American Institute of Aeronautics and Astronautics), a digital twin is necessarily composed by a physical asset, a digital (virtual) representation of the physical entity, and a one, or two-way, flow of information from the real counterpart to the virtual replica to appropriately mimic the behavior of the real-twin, and perform actions in case of developing control applications. However, several definitions exist in other domains such as in project and production management (Grieves, 2002). This fact demonstrates the importance of digital twins across industries. They have applications in numerous industrial and societal domains, including the factory of the future, smart cities (Barresi, 2023), and energy infrastructure management. Despite the industrial and societal awareness of this technology, they pose several issues for their real usage, notably regarding the possibility of interaction with the virtual twin and its adaptivity to the environment.

On one hand, the modeling techniques behind digital replicas have progressively evolved toward more advanced representations that not only improve accuracy but also adapt to changing environmental conditions and interactions with the real replica. This paradigm shift has led to the emergence of two new types of digital twins: hybrid and cognitive twins, as shown in Fig. 1.

Hybrid twins (HT) (Chinesta et al, 2020) merge physics-based (white-box) and data-driven ML models (black-box) to form a comprehensive representation (grey-box) of physical systems, enhancing understanding and predictive accuracy by incorporating data into the modeling of the replica. Hence, HTs offer substantial advantages in terms of accurate forecasting, real-time observation, and assistance with decision-making in diverse contexts.

Cognitive Digital Twins (CTs) (Abburu et al, 2020) represent an emerging subclass of Digital Twins that incorporate cognitive-like abilities such as sensing, autonomous interaction, and smart adaptation. While current applications mimicking cognition are limited, CDTs aim to integrate these abilities to facilitate autonomous and context-aware decision-making (Zheng et al, 2022). CDTs use data for complex interpretation and adjustment of performance through autonomous decision-making and user interactivity (Moya et al. 2022, Moya, Badias et al. 2022). An expert-in-the-loop is essential in complementing the CDT's cognitive and interoperability requirements, enhancing model explainability and decision rationale comprehension throughout various interaction phases.

Human in the loop digital twins (HiLDTs) is a concept closely related to that of human in the loop cyber-physical systems (HiLCPS) (Cuckov et al., 2017, Poursoltan, 2023). In both cases, humans are included in the feedback and decision-making cycle of the tool. The decisions and interaction between the human and the twin will affect the operation of the system. As a result, they have the purpose of enhancing human interaction with the physical environment.

Cognitive Twins together in a HiLDTs paradigm enable intelligent, adaptive, and safe environments where human decision-making is enhanced by real-time data and advanced AI-driven insights (Liang, Moya et al. 2024).

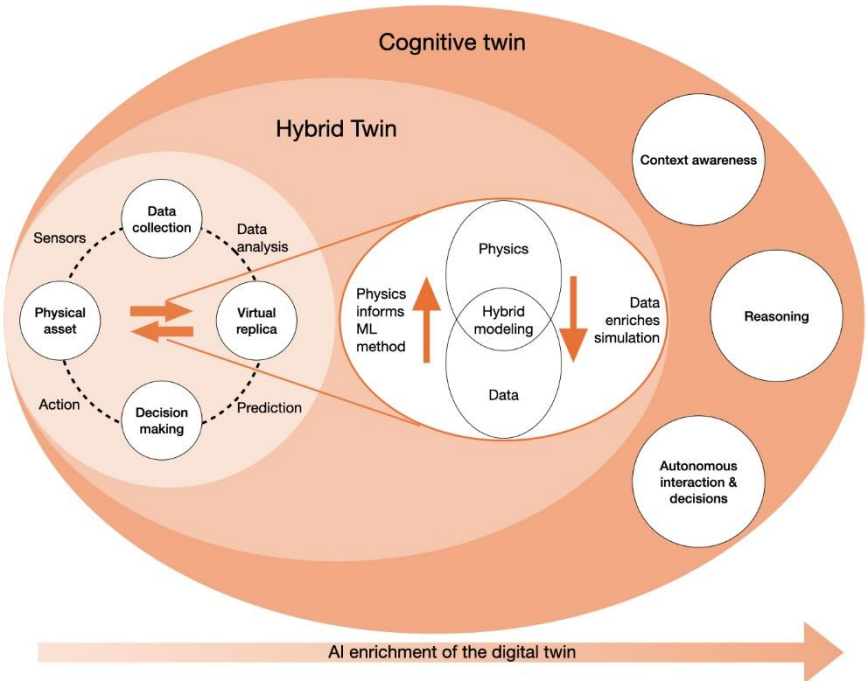

Fig 1. Representation of the digital twin landscape and the enrichment of digital twin representations to hybrid and cognitive twins, involving high-end simulation, adaptation, and interaction. From Liang, Moya et al. 2024

Visualization has evolved alongside the increasing complexity and use of digital twins for interaction. As a result, the representation of information and the ability to interact with it have become essential components of digital twins, particularly hybrid and cognitive twins. Notable examples of this include augmented engineering applications, decision-making tasks for environmental tools, such as heat island strategy design and drone planning. However, the complexity and heterogeneity of the data they provide pose a significant challenge in terms of intelligibility.

A proper understanding of the information generated by digital twins is essential to enable users to make informed decisions. This need is particularly critical in collaborative contexts, where multiple users must interact with the digital twin simultaneously. The way in which this information is presented and explored directly impacts the quality of the decisions made. Yet, most current digital twins rely on traditional interfaces (dashboards, static visualizations) that do not allow for seamless interaction with complex data.

The PhD project aims to explore how to enhance the intelligibility of digital twins through interactive and immersive interfaces, considering both individual user needs and group dynamics in collaborative settings.

To achieve this objective, the project is structured around three main phases:

1. Studying the impact of interactivity on data comprehension and decision-making. Unlike other forms of data presentation, digital twins allow for scenario simulations and the observation of their consequences. This phase will analyze their cognitive impact to identify their strengths and limitations.
2. Analyze the required degree of adaptability of the twins to work on the development of DT application that fulfils the flexibility requirements if efficient augmented engineering tools.
3. A comparative study of devices, including immersive technologies such as virtual and augmented reality, to situate data within the appropriate context (Christmann et al., 2022). This will help identify the most effective tools for collaboration around complex interactive data.
4. Design and evaluation of an additional functionality aimed at improving data intelligibility within the digital twin. This could involve integrating generative artificial intelligence to guide users or implementing differentiated interfaces to enable asymmetric collaboration (Agnès et al., 2023).

Real-world industrial use cases for this PhD project, which aims to produce generalizable findings, will be considered in collaboration with the company Duoverse to foster the transference of the results obtained in the context of the PhD thesis. A focus will be made on environmental tools, and an analysis of the needs of the users and the territories. The research will follow an experimental cognitive ergonomics approach, inspired by the design methodology of Fleury & Chaniaud (2023) for collaborative tool development.

In terms of timeline, the project includes six months dedicated to a scientific literature review and familiarization with existing tools and projects. Three experiments (one per phase) will be conducted, leading to articles and conference presentations in international venues, with each experiment lasting approximately eight months. Finally, the last six months will be devoted to writing the dissertation.

Nature of digital collaboration (1 page max)

The collaboration studied in this project is a synchronous interdisciplinary collaboration assisted by an interactive digital twin. More specifically, it is a human-to-human collaboration mediated by a shared virtual environment representing a real system (e.g., a modeled urban territory). The function of this digital collaboration is to allow multiple decision-makers or analysts to jointly understand a complex situation and make informed collective decisions, based on the visualizations and simulations provided by the digital twin. This can be described as simulation-assisted decision collaboration.
Each collaborator may have a different role (technician, expert, elected official, etc.), and the digital twin serves as a common support for exchanging information, discussing "what-if" scenarios, and constructing a shared understanding of the problem to be solved. Thus, the purpose of digital collaboration here is to enhance collective decision-making by providing a shared virtual space for reflection, akin to a digital crisis room where participants can interact with a central digital model.
The primary time scale considered is real-time synchronized collaboration (e.g., an interactive working session lasting 30 minutes to 2 hours, during which participants explore the digital twin live). However, asynchronous modalities could also be considered as a complement (e.g., a user leaves annotations that others will review later), but the core of the project focuses on real-time interactions.
Regarding group size, the target is small collaborative groups, typically 2 to 5 people. The main scenarios include duos or trios of experts working together or a small team of decision-makers. This limited size aligns with technical constraints (as large-scale multi-user VR remains complex) and enables detailed observation of interactions. However, findings from the study could be extrapolated to slightly larger groups if necessary (e.g., a participatory workshop with participant rotations on the digital twin).
The project will examine several collaborative configurations: Co-located collaboration, Remote collaboration and Hybrid collaboration

1. Co-located collaboration
All participants are in the same physical space (e.g., a meeting room equipped with a large touchscreen or an automatic 3D cave system), allowing for direct verbal communication in addition to using the digital tool. The digital twin can be displayed on a central device (screen, interactive table) that participants manipulate either sequentially or simultaneously.

2. Remote collaboration
Participants are geographically distributed and interact over a network within a shared virtual world. For instance, each person wears a VR headset or uses a PC, and they meet in the virtual replica of the system, with avatars or pointers representing each participant. Communication occurs via voice chat and possibly integrated text chat.

3. Hybrid collaboration

This configuration combines both approaches: some participants are co-located (e.g., in a control room with a large screen), while others connect remotely (e.g., via a mobile AR device on the field or in VR from another site).
Special attention will be given to this hybrid situation, as it is very common in real-world scenarios (e.g., an off-site expert consulted while a team operates on-site). Each configuration presents slightly different challenges (e.g., control sharing, dialogue fluidity, and context management).
To address these challenges, the digital twin must be designed as a flexible collaborative workspace, supporting both physical co-presence (e.g., multi-user interactions on a shared screen) and virtual telepresence (e.g., joint immersion in VR), in alignment with the interoperability and openness objectives of the eNSEMBLE project.

Contribution to digital collaboration: Expected results and Impact (1 page max)

On a theoretical level, this research will deepen our understanding of the cognitive processes involved in interpreting the complex information provided by digital twins. By leveraging principles from cognitive psychology, the study will explore how users perceive, process, and comprehend data generated by these digital representations. It will identify key cognitive factors that influence individuals' ability to interpret complex visualizations and make informed decisions. Expected outcomes include a model of the specific cognitive processes associated with interactions with digital twins, thereby enriching existing literature on human cognition in advanced technological environments.

On a practical level, the research will lead to concrete recommendations for designing more ergonomic and user-centered digital twins. These recommendations will focus on the optimal integration of immersive technologies to enhance data intelligibility and facilitate collaboration. For example, the study will provide guidelines on the most suitable media types depending on the nature of the data being presented. Furthermore, the thesis could result in the development of a prototype incorporating an innovative feature, such as an intelligent analysis assistant using artificial intelligence to guide users in interpreting complex data. This technical contribution will demonstrate the feasibility and potential benefits of integrating such functionalities into digital twins.

The findings of this research will have a direct impact on professional practices, particularly in sectors where digital twins are used to manage complex systems, such as manufacturing, urban planning, and energy infrastructure. By providing more intuitive interfaces and facilitating collaboration, professionals will be able to make more informed and effective decisions, thereby reducing errors and improving operational efficiency. The recommendations from this thesis could also be integrated into professional training programs, fostering better adoption of immersive technologies across various industries.

Positioning in the eNSEMBLE program (½ page max)

The PhD project is closely aligned with the objectives of Targeted Project 1 (PC1) titled "CATS - Collaboration Spaces" within the PEPR eNSEMBLE program, which aims to redefine digital tools for future collaboration. PC1 focuses on the diversity of devices and interaction modalities for heterogeneous collaboration spaces.

The PhD project proposes to explore the impact of different immersive media, such as virtual reality (VR) and augmented reality (AR), on the comprehension of information provided by digital twins and on user collaboration. This exploration directly addresses PC1’s objective of considering a variety of devices and interaction modalities for heterogeneous collaboration spaces. By evaluating how these immersive technologies influence users' perception and interaction with complex data, the research will help identify the most suitable tools for different collaborative contexts.

The PhD project also aims to investigate hybrid collaboration configurations, combining co-located and remote participants, which aligns with PC1’s concerns regarding the flexibility of collaboration spaces. By analyzing how digital twins can facilitate seamless interaction

between users in different physical environments, the research will contribute to the design of more adaptive and resilient collaboration spaces.

Planned expenses

This is an interdisciplinary project, based on co-supervision between a researcher in cognitive psychology and interface ergonomics, and a pair of researchers specializing in the technical and mathematical aspects of digital twins. We hope that the candidate will be able to spend time in both laboratories. The 10K grant will therefore be partly dedicated to this purpose, but also to financing an international conference and the computer equipment needed for the experiments.

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