Human-Centered Design of Digital Twins for Ambient Assisted Living

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***Abstract*—This work presents a human-centered conceptual architecture for DT-based Ambient Assisted Living systems aimed at fostering sustainability and engagement. Here, two interconnected DTs are integrated: one representing the elderly individual and another representing the smart home environment. End-User Development supports long-term sustainability by empowering caregivers to configure smart home behaviors in response to changing needs, while engagement is promoted through Explainable Artificial Intelligence and gamification strategies.**

***Index Terms*—Sustainability, end-user development, gamification, explainability**

I. Introduction

Population aging and the increasing prevalence of chronic diseases pose significant challenges to healthcare and social care systems [1]. Ambient Assisted Living (AAL) has emerged as a promising paradigm for supporting independent living through pervasive, intelligent technologies [2], [3]. In this context, Digital Twins (DTs) are gaining attention as innovative tools for the real-time, dynamic representation of individuals and their surrounding environments by integrating data from wearable and ambient sensors [4]. This capability supports real-time monitoring, early detection of health risks, and personalized assistance. However, as DTs become increasingly autonomous, concerns arise regarding the potential reduction of human agency and over-reliance on algorithmic decision-making in care processes. There is, therefore, a growing need to design DT-based AAL systems that are human-centered, ensuring transparency, trust, and collaboration among elderly people, caregivers, healthcare professionals, and intelligent technologies. Indeed, research on digital twins across domains such as manufacturing, urban design, smart cities, education, and healthcare often treats users as passive recipients of data or as mere process supervisors [5]. In this way, several works address technical issues related to machine learning algorithms and big data management [6], [7]; when users are considered, research focuses mainly on information visualization with traditional or immersive interfaces leveraging extended reality; thus, the field lacks suitable methodologies for designing meaningful interactions between users and digital twins [8].

In this extended abstract, we present a conceptual architecture that, beyond guiding the development of a system in the AAL domain, will inform a human-centered methodology for designing *sustainable* and *engaging* digital twins of smart environments.

The final goal of this AAL project is to develop a socio-technical system that interacts and co-evolves with the *elderly* being monitored and supported in their independent living, and the *caregivers* (family members, nurses, care assistants) who must shape the smart environment to tailor its behavior to their and the elderly's needs. *Sustainability* is here conceived as a broad term that encompasses not only health, well-being, inclusivity, decent work, and innovation, but also the long-term management of AAL systems after their installation and configuration by hardware/software professionals. *Engagement* is pursued to motivate users to participate in shaping the system and to use it in the long term.

After delineating the conceptual system architecture, this extended abstract will focus on the methods we plan to integrate for supporting sustainability and engagement, namely end-user development, explainable artificial intelligence, and gamification.

II. Conceptual System Architecture

We propose a conceptual system architecture (see Figure 1) encompassing i) the DT of the elderly individual, which contribute to the collection of physiological, behavioral, and contextual data through the use of sensors and wearable devices, and provide access to the gathered data, properly visualizing and explaining them; and ii) the DT of the smart home where the elderly individual lives, allowing the caregiver to simulate, monitor, and configure smart device behaviors and automation rules. The DTs can exchange data to address emerging needs and progressively adapt their behavior.

III. Fostering Sustainability with End-User Development

A DT for AAL can contribute to achieving a variety of Sustainable Development Goals (SDGs)[1], such as "Good health and well-being", "Reduced inequalities", "Sustainable cities and communities". However, the sustainability of AAL systems themselves depends primarily on their ease of use, as individuals' routines, health conditions, and needs change

[1]https://sdgs.un.org/goals

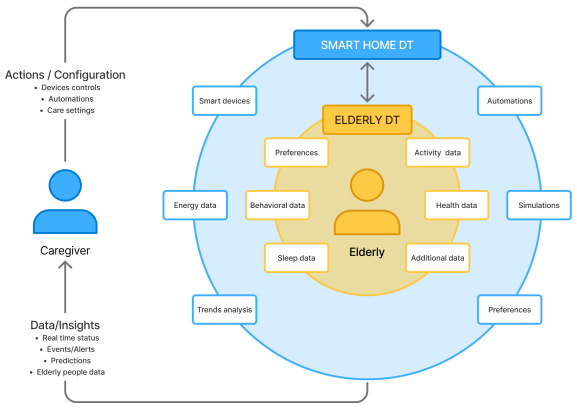

Fig. 1: Diagram representing the conceptual system architecture. In yellow is the *Elderly People Digital Twin*, while in blue is the *Smart Home Digital Twin*.

over time. End-User Development (EUD) methods and tools have been proposed to empower end users who are not experts in computer technologies, nor do they want to be, to create, modify, and adapt software artifacts [9]. In the AAL context, EUD can be exploited to support caregivers in shaping the behavior of smart environments (e.g., smart homes) to the specific and evolving needs of inhabitants. In the literature, various proposals leverage EUD based on trigger-action rules to define automated behaviors for smart environments supporting AAL (e.g., [10], [11]). However, defining the logical structures of rules is often tricky for caregivers; in addition, they may not be fully aware of the system's capabilities, which can limit their ability to shape effective, useful behaviors of the smart home.

We propose an AI-assisted EUD environment to support caregivers in configuring smart homes and defining trigger-action rules by incorporating knowledge of inhabitants' behaviors, prior system interactions, and contextual conditions. In a preliminary implementation, this environment provides suggestions based on data stored for a particular individual regarding their therapy plan and assists the caregiver in identifying conflicts or unsafe configurations during rule creation or when setting a particular device.

IV. Fostering Engagement with Explainability and Gamification

To foster caregivers' engagement, the EUD environment should implement explainability mechanisms that enable caregivers to interpret AI-driven suggestions and system decisions. The existing literature on human-centered explainable artificial intelligence (XAI), including approaches that address users' goals, mental models, and decision-making processes, has informed the design of a preliminary explanation mechanism tailored to caregivers. It features a hybrid approach that combines Large Language Models with deterministic functions to enforce structural and safety constraints [12].

The engagement of elderly individuals should also be considered as a fundamental requirement. Older adults are more likely to accept and use wearable devices when they perceive them as trustworthy, understandable, and supportive of their autonomy and well-being, thereby overcoming the perception of them as intrusive surveillance devices. For elderly users, gamification can foster both physical and cognitive engagement by encouraging motivation through personalized goals, such as daily step counts or hydration targets. Positive feedback or virtual rewards can reinforce a sense of accomplishment and encourage continued interaction with the technology.

V. Conclusion

In this extended abstract, we have delineated the conceptual architecture of a DT-based AAL system that leverages EUD, XAI, and gamification to foster sustainability and engagement. Future work might consider including health professionals in the ecosystem, who should be continuously informed about the elderly's health and safety conditions and intervene to change treatment when necessary. This might imply extending the conceptual architecture by treating each diad "elderly DT-smart home DT" as a single DT for an assisted individual, thereby making health professionals responsible for several of these diads.

References

[1] World Health Organization, "Ageing: Global population," 2025.

[2] G. Cicirelli, R. Marani, A. Petitti, A. Milella, and T. D'Orazio, "Ambient assisted living: A review of technologies, methodologies and future perspectives for healthy aging of population," *Sensors*, vol. 21, no. 10, 2021.

[3] M. Jovanovic, G. Mitrov, E. Zdravevski, P. Lameski, S. Colantonio, M. Kampel, H. Tellioglu, and F. Florez-Revuelta, "Ambient Assisted Living: Scoping Review of Artificial Intelligence Models, Domains, Technology, and Concerns," vol. 24, no. 11, p. e36553.

[4] D. Binni, A. Corneli, M. Vaccarini, and B. Naticchia, "Development of digital twin models supporting ambient assisted living," in *Proceedings of the European Conference on Computing in Construction (EC3)*, 2022.

[5] F. Vainionpää, M. Kinnula, A. Kinnula, K. Kuutti, and S. Hosio, "HCI and digital twins – a critical look: A literature review," in *Proceedings of the 25th International Academic Mindtrek Conference*, Academic Mindtrek '22, (New York, NY, USA), p. 75–88, ACM, 2022.

[6] D. Jones, C. Snider, A. Nassehi, J. Yon, and B. Hicks, "Characterising the digital twin: A systematic literature review," *CIRP Journal of Manufacturing Science and Technology*, vol. 29, pp. 36–52, 2020.

[7] C. Semeraro, M. Lezoche, H. Panetto, and M. Dassisti, "Digital twin paradigm: A systematic literature review," *Computers in Industry*, vol. 130, p. 103469, 2021.

[8] B. R. Barricelli and D. Fogli, "Digital twins in human–computer interaction: A systematic review," *International Journal of Human–Computer Interaction*, vol. 40, no. 2, pp. 79–97, 2024.

[9] B. R. Barricelli, F. Cassano, D. Fogli, and A. Piccinno, "End-user development, end-user programming and end-user software engineering: A systematic mapping study," *Journal of Systems and Software*, vol. 149, pp. 101–137, 2019.

[10] L. Corcella, M. Manca, J. E. Nordvik, F. Paternò, A. M. Sanders, and C. Santoro, "Enabling personalisation of remote elderly assistance," *Multimedia Tools and Applications*, vol. 78, pp. 21557–21583, 2019.

[11] L. Stegner, D. Porfirio, M. Roberts, and L. M. Hiatt, "Considerations for end-user development in the caregiving domain," in *Proceedings of the AAAI Symposium Series*, vol. 2, pp. 532–536.

[12] D. Fogli, L. Gargioni, and D. Guizzardi, "Who holds the agency? Meta-design in the age of generative AI," in *Proceedings of the Tenth International Workshop on Cultures of Participation in the Digital Age (CoPDA 2026)*, vol. 4216 of *CEUR Workshop Proceedings*, CEUR-WS.org, 2026.