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Digital Twin Architecture for Ambient Assisted Living

Abbas Ramadan, Florent Frizon De Lamotte, Nathalie Julien

Abstract Our goal is to enhance the day-to-day lives of elderly and disabled individuals through the use of Ambient Assisted Living (AAL) supported by a digital twin. This paper proposes an architecture for the development of a digital twin for AAL principles. We begin by introducing the concept of AAL, going through various digital twin versions, and highlighting the benefits for different users, including residents, caregivers, and technicians. Next, we describe the current AAL system and introduce a digital twin framework aligned with the ISO 23247 standard. Finally, we discuss the experiments conducted using this digital twin architecture, alongside outlining potential development paths towards a more advanced version.

Key words: Ambient Assisted Living, personal health monitoring, healthcare IT, Digital twin, Activity Recognition.

1 Introduction

As the global population ages – United Nations estimates 727 million persons aged 65 years or over worldwide in 2020, a number projected to more than double by 2050 [1] – more elderly individuals are choosing to age in place [2]. Additionally, the World Health Organization (WHO) estimates that 1.3 billion people, representing 16% of the world’s population, suffer significant disabilities [3].

Ambient Assisted Living (AAL) aims to support the independence of these individuals within their own homes. AAL systems are designed to improve the quality of life by providing digital products and services that ensure the safety, health, activity, and independence of seniors and those with disabilities [4]. Examples of such

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technologies include companion robots, home automation devices, innovative physiological sensors, and coaching services, etc.

To further enhance the benefits offered by smart homes, we propose integrating the concept of Digital Twins (DT). A Digital Twin is a dynamic, real-time virtual representation of a physical system. It enables monitoring, simulation, and optimisation of the system's performance. In this context, the Digital Twin offers opportunities to detect risk situations, identify emerging frailties, and automate scenarios based on individual habits and behaviours [5]. This approach has the potential to significantly enhance the effectiveness of home assistance and improve the quality of services provided to the elderly and disable individuals.

2 Background

This article focuses on improving solutions that help people to stay healthy and independence. It also aims to find solutions that facilitate the tasks of healthcare professionals and caregivers.

2.1 *Ambient Assisted Living*

Ambient Assisted Living (AAL) solutions address to various user groups. To gain a better understanding of their requirements, it is essential to identify the main user group. In the work of Acerbi et al [6], they elucidate the distinct roles of the human factor in Ambient Assisted Living, highlighting the functions carried out by the resident, caregivers, and IT technicians, each one is different but complementary to the others.

The resident is an elderly or disabled person who lives in the AAL environment and serves as the primary beneficiary of AAL services, where the technologies installed are defined according to his needs. By using the environment, the resident contributes participates in generating data that are used to enhance the living service after. Finally, they can communicate with healthcare professionals and technicians to alert them of any problems or needs.

Caregivers, such as physicians, nurses, and occupational therapists, are responsible for tracking the health and comfort of users and providing healthcare when necessary.

Technicians are in charge of the installation, configuration, maintenance, and technical support of systems within the environment. They ensure the proper operation of the system, solve technical problems and guarantee the security of the data and infrastructure.

2.2 Transition to Digital Twins

Digital Twin technology has mainly been used in the domain of industries, including manufacturing, aerospace, and automotive. But in recent years, this technology has been applied to healthcare.

The use of digital twin technology in AAL can provide numerous benefits for the resident, caregivers, and technicians [7]. One of the main benefits of DT is to organise the information management among users based on their roles. Consequently, it is envisaged to develop multiple DT versions customized for specific users and their specific functionalities [8].

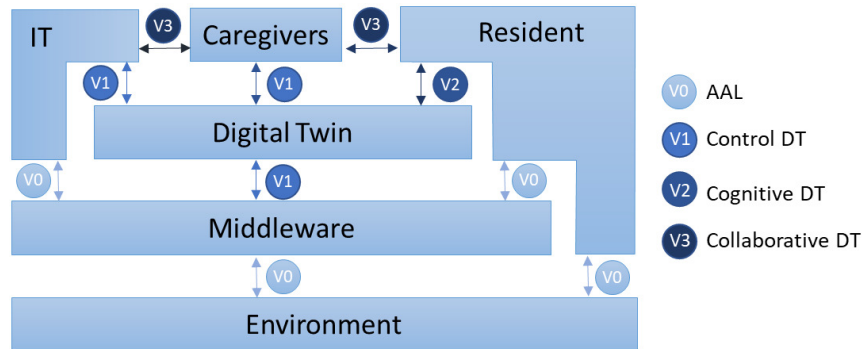


Fig. 1 Interaction between system's collaborators of the different versions of DT

Figure 1 shows the interaction among the system's collaborators according to the different versions of DT :

Version V0 represents the basic AAL system, where the technician is responsible for system installation and configuration. The resident, living in the environment, has manual control over the equipment through middleware interfaces. Caregivers can contact the resident to inquire about their health and well-being.

The introduction of Digital Twin (DT) technology in version V1 enables IT members to handle the installation and configuration process of middleware within the environment. This is achieved by creating an application that includes device information, such as identifiers, positions within the home, communication methods, and available options. This initialisation phase marks the inception of the first version (V1) of DT. The primary objective of V1 is to offer caregivers a straightforward solution for accessing individual information and monitoring the health and well-being of residents. Through this version, caregivers can easily track vital signs, monitor daily activities, and detect changes in behaviour, enabling them to provide appropriate services. V1 serves as the control version of the Digital Twin (DT) [8].

In the second version, V2, all the features from V1 are retained, with the addition of an advanced capability to automatically analyse daily activities and behaviours to predict services and life scenarios. This version introduces an application based

on augmented reality (AR) as an interface to suggest services and scenarios to the resident. Consequently, V2 can be referred to as the cognitive version.

The third version represents the most comprehensive iteration, taking on the responsibility of managing decisions and facilitating communication among different users within the system. For example, residents can easily reach out to caregivers to report issues or request assistance, while caregivers can contact technicians for necessary modifications to improve the middleware service or the DT itself. This version exemplifies the collaborative nature of the DT.

3 Configuration of DT versions

Building on the needs and objectives mentioned earlier, a phase of configuration of our digital twin will be necessary. We employ the typology proposed by Julien & Martin (2021) [9], including the following 13 criteria (presented in Table 1):

- **DT Entity:** The ISO/DIS 23247 standard defines the entity by “thing (physical or non-physical) having a distinct existence” along with the observable manufacturing element (OME) as an “item that has an observable physical presence or operation in manufacturing”. In our case the DT Entity is the apartment of assisted living.
- **Type and version:** This work will be applied in the research field, so all three versions of the digital twin will be internal. There are three different types of DT (Prototype; Instance; aggregate). The instance describes an individual object in particular related to the production/exploitation phase; this is the type of V1. The aggregate is formed by combining all the DT instances for the same entity; these are the types of V2 and V3.
- **Level:** Considering the smart apartment is composed of several pieces of equipment, it can either be viewed as a standalone system or network of systems, where each piece of the equipment is an individual system. A hybrid approach is also possible.
- **Maturity:** Digital representations are classified according to their maturity. The digital shadow represents all the digital activity of the DT entity and provides its dynamic image; where this is the case of version V1. For the second version (V2), we integrate algorithms for the recognition of the person’s daily life activity to have predictive abilities, therefore it evolves to a Cognitive DT. Finally, with more decisions and control capabilities, V3 is an upgrade to become a Collaborative DT.
- **Topology:** The topology qualifies the connection between the observable manufacturing asset and the digital twin. In our case, the DT is directly connected to its entity, but physically disjoint.
- **Decision loop:** In V1, the caregivers control the equipment but not the DT, resulting in an open loop. In the following versions, DT prediction influences decisions, leading to a mixed loop, with final decisions made by the user.

- **Users, Usages, and Applications:** According to (Standard ISO 23247, 2021) [11], appropriate interfaces must be provided to different DT users. The first version DT is intended for caregivers, that provides them with the means to monitor the resident’s activities, supervise him, and analyse his situation. The second version is intended for the resident to predict and propose future actions, making it cognitive. In the third version, the DT collaborates with all users (IT, caregiver, and resident) by comparing the predicted situation and the actual situation to adjust the environment optimally or avoid problems, so that the use of the DT is a comparison.
- **Synchronisation:** Given the variability in sensors operation modes, the DT can function in either asynchronous or synchronous modes.
- **Accuracy:** among the three types of Accuracy defined in [10] which are “fixed”, “variable” and “configurable”, the last is most relevant, as precision varies based on predetermined scenarios.
- **Models:** V1 is a monitoring version based on sensor network data, so the model is conceptual. V2 is based on the analysis of resident activity to predict actions, so the model is empirical. V3 focus on the management of tasks between the DT and users, so the model will be deterministic.

Table 1 Typology of DT versions

	V1	V2	V3
DT Entity	Smart Home		
Type	Instance	Aggregate	Aggregate
Version	Internal version		
Level	System / System of system		
Maturity	Control DT	Cognitive DT	Collaboratives DT
Topology	Connected & Disjoint		
Descision loop	Open loop	Mixed loop	Mixed loop
Users	IT, Caregivers	Other DT, Resident	All
Usages	Analysis	Control/Cognition	Comparison
Application	Monitoring	Real-time control	Diagnostic support
Synnchronization	Synchronous/Asynchronous		
Accuracy	Configurable		
Models	Conceptual	Empirical	Deterministic

4 Methodology

4.1 Current system of AAL

Our Living Lab, a hub for research projects, is equipped with a range of technologies, including intelligent home systems, home automation, and the Internet of

Things. These technologies hold the potential to enhance the quality of life within homes by improving comfort, well-being, energy efficiency, and supporting assisted living.

However, the AAL middleware is more than just a collection of automated devices and connected objects. The issue of interoperability becomes critical due to the diversity of available devices and proprietary solutions offered by different vendors. This diversity often complicates the integration of devices with varying physical layer characteristics and transmission channels.

To address these limitations, the xAAL system has been adopted. As described in [11], the xAAL system is a network of functional entities communicating via a message bus based on multicat-IP. This system is specifically designed for home automation facilities and includes the following components:

- Native equipment that can communicate using the xAAL protocol via elementary gateways, which translate messages between proprietary manufacturer protocols and the xAAL protocol.
- A database of metadata that stores device information, such as its location, friendly name, or other relevant details.
- A cache that stores at least the values of attributes carried by notifications sent by the devices and associates a timestamp with the cached information.
- User interfaces that provide various means for users to interact with the home automation system. These interfaces can be hardware devices, microphones, software components that generate web pages, REST APIs, or other types of software that grant access to the system's features.

xAAL has been developed as middleware for the AAL apartment and implemented the following set of devices:

- Standard home automation: Sensors (Motion, temperature, electrical consumption, door, bed lift, etc.), actuators for control (light, shutter, plug, adjust kitchen worktop, etc.) ;
- Robotics: companion robot, coaching robot, cleaning robot, etc. ;
- Evolved (innovative) sensors: especially the sensors allow to know information about the resident himself. For example, indoor localisation or vital signs with a system of radar or connected floor.

4.2 Digital Twin Framework for AAL based on ISO 23247

The ISO 23247 series provides a framework for creating digital twins of observable manufacturing elements, including personnel, equipment, materials, manufacturing processes, facilities, environment, products, and supporting documents [12].

Based on the analysis of the needs and interactions between the system collaborators according to the different versions of the DT (subsection 2.2), as well as the typology of each version (section 3), the framework of our DT can be defined based on the ISO 23247 standard.

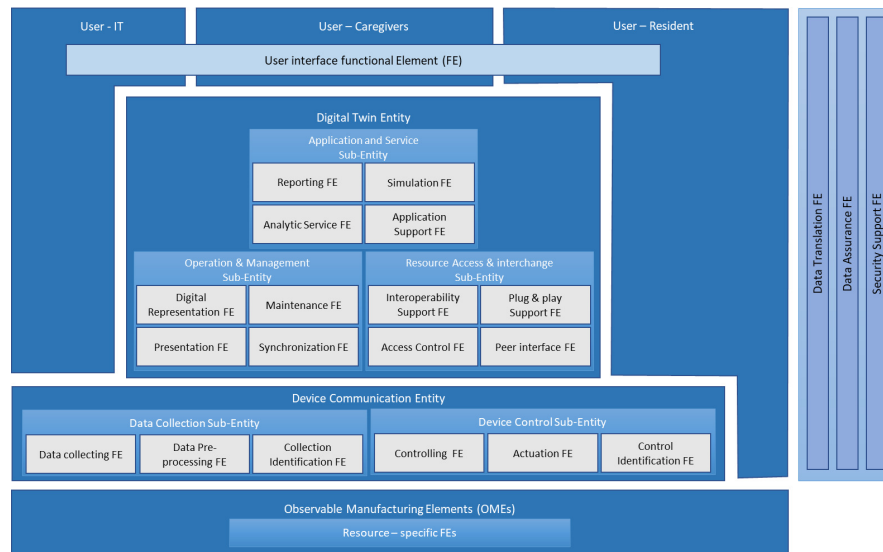


Fig. 2 The digital twin framework for AAL adapted from ISO 23247

Figure 2 represents the digital twin reference model in the ISO 23247 standards. This reference model comprises four main entities:

- The user entity, which includes all the necessary components for interfacing with the digital twin (Resident, Caregivers, IT).
- The digital twin entity, which encompasses all applications, services, operations, and management access. It serves as the core entity responsible for building models and performing simulations.
- The data collection and control entity.
- The observable manufacturing elements entity, represented by the apartment's environment. This includes equipment, materials, processes, robots, sensors, and supporting documents.

To apply this framework to an AAL operation, including functional sub-entities, different standards and technologies are used in the different steps:

- Building Information Modeling (BIM) is a method for designing, constructing, and managing construction projects using an intelligent 3D model to create and manage data throughout the building's life cycle [13]. The BIM model is used to create a detailed 3D representation of the resident's home, comprising the static part of the apartment's 3D representation. Real-time or historical equipment data can then be integrated to simulate the resident's behaviour. These standards and technologies correspond to a specific part of the sub-entity of the Digital Twin. If BIM is unavailable for an apartment, technologies such as 3D cameras can be utilised to create the 3D model, as demonstrated in [14].

- As mentioned in Section 4.1, xAAL primarily provides a service for controlling the different equipment in the environment. It records and processes data related to interactions with the person, resulting in a unified format known as Activities of Daily Living (ADLs). This service also includes applications that facilitate access management among users. Therefore, by aligning with the ISO architecture, xAAL can serve various sub-entities, including Resource Access and Interchange, Device Control, and Data Collection.
- Two essential aspects of the application and service sub-entity in the ISO are the analytic and reporting services. These services enable descriptive, diagnostic analytics to identify why specific events occurred, predictive analytics to forecast likely future events, and prescriptive analytics to determine how to make desired outcomes happen and assess the consequences.
- To support these services, our goal is to identify the Activities of Daily Living (ADLs). ADLs encompass routine activities performed daily, such as dressing, cooking, cleaning, etc. employing activity recognition algorithms and processing data generated by AAL technologies, can automatically detect and classify these activities in real-time or offline.
- applications adapted to each type of user are developed for the service. The first application is for residents to control the environment in an adapted manner and receive predictions proposed by the DT. Another application is designed for caregivers to access information and receive notifications of detected problems or risks.

5 DT Architecture and Experimentation

Building upon the requirements of DT versions, their topology (Subsection 2.2 and section 3), our existing AAL system (Subsection 4.1), and the DT framework defined by the ISO 23247 standard (Subsection 4.2), we can now propose a comprehensive system architecture, as depicted in Figure 3.

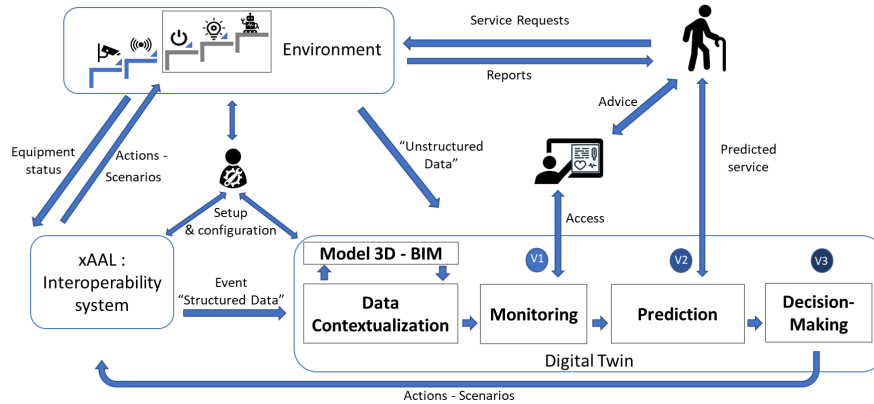


Fig. 3 System Architecture

Version 1 of DT (Monitoring and Control): For the initial version, Unity3D has been chosen as the development platform to create an application for monitoring the Activities of Daily Living (ADLs) of the resident and offer them relevant services. Unity3D is a versatile cross-platform game development engine and integrated development environment (IDE) designed for creating interactive 2D and 3D games, simulations, and other interactive experiences, including augmented reality (AR) and virtual reality (VR) applications. Specifically, VirtualHome [15] is a platform built on Unity3D has been used, which offers predefined functions for simulating household activities. The monitoring model consists of two main components: the Static and Dynamic models.

- Static model 3D : The BIM information is used to construct the static environment within VirtualHome, accurately mapping sensors and equipment.
- Dynamic model : To animate the static model, information is integrated about the status of interconnected equipment via xAAL. Additionally, a radar system has been developed to capture information about the resident (position, point-cloud data, speed of movement) to represent their presence within the environment.

Version 2 of DT (Prediction): To enable predictive capabilities, an algorithm is developed and it is inspired by the approach proposed by [16] for activity recognition based on temporal patterns. This algorithm processes structured data provided by xAAL (representing values from connected equipment) and unstructured data directly from sensors (without passing through xAAL due to their voluminous nature). The results of this processing, are used to offer services and detect potential risk situations.

Version 3 of DT (Decision-Making): In this advanced version, we are considering the application of a decision-making method, such as a Markov decision process. This method will facilitate decision-making among different entities (DT, resident, and caregiver) based on priorities and acceptability factors.

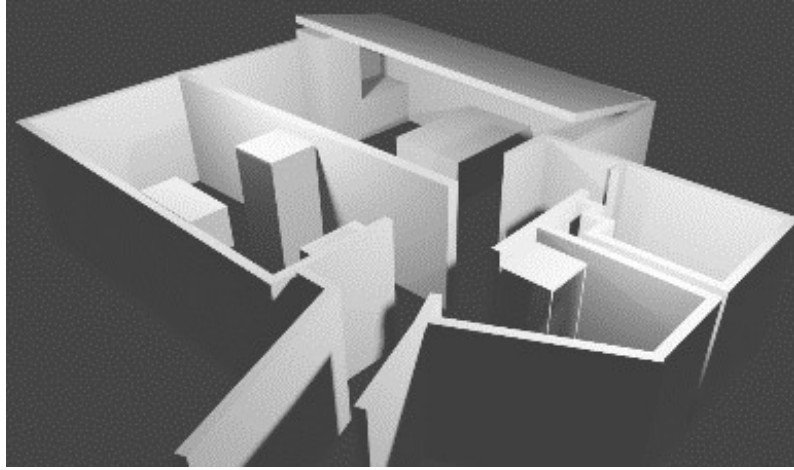


Fig. 4 3D model (digital shadow) of the apartment

The approach is being developed in an experimental flat, which includes a kitchen, bathroom, toilet, and a bedroom with furniture. In V1, Figure 4 illustrates the creation of a 3D model of the apartment to simulate the AAL environment. Additionally, the development of V2 prediction algorithms for activity recognition is currently in progress, and the results will be presented in a future publication.

6 Conclusion

In this paper, an approach is presented for the development of a digital twin-driven assisted living system aimed to maintain and improve the quality of life for elderly and disabled individuals at home. The methodology for creating digital twins is outlined, building upon an existing AAL system and ensuring compliance with the framework defined by ISO 23247. However, further research is needed to explore the utilisation of 3D models (BIM) for managing the data flow among the network of connected devices in the environment. The next challenge entails studying and defining a protocol for decision-making processes between the Digital Twin and its users.

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