Living Lab Assessment for the Development of a Non-Invasive Sensor Network for Measuring Activities and Comfort in Multi-Resident Contexts

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***Abstract*— The global aging trend has intensified the need for innovative, unobtrusive technologies that support independent living and health monitoring in domestic environments. In response, the Age-SenseAI project developed a novel Living Lab infrastructure specifically tailored to the study of multi-resident scenarios, enabling the testing and validation of sensor-based systems for monitoring human activity and environmental comfort. Grounded in co-design principles and informed by a comprehensive literature review, the Living Lab integrates a heterogeneous sensor network combining non-invasive devices, wearable technologies, smart objects, and both reference-grade and low-cost environmental sensors. A Real-Time Location System (RTLS) with inertial tags was selected as the ground-truth system due to its accuracy and proven effectiveness in tracking user behavior and movement in ambient intelligence applications. The spatial layout of the Living Lab simulates realistic residential environments, including zones for daily activities such as cooking, sleeping, working, and social interaction. Sensor deployment was optimized based on ergonomic criteria, environmental dynamics, and state-of-the-art guidelines from recent literature. This infrastructure enables multimodal data collection and supports the development of algorithms for activity recognition, comfort assessment, and behavioral analysis in shared domestic contexts.**

Keywords—living lab, human activity measurement, environmental comfort monitoring.

I. INTRODUCTION

The global demographic shift toward an increasingly aging population has prompted significant attention from both the scientific and technological communities. Ensuring the health, safety, and quality of life of older adults has become a central concern, particularly as many individuals express a strong preference for "aging in place"—remaining in their own homes and communities for as long as possible. In this context, the ability to unobtrusively monitor daily activities and environmental conditions within the living environment is of paramount importance. Such monitoring not only enables the early detection of physical and cognitive decline, but also supports proactive interventions aimed at maintaining independence and well-being [1].

Daily activity monitoring provides a wealth of information relevant to assessing cognitive function, mobility, routine adherence, and general health status [2]. Changes in activity patterns—such as reduced movement, increased sedentary behavior, or deviations from established routines—can be early indicators of conditions such as dementia, depression, or physical frailty [3]. For this reason, activity recognition and behavior modeling have become key research areas within the fields of ambient assisted living (AAL) and smart home technologies.

In parallel, environmental comfort is a critical yet sometimes underappreciated factor in the health and psychological well-being of older adults [4]. Age-related physiological and cognitive changes often impair the ability to accurately perceive environmental stimuli, leading to situations where individuals may not be aware of being in excessively hot or cold environments, or exposed to poor indoor air quality. Inadequate lighting, noise levels, or humidity can also negatively affect mood, sleep, and overall quality of life. Ensuring optimal environmental conditions, therefore, becomes a fundamental component of a holistic approach to elderly care.

The challenge becomes even more complex in multi-resident settings, such as shared homes, retirement communities, or residential care facilities (e.g., nursing homes and assisted living residences) [5]. In these environments, the coexistence of multiple individuals introduces additional variability in activity patterns and environmental preferences, complicating the monitoring process. Furthermore, the deployment of sensing systems in shared spaces raises critical concerns related to privacy, user acceptance, and ethical considerations. While advanced technologies—such as cameras [6], wearable sensors, non-invasive sensors and tags [7], and ambient sensor networks—offer high accuracy and detailed insights, they are often perceived as intrusive, particularly by older adults who may have heightened sensitivity to surveillance and loss of autonomy [8].

As a result, current research is increasingly oriented toward the development of minimally invasive, privacy-preserving, and non-stigmatizing solutions for activity and environmental monitoring. These technologies aim to balance the need for accurate and continuous data collection with the imperative to respect users' dignity, preferences, and trust. This paper situates itself within this line of research, exploring approaches that enable effective monitoring in multi-resident environments while minimizing the impact on users' daily lives.

Within this context, the present work aims to contribute to the advancement of unobtrusive monitoring technologies by designing and implementing an innovative experimental Living Lab specifically tailored for the study of multi-resident environments. The goal is to enable the development, integration, and evaluation of innovative sensor systems and sensor networks capable of capturing both individual and collective activity patterns, as well as environmental comfort parameters, in shared living spaces. This initiative is carried out within the framework of the Age-SenseAI project, which has the overarching objective of establishing a novel Living Lab infrastructure dedicated to aging-related research. The envisioned Living Lab is designed not only as a physical space equipped with state-of-the-art technologies, but also as an open, dynamic environment that fosters interdisciplinary collaboration. It will serve as a testbed for defining real-world scenarios and use cases, co-designing new solutions with stakeholders, and rigorously validating the performance, usability, and acceptability of emerging technologies in realistic conditions. Ultimately, the Living Lab aims to become a valuable asset for the scientific community, providing a standardized and extensible platform for evaluating intelligent monitoring systems that support healthy and independent aging in multi-user contexts. By bridging technological innovation with real-world applicability, this work contributes to the development of inclusive, effective, and ethically responsible solutions for ambient assisted living.

The remainder of this paper is organized as follows. Section 2 reviews the existing literature on Living Lab developed for activity and comfort monitoring in shared environments. Section 3 describes the methodology adopted for the design and development of the Living Lab, including the definition of use cases, system architecture, and sensor selection. Section 4 presents preliminary results from the initial deployment phase, highlighting the potential of the proposed infrastructure. Finally, Section 5 discusses the main findings, outlines current limitations, and provides directions for future work.

II. RELATED WORKS

The aim of this work is to design and develop a novel Living Lab, Age-SenseAI, dedicated to testing sensor-based systems for monitoring activity and environmental comfort in multi-resident settings. To guide its development, relevant literature and existing Living Lab models have been analyzed. In recent years, several initiatives have emerged to support aging populations through real-world testing of monitoring technologies. Notable examples include the ALLEGRO project in France, the H-IEQ Living Lab in Italy, and the AUSILIA initiative, all offering valuable insights into the design of experimental platforms focused on health, comfort, and autonomy in elderly care.

A. ALLEGRO Living Lab

The ALLEGRO (Angers Living Lab En GéRiatrie hOspitalière) initiative was launched in 2018 at the Geriatrics Department of the University Hospital of Angers, France. Its primary objective is to foster co-creation and the participatory development of gerontechnologies by integrating frail elderly patients, healthcare professionals, and caregivers directly into the innovation process. The laboratory includes both co-design workshops and an experimental hospital room where real patients test emerging technologies during their hospital stay. Sensor integration within ALLEGRO plays a critical role in evaluating the usability and clinical impact of these technologies. The environment is equipped with sensors that monitor room temperature, humidity, and air quality to ensure comfort and safety. Patients are also equipped with wearable sensors that track physiological parameters such as heart rate, sleep patterns, and mobility. In parallel, ambient sensors and activity recognition systems provide data on patient behavior and interaction with assistive technologies [9]. Many of the sensors employed in ALLEGRO—such as those for environmental monitoring and activity tracking—have also been adopted in the Age-SenseAI Living Lab. However, while ALLEGRO primarily addresses clinical aspects within hospital settings, the Age-SenseAI project emphasizes sensor deployment in real-life, multi-resident residential environments, where the dynamic interplay between individuals and the shared space introduces new challenges in activity recognition and comfort personalization.

B. H-IEQ Living Lab

The H-IEQ (Healthy Indoor Environmental Quality) living lab is part of the MIRABLE project, developed through a collaboration between the Italian National Institute of Metrology (INRiM) and Politecnico di Torino. This living lab aims to develop and validate a scalable, sensor-based infrastructure for the assessment of environmental quality in indoor spaces, particularly in the context of energy-efficient and healthy buildings. The living lab supports several use cases, including the continuous environmental monitoring of spaces to maintain occupant comfort and well-being, and the integration of sensor data into Building Information Modeling (BIM) systems for dynamic facility management. To this end, H-IEQ deploys a multi-domain sensor network capable of monitoring thermal conditions, lighting quality, acoustics, and indoor air quality. Thermal sensors assess parameters such as air temperature and radiant temperature. Air quality is monitored through sensors measuring CO_2 levels, particulate matter (PM2.5), and volatile organic compounds. Lighting conditions are evaluated with spectral sensors capturing both intensity and distribution of light, while acoustic quality is measured through sound level meters that assess background noise and sound dynamics [10]. This initiative represents a state-of-the-art reference for sensor selection in Age-SenseAI. However, unlike H-IEQ, which focuses primarily on optimizing environmental parameters in building systems, Age-SenseAI integrates environmental comfort with human activity monitoring in a holistic manner—particularly addressing the complexities that arise in shared living spaces inhabited by older adults with diverse needs and behaviors.

C. AUSILIA Living Lab

The AUSILIA project is an ecosystem-based living lab that brings together enterprises, public services, and citizens, with a specific focus on supporting elderly and vulnerable populations through technology-enabled social innovation. Its key aim is to enhance the quality of life and autonomy of individuals by fostering a collaborative process of service and product development embedded in the local community.

In AUSILIA, various sensor technologies are employed to monitor both health and environmental parameters across residential and communal spaces. The project uses environmental sensors to track indoor conditions such as temperature, humidity, and air quality, ensuring safe and comfortable environments. In addition, wearable health-monitoring devices are used to collect data on physiological states, including physical activity levels and cardiovascular metrics. Activity recognition systems, often based on motion sensors or ambient intelligence platforms, help detect patterns in daily routines, which are critical for assessing independence and identifying early signs of decline [11]. While AUSILIA effectively supports community-driven innovation and aging in place, Age-SenseAI distinguishes itself by emphasizing the real-time fusion of environmental and behavioral data in cohabited residential settings, enabling more precise differentiation between multiple occupants' activities and comfort needs—an aspect less explored in existing Living Labs.

III. METHODOLOGICAL APPROACH

The methodological approach underpinning the design and implementation of the Age-SenseAI Living Lab is based on the analysed literature on Living Labs and grounded in three fundamental and interrelated pillars: co-design with stakeholders, technology development, and iterative testing in realistic conditions. These pillars align with the core principles of Living Lab research, which emphasize user-centered innovation, contextual experimentation, and collaborative knowledge generation [12]. Furthermore, the research activities carried out within the Living Lab comply with the ethical standards established by the Ethical Committee of Università Politecnica delle Marche (UNIVPM), Ancona, Italy, as approved for the Age-SenseAI project. This ethical oversight ensures the responsible use of sensing technologies, with full respect for participants' rights, privacy, and informed consent, including robust procedures for data anonymization and secure handling throughout all stages of the study.

Co-design with stakeholders represents the foundational step in the creation of the Living Lab. A participatory process is adopted to involve a diverse range of stakeholders, including older adults, caregivers, healthcare professionals, technologists, and service providers. Through workshops, interviews, and focus groups, stakeholders contribute to defining relevant use cases, identifying unmet needs, and shaping the requirements for unobtrusive monitoring technologies. This collaborative process ensures that the developed solutions are grounded in the real-world experiences and expectations of end users, increasing the relevance, usability, and social acceptability of the outcomes.

Technology development constitutes the second pillar and focuses on the integration of ambient and wearable sensors, edge computing modules, and communication infrastructures into a unified, extensible platform. Particular attention is given to unobtrusiveness, interoperability, and privacy-aware data acquisition. The system is designed to monitor environmental parameters (such as temperature, humidity, noise level, and air quality), individual behaviors (e.g., mobility patterns, physiological parameters), and collective dynamics (e.g., presence and interaction among co-residents). Sensor selection and deployment are informed by the requirements elicited during the co-design phase and are iteratively refined in response to user feedback and technical evaluation.

Testing and validation represent the third methodological component and are conducted within a controlled environment. The Living Lab is structured to emulate realistic multi-resident domestic settings, enabling the simulation of typical daily activities and interactions. Technology prototypes are deployed in situ and evaluated through longitudinal studies that combine quantitative metrics (e.g., sensor accuracy, system reliability, detection precision) with qualitative assessments (e.g., user satisfaction, perceived intrusiveness, ease of use). This stepwise validation approach supports both formative and summative evaluation of the technological solutions, ensuring alignment with user needs and scientific standards.

By integrating these three methodological pillars, the Age-SenseAI Living Lab aspires to become a model environment for the inclusive, iterative, and evidence-based development of intelligent monitoring systems. This methodology not only supports the advancement of ambient assisted living technologies but also contributes to the broader discourse on how innovation ecosystems can responsibly address the challenges of aging in place.

A. Spatial configuration of the experimental environment

The spatial organization of the Living Lab has been carefully designed to emulate realistic multi-resident living scenarios while supporting flexible experimental protocols. The layout comprises four interconnected functional areas: an entryway, a kitchen and dining space, a combined living and bedroom area, and a home office corner. This configuration reflects contemporary residential settings and enables the observation of diverse daily activities, including individual and shared behaviors, transitions between zones, and interactions with objects. The design process prioritized accessibility, modularity, and the capacity to support a variety of use cases relevant to aging-related research.

B. Sensor System Architecture

The design of the Age-SenseAI Living Lab includes a heterogeneous network of sensors strategically selected and categorized according to their function and degree of intrusiveness. The system architecture is structured around two primary use cases: (i) the observation of human activity in multi-resident environments and (ii) the continuous assessment of environmental comfort parameters. Each category employs a distinct set of sensing technologies to balance data quality, user acceptability, and scalability.

1) Activity monitoring sensors: to address the complexity of activity recognition in shared living spaces, a multi-modal sensor infrastructure has been implemented. The sensors used for activity monitoring are classified into three main categories: non-invasive sensors, wearable sensors, and smart objects. Non-invasive sensors include technologies such as passive infrared (PIR) motion detectors, door and windows sensors, ultrasound sensors and cameras. These devices are strategically placed in the environment to unobtrusively detect movements, activity, presence, and posture transitions without requiring direct user interaction or data entry. This class of sensors is particularly suited for long-term deployment in residential settings due to its minimal impact on daily routines. Wearable sensors consist of inertial sensors, wristbands, and head-band sensors capable of capturing physiological and movement-related data. These sensors offer higher granularity in tracking physical activity, behavioral patterns, and physiological parameters. Their integration in the Living Lab is carefully managed to ensure comfort and acceptance by older adults, prioritizing ergonomic design. Smart objects refer to instrumented items within the living environment, such as sensorized furniture (i.e. smart mattress), smart appliances (i.e. energy meters), or interactive assistive devices (i.e. robots and Virtual Reality systems). These objects provide contextual data by detecting user interaction patterns, thereby enriching activity recognition with information about daily routines and collaborative behaviors in multi-resident scenarios.

2) Environmental comfort sensors: For the continuous monitoring of environmental comfort, two complementary sensor types have been deployed: reference-grade sensors and low-cost sensors. Reference-grade sensors are used to establish accurate baseline measurements of key environmental parameters, including temperature, relative humidity, solar radiation, wind velocity. These devices are calibrated and traceable to metrological standards, ensuring high-quality data for benchmarking purposes and for validating other sensing components. Low-cost sensors, on the other hand, are selected for their affordability, scalability, and potential for large-scale deployment. These sensors are typically based on microelectromechanical systems (MEMS) or optical detection technologies and are embedded throughout the living space to provide high-resolution spatiotemporal data. Although these devices may be less accurate than reference sensors, their performance is continuously evaluated and corrected using data fusion and cross-calibration techniques.

C. Sensor deployment optimization

A preliminary effort was undertaken to optimize the placement of sensors throughout the Living Lab, with the aim of supporting accurate data collection, minimizing user burden, and preserving the ecological validity of the environment. This ongoing optimization process integrates literature review, ergonomic principles, and expert feedback. For each sensor type, deployment parameters such as position, orientation, height, and spacing are being evaluated to enhance coverage and reduce signal noise. The evolving configuration also considers typical user movement patterns and environmental dynamics (e.g., airflow and lighting), with particular attention to achieving synchronized, multimodal data acquisition across spatial zones.

IV. LIVING LAB DEVELOPMENT OUTCOMES

The implementation of the Age-SenseAI Living Lab has involved the translation of methodological principles into a functional and configurable physical infrastructure. This section outlines the architectural layout of the experimental environment, the sensor selection process, and the optimization strategy adopted for sensor deployment.

A. Spatial Configuration of the Living Lab

To replicate realistic domestic scenarios in a controlled experimental setting, the Living Lab was spatially divided into re-configurable four functional areas, thanks to the installation of moving walls, Fig. 1,: an entryway, a kitchen and dining area, a combined living and bedroom space, and a dedicated office. This configuration was chosen to reflect typical zones in compact multi-user apartments or assisted living facilities.

The entryway serves as a transitional space for presence detection, visitor identification, and activity initiation.

The kitchen area allows for monitoring of routine tasks such as meal preparation, eating, and object interaction, offering opportunities for detecting collaborative or overlapping activities.

The living and bedroom space supports a variety of postural and mobility-related activities, including resting, entertainment, sleeping, and movement between furniture. This hybrid design enables simultaneous observation of daytime and nighttime behaviors.

The office space is designed to capture sedentary and task-oriented activities, which may include reading, computer use, or telephone conversations, relevant to cognitive engagement and daily function.

The layout also allows for flexibility in rearranging furniture and adapting the environment for different experimental conditions or user profiles. Each zone was equipped with sensors tailored to its expected activity types and environmental conditions, enabling localized and contextual data acquisition.

B. Sensor Selection Strategy

The design of the sensing infrastructure was guided by the dual objective of monitoring both user activity and environmental comfort in a multi-resident setting. As detailed in the methodology, sensors were classified into three categories for activity monitoring (non-invasive, wearable, and smart objects) and two categories for environmental monitoring (reference-grade and low-cost sensors), Tab. 1.

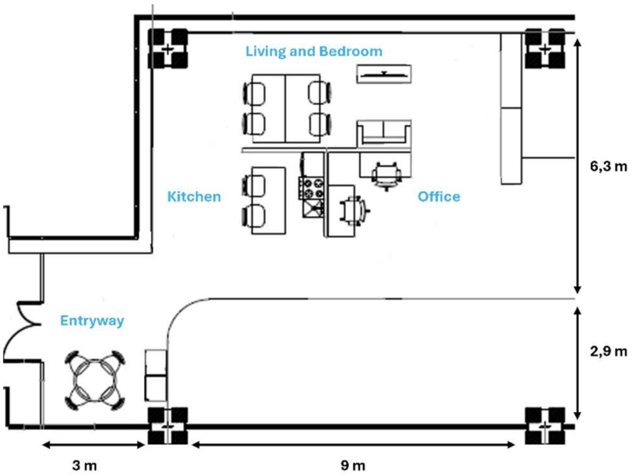

Fig. 1: Map of the Age-SenseAI Living Lab

Table 1 Sensors specifications

Sensor	Type	Measured Parameter	Accuracy / Specifications
Leonardo Personal Tags	Non-invasive	9-axis (accelerometer), barometer, UWB positioning	localization accuracy, up to 30 cm
Shelly Blu PIR	Non-invasive	Motion and presence detection	Passive infrared sensor (PIR), range ~9 meters

Shelly Blu Door/Window Sensor	Non-invasive	Door/window open/close status	Magnetic reed switch, no stated accuracy
Intel RealSense D455	Non-invasive	Depth, 3D vision, skeletal tracking	Depth accuracy < 2% at 4 meters; RGB resolution: 1280×720 @ 90 fps
Xovis PC2SE	Non-invasive	People counting, direction, presence	Accuracy > 99% in indoor bi-directional counting
LiDAR L515 High-Res Depth	Non-invasive	3D environmental mapping, high-resolution depth sensing	Resolution: 1024×768; accuracy ± 5 mm at 1 m of distance
Withings Sleep Analyzer	Smart object	Sleep cycles, heart rate, breathing patterns	Clinically validated
EEG Muse S	Wearable	EEG activity, meditation, sleep quality	4-channel EEG, 256 Hz sampling rate
Empatica EmbracePlus	Wearable	Physiological parameters (EDA, BVP, skin temperature, movement)	EDA: 0.01 µS; Temp: ±0.2°C; BVP: 64 Hz
TP-Link Tapo P125M (Smart Plug)	Smart object	Electrical appliance energy consumption	n.a.
Delta OHM Weather Station	Reference-grade sensor	Temperature, humidity, barometric pressure, wind speed/direction, solar radiation	Temp: ±0.2°C; Humidity: ±2%; Pressure: ±0.5 hPa; Wind: ±0.2 m/s;
Sensibo Smart AC Controller	Low-cost sensor	Temperature, humidity, air quality (VOC, CO_2), motion detection	Temp: ±0.5°C; Humidity: ±5%;
Netatmo Weather Station	Low-cost sensor	Temperature, humidity, barometric pressure, CO_2, noise level	Temp: ±0.3°C; Humidity: ±3%; Pressure: ±1 hPa;

The selection of the sensors suite implemented in the Age-SenseAI Living Lab was guided by a comprehensive review of the literature on AAL, unobtrusive monitoring, and multi-resident indoor environments and a co-design activitiy among external stakeholders and partners of Age-SenseAI and Age-it projects. Among the technologies deployed, the integration of a Real-Time Location System (RTLS) combined with inertial sensors tags—specifically, the Leonardo Personal tags from Sewio—was chosen as the reference system for ground-truth acquisition and high-resolution activity tracking for multi-resident contexts, Fig. 2.

RTLS technologies, particularly those based on Ultra-Wideband (UWB), have been widely validated for their high positioning accuracy (10 cm) and robustness in complex indoor environments [13], [14]. Their use in ambient intelligence systems is well-documented, especially for applications requiring precise spatial awareness, such as fall detection, mobility assessment, and social interaction analysis in multi-user scenarios [15], [16]. The Leonardo Personal Tag integrates a 9-axis accelerometer and a barometric sensor, enabling accurate and low-latency motion and orientation tracking. Within the Living Lab, five anchors (represented in green in Fig. 2) have been installed to communicate with the tags via UWB signals, allowing precise localization of participants. The continuous exchange of data between the anchors and the tags enables real-time monitoring of participants' trajectories, as reported in blue in Fig.2.

C. *Optimization of sensor deployment*

The ongoing optimization of sensor deployment within the Age-SenseAI Living Lab represents a preliminary phase aimed at supporting accurate data collection with minimal disruption to users. A multidisciplinary approach—integrating literature review, ergonomic considerations, and expert feedback—has guided this process in alignment with best practices in intelligent environment design. Preliminary placement of motion and presence sensors has been informed by spatial coverage simulations and human activity flow models to reduce occlusions and improve detection fidelity. Prior studies, such as Yang et al. [18], emphasize the importance of spatial optimization for vision-based and LiDAR systems in dynamic, shared environments. Similarly, Ciuffreda et al. [19] demonstrated that carefully deployed PIR sensors, particularly when integrated into robotic platforms, can unobtrusively track older adults and support real-time behavioral analysis.

Wearable and location-aware systems—including RTLS and inertial sensor tags—are being evaluated based on their documented utility in elderly care, with deployment strategies focusing on signal continuity and user acceptability [20].

The preliminary positioning of environmental comfort sensors considers thermal zoning, airflow dynamics, and occupancy profiles. As noted by Jia et al. [21], spatial variability in temperature, humidity, and air quality necessitates distributed sensing and careful placement away from sources of bias such as vents or transient heat sources.

While this optimization is still under refinement, early configurations aim to balance technical performance and user-centered design, enabling multimodal data collection that respects the natural dynamics of the living environment.

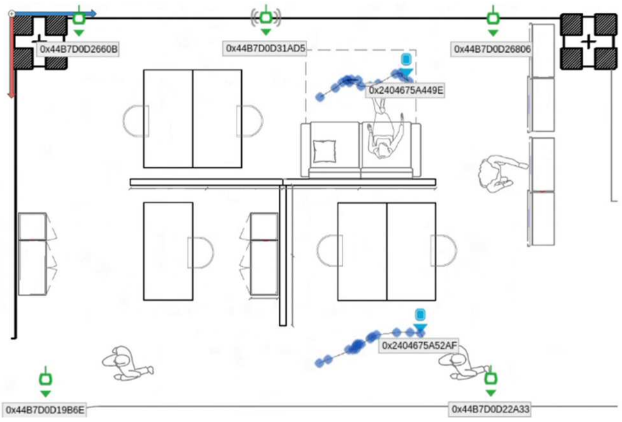

Fig. 2. Measurement setup of the RTLS technology and tags. In green the RTLS systems installaled in the Living Lab and in blue the trajectories of two participants.

V. CONCLUSIONS

This work presents the preliminary design and implementation of the Age-SenseAI Living Lab—a replicable experimental platform for the development and validation of unobtrusive monitoring technologies in multi-resident domestic environments. Through a co-design process involving stakeholders and guided by an extensive literature review, a heterogeneous sensor network was configured to monitor both human activity and environmental comfort. The integration of a high-precision RTLS and inertial sensors as a ground-truth reference enhances the reliability of behavioral data and supports the training of advanced recognition algorithms.

The Living Lab's modular architecture and optimized sensor deployment ensure adaptability to diverse research needs but also scalability across different real-life settings, including private homes and assisted living facilities. Its infrastructure supports longitudinal studies and facilitates the real-world evaluation of sensor systems in terms of technical performance, usability, and user acceptance. By bridging interdisciplinary domains—including gerontechnology, smart environments, and human-centered design—this initiative contributes to the development of scalable, ethical, and context-aware solutions for aging in place.

Future work will focus on the integration of AI-driven analytics for behavior modeling, the refinement of multimodal data fusion strategies, and expanded engagement with end-users to assess long-term acceptability and effectiveness in supporting health, autonomy, and quality of life for older adults in shared living environments.

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