# The Unified Digital Twin: A Framework for Robust Robotic Workforce Integration in a Hybrid KNX-Matter Smart Living Laboratory

## Abstract

This report proposes a novel research framework for the deep integration of a generalist robotic workforce within a smart living environment. It begins by establishing the current state-of-the-art in smart living solutions 1 and domestic robotic platforms.1 A critical gap is identified in the existing literature and technology: the disconnect between building automation platforms, which model digital *state*, and robotic simulation frameworks, which model *physical* kinematics. Current robotic simulators, such as the promising RoboCasa framework, are designed to train robots in static or self-contained environments but lack the native capability to integrate with or query real-world smart home protocols like KNX or Matter, limiting sim-to-real transfer and robust deployment in dynamic smart environments.1

The central contribution of this work is the proposal of the **Assistive Living Unified Digital Twin (AL-UDT) Laboratory**. This project is conceptualized as a retrofit of an existing 70m² apartment, built upon a resilient hybrid infrastructure. This infrastructure combines the robust, wired **KNX** standard for all safety-critical building systems (lighting, HVAC, automated doors) 1 and the flexible, IP-based **Matter** standard for all user-facing, plug-in, and assistive devices.1

This complex hybrid infrastructure will be centrally managed by the **Home Assistant** open-source platform, chosen for its extensive integration library and its emerging application as a **Building Digital Twin (BDT)**.1 The project's core novelty is the design, implementation, and validation of a **Unified Digital Twin (UDT)**. The UDT is a bi-directional data-binding layer that synchronizes the *state-based* BDT (from Home Assistant) with a *physics-based* **Robot Task Simulation (RTS)** (modeled after the RoboCasa framework).5

This Unified Digital Twin will, for the first time, allow a generalist mobile manipulator to be trained in a high-fidelity virtual environment that is a perfect, protocol-level, real-time mirror of the physical home. This framework will be used to investigate robust, safe, and context-aware robotic assistance for assistive living and aging-in-place scenarios. This approach directly addresses key human-robot interaction (HRI) challenges related to trust and predictability 1, as well as the profound ethical and safety considerations inherent in deploying autonomous systems in private, human-centric spaces.1 A three-year research plan detailing the lab's implementation and experimental validation is presented.1

## Part 1: The Co-Evolution of Smart Living and Domestic Robotics

### 1.1 Defining the Smart Living Ecosystem

The term "smart living" has transcended its origins in simple home automation. It is now recognized as a multi-dimensional concept that applies technology to fundamentally improve quality of life, increase efficiency, and reduce environmental impact.1 Academic frameworks define smart living as a convergence of four primary domains: technology, security, health, and education.1 This holistic paradigm is essential for the design of next-generation environments, particularly in the context of this project's focus on assistive living, where the "health" and "security" dimensions are the principal drivers for technological adoption.

This ecosystem-level thinking positions smart living as a core component of the broader Smart City concept, which integrates intelligence across six components: smart economy, smart people, smart governance, smart mobility, smart environment, and smart living itself.1 Therefore, any proposed solution cannot be a siloed gadget but must integrate into a complex system of systems, managing energy, data, and human well-being.

### 1.2 The Emergence of the Generalist Robotic Workforce

Concurrently, robotics is undergoing a fundamental transformation. The field is rapidly moving beyond the traditional, caged industrial robots of the past, which were defined by their strict physical separation from humans.1 The emergence of "collaborative robots (cobots)" and autonomous personal service robots has shifted the paradigm.1 These new systems are designed to operate *directly alongside* humans in shared, unstructured environments.

This shift fundamentally alters the primary research challenges. As robots and mobile robots become ubiquitous, traditional safety measures like physical guarding become obsolete.1 Consequently, research in Human-Robot Interaction (HRI) has become essential. The focus must evolve beyond basic task execution (e.g., "can the robot grasp the cup?") to address far more complex, socio-technical questions of "mutual understanding, predictability, trust, and safety in shared workspaces".1 This project, by proposing a predictable, state-aware robot, targets this HRI challenge directly. Furthermore, the integration of a robotic workforce is not merely a question of human labor replacement; it represents a "dual opportunity" for job *transformation* and *creation*, fostering new, highly-skilled roles in robot design, programming, maintenance, and data analysis.1

### 1.3 Foundational Gap Analysis: The "Sensor-Action" Disconnect

The most apparent synergy between smart living and robotics lies in integrating the *sensing* capabilities of the smart home with the *physical action* capabilities of the robot.1 The home provides the environmental context; the robot provides the physical agency.

However, a deeper analysis reveals a foundational "Sensor-Action Gap." Current research and technology largely exist in two distinct, non-communicating silos:

1. **Sensor-Rich, Action-Poor:** Smart homes are exemplary sensing platforms. They are built upon advanced Information and Communication Technology (ICT), smart sensing, and big data analytics.1 They excel at monitoring occupancy, energy consumption, environmental conditions, and even human actions via Human Action Recognition (HAR).1 However, their ability to *act* upon this data is primitive, typically limited to simple binary actuators like switches, valves, and locks.
2. **Action-Rich, Context-Poor:** Robotic systems, conversely, are masters of complex physical action. A generalist robot can navigate, manipulate objects, and perform sophisticated kinematic tasks.1 However, they often operate in environments that are "dumb," static, or, in the case of simulation, completely isolated from real-world digital systems. State-of-the-art simulators like RoboCasa 1 train robots to interact with 3D models of objects, but these models are not linked to any real-time, protocol-level digital twin.2 The simulated "stove" in RoboCasa is a self-contained 3D model, not an object whose *state* is governed by an external automation platform.

This gap creates a critical, and currently unaddressed, failure mode. A robot trained in a "dumb" simulation will learn the wrong interaction model. It may learn to *physically twist the knob* on a smart stove, an action that is both futile and potentially damaging, as the stove's actual control is *digital*. The robot must instead learn to *send a digital command* to the home's automation system.

Conversely, a smart home's automation is brittle. It can recognize a fall event using HAR, but it cannot dispatch a robot to pick up a dropped telephone or glass of water.

Therefore, the foundational gap is the *bi-directional integration layer*. The robot must be able to *query and command* the building's digital state, and the building must be able to *request and verify* the robot's physical actions. This project's **Unified Digital Twin** is the proposed engineering solution to bridge this critical "Sensor-Action Gap."

## Part 2: The Smart Home Technological Backbone: Protocols and Platforms

### 2.1 Core Components and Key Indicators

A successful smart living environment is built upon a foundation of integrated technologies. These include robust ICT, smart sensing, big data analytics, and intelligent decision-making frameworks.1 A critical component that bridges sensing with intelligent action is **Human Action Recognition (HAR)**. HAR is identified in the literature as a "critical success factor" for advanced smart living services.1 Its ability to accurately identify and interpret human actions empowers a system to move beyond simple automation to provide "real-time responses, delivering personalized support and assistance".1 In the context of the proposed assistive living lab, HAR will serve as a primary trigger for autonomous robotic tasks, enabling the system to anticipate user needs and interact in a natural, context-aware manner. The capabilities of the proposed lab will be benchmarked against the established indicators for smart living, including Foundational Technologies, Core Operational Aspects, and Societal & Environmental Impact.1

### 2.2 The Professional Standard: KNX (The "Backbone")

To build an environment suitable for assistive living, reliability is not a feature; it is a safety-critical prerequisite. The **KNX** standard (EN 50090, ISO/IEC 14543) is the definitive choice for this foundational layer.1 With a 30-year history and over 500 manufacturers producing compatible products, KNX is an open, decentralized standard renowned for its robustness.1

Its architecture is a key advantage. KNX is decentralized, meaning each device possesses its own intelligence and communicates directly with other devices on the bus.1 This eliminates the single point of failure inherent in centralized controllers, ensuring that a server crash does not disable the home's basic functions. While KNX supports multiple communication media (Radio Frequency, Powerline, IP), this project will utilize **KNX Twisted Pair (TP)** for all critical building infrastructure. This dedicated, wired bus provides the highest possible immunity to interference and ensures deterministic communication.

The rationale for this choice is clear: in an assistive living scenario, the failure of lighting, heating, or automated door systems is an unacceptable risk. The high initial cost and programming complexity via specialized ETS (Engineering Tool Software) are acknowledged 1, but they are a necessary trade-off for the non-negotiable reliability this "backbone" layer provides.

### 2.3 The Interoperability Standard: Matter (The "Flexibility Layer")

While KNX provides a rigid and reliable backbone, a modern assistive living environment must also be flexible and adaptable. New health sensors, assistive gadgets, and consumer appliances will be added continuously. This "flexibility layer" will be managed by **Matter**.1

Matter is a new, IP-based *application layer* protocol, not a full-stack system like KNX.1 Backed by major industry players including Apple, Google, Amazon, and the Connectivity Standards Alliance (CSA), its entire purpose is to unify the fragmented "walled gardens" of consumer IoT devices.1 Matter operates over existing network protocols like Wi-Fi, Ethernet, and Thread, providing a common language for devices to communicate securely and locally.1

For this project, Matter is the essential "future-proof" layer.8 It allows the resident and research team to seamlessly integrate new, off-the-shelf health sensors, smart plugs, and other assistive devices without needing to perform complex KNX programming. This hybrid KNX/Matter architecture represents a novel, best-of-both-worlds approach: KNX for mission-critical reliability, Matter for user-facing flexibility.

### 2.4 Central Integration Platforms: Home Assistant and openHAB

A hybrid KNX/Matter environment requires a powerful central integration platform to act as the "brain." The two leading open-source candidates are openHAB and Home Assistant.

* **openHAB (Open Home Automation Bus)** is a mature, Java-based platform built on a powerful OSGi architecture.1 Its key strength lies in its deep abstraction layer, which separates "Things" (physical devices) from "Items" (their capabilities), making it a robust, developer-centric platform for complex, customized installations.1
* **Home Assistant** is a Python-based platform known for its massive, active community, a user-friendly interface, and over 1,000 integrations.1 It has a strong focus on local control and privacy, which are critical for an assistive living lab.1

For this project, **Home Assistant** is the superior choice, for one critical reason. The project's primary challenge is *integration*: a legacy protocol (KNX), a new-generation protocol (Matter), and a complex robotic API. Home Assistant's *breadth* of integrations is a key advantage. Its community is already actively developing and troubleshooting KNX integrations 9 and supports a wide array of robotic devices.12

Most importantly, the Home Assistant community is *already* building the foundational concepts for this project's core idea: the **Building Digital Twin (BDT)**. Researchers and advanced hobbyists are actively using Home Assistant as a platform for real-time energy digital twins 4 and creating live, 3D-visualizations of home state.3 While the openHAB community has *discussed* digital twins 16, the *practical, demonstrable momentum* in the Home Assistant ecosystem 3 makes it the clear choice to serve as the host platform for our BDT.

This choice is not without its challenges. The integration of KNX into Home Assistant is non-trivial, requiring careful configuration of the KNX IP Interface and meticulous mapping of group addresses from the ETS software.9 Furthermore, using Home Assistant as the primary "brain" 10 creates a potential single point of failure. The physical lab's design must account for this by programming redundant, critical-path logic directly into the KNX actuators (e.g., a physical light switch *must* still work if the Home Assistant server is offline).10

### 2.5 Case Studies in Living Lab Implementation (The "Problem Space")

The proposed research is heavily inspired by the "Living Lab" methodology, particularly the work at the **Wuppertal Living Lab NRW**.1 This facility, coordinated by Professor Karsten Voss 20, serves as the premier model for this research. It demonstrates how to effectively use real-world building demonstrators to conduct research on complex topics like building-grid interaction 20, sustainability, and user-centric design.23 The two flagship projects at this lab, Local+ Aachen and MIMO Düsseldorf, serve to define the problem space that our proposed UDT will solve.

1. **Case 1: Local+ Aachen (FH Aachen):** This project focuses on *dynamic space* and *complex energy management*.1 Its defining features include movable "CUBES"—multifunctional furniture modules that reconfigure the living space 1—and a sophisticated energy system using photovoltaic thermal collectors (PVT) and hydrogen/ice storage.26
2. **Case 2: MIMO Düsseldorf (Hochschule Düsseldorf):** This project focuses on *dynamic facades* and *deep systems integration*.1 Its key innovation is a "Climate Shell" composed of movable, energy-generating slats that dynamically adapt to the environment.28 This is linked via an "energiBUS" that intelligently couples heat pumps and household appliances.29

These case studies prove *why* a simple, vision-based robot is insufficient for a truly smart home. Imagine deploying a robot in these environments. In the Local+ house, the robot's static map would be invalidated the moment a resident moves a "CUBE".26 In the MIMO house, the robot could not predict room temperature or plan a path to a window without *knowing* the current state of the "Climate Shell".28

This information is *not* reliably available to a robot's visual or LiDAR sensors. It is *only* available via the building's digital automation protocol. These dynamic, digitally-controlled architectures prove that a robust, generalist robot *must* be deeply integrated with the building's digital twin. Vision and LiDAR are insufficient to navigate a building whose *core architecture is dynamic*.

This project will directly address this challenge by creating a Unified Digital Twin that binds the robot's "brain" to the building's digital state. The key protocols and their relationship, which forms the basis of this project's hybrid architecture, are summarized below.

**Table 1: Comparative Analysis of Smart Home Protocols (KNX vs. Matter)**

| **Feature** | **KNX (Standard)** | **Matter (Application Layer)** |
| --- | --- | --- |
| **Standard** | Open Standard (EN 50090, ISO/IEC 14543) 1 | Open Standard (Connectivity Standards Alliance) 1 |
| **Topology** | Decentralized Bus, Tree, Star 1 | IP-Based (Star, Mesh via Thread) 1 |
| **Primary Medium** | Twisted Pair (TP), RF, Powerline, IP 1 | Wi-Fi, Thread, Ethernet 1 |
| **Data Rate** | 9.6 kbit/s (KNX-TP) | 250 kbit/s (Thread) to 600+ Mbit/s (Wi-Fi) |
| **Reliability** | Extremely High (Wired, deterministic, decentralized logic) [6] | High (IP-based, self-healing mesh via Thread) |
| **Interoperability** | Certified interoperability between 500+ manufacturers 1 | Aims to unify "walled gardens" of Apple, Google, Amazon [7, 8] |
| **Cost** | High (Specialized hardware, cabling, and ETS software) 1 | Low (Relies on existing network hardware, commodity chips) |
| **Primary Use Case** | **Project Backbone:** Critical infrastructure (HVAC, lighting, automated doors, security) | **Project Flexibility Layer:** Consumer electronics, health sensors, smart plugs |

## Part 3: The Robotic Workforce: From Simulation to Physical Deployment

### 3.1 Classification and Applications for Assistive Living

The robotic workforce for this project falls into the categories of **Assistive Robots** and **Personal Service Robots**.1 The research objective is to move significantly beyond the simple, single-task robots currently in a few homes (e.g., robot vacuums) 13 and develop capabilities for complex, meaningful assistance in an assistive living context.

The target applications are those that directly support aging-in-place. This includes providing medication reminders, conducting passive health monitoring, offering support for physical rehabilitation exercises, and assisting with mobility and daily chores.1 Specific, high-impact tasks include assistive feeding for individuals with motor impairments 32 and the retrieval and transport of critical items (e.g., medication, water, a telephone).10

A crucial component of this research is the HRI goal. Beyond physical assistance, the robotic system must be designed to address the significant mental health challenges prevalent among older adults, such as depression, anxiety, and loneliness.1 This requires a system that is not just functional, but *predictable*, *reliable*, and *trustworthy*, aligning with the core HRI challenges of mutual understanding and safety.1

### 3.2 Simulation Frameworks for Generalist Robots: The RoboCasa Study

To train a robot for such a wide array of tasks, a simulation framework is essential. The **RoboCasa** simulation framework 1 is the state-of-the-art model for this domain. It is a large-scale simulation environment designed specifically for training generalist robots to perform *everyday tasks* in human-centric environments.5

RoboCasa's key features make it the ideal starting point for this project's Robot Task Simulation (RTS). It focuses on kitchen environments 33, includes over 120 diverse scenes, more than 2,500 3D object assets 2, and a suite of 100 defined tasks (25 atomic, 75 composite).35 To facilitate imitation learning, it provides a massive dataset of over 100,000 training trajectories.33

Its most critical capability, for the purpose of this project, is the simulation of *articulated objects* and *state changes*. For example, the RoboCasa simulation allows a robot to twist a knob on a stove, which then causes the virtual burner to register a state change and "turn on".2

However, this very feature highlights the "RoboCasa Gap" and provides a core justification for the proposed research. As confirmed by analysis, the RoboCasa framework has *no* integration with real-world smart home protocols like KNX or Matter.2 The "stove" in RoboCasa is a *self-contained 3D model*. Its state is internal to the simulation.

In the proposed physical lab, the "stove" is a *hybrid object*: a physical appliance whose state is controlled and reported by a *Matter entity* within *Home Assistant*.

This creates a critical sim-to-real mismatch. A robot trained in standard RoboCasa *will fail* the task. It will learn to twist a physical knob that may be disconnected or, worse, will conflict with the digital state. The robot *must* learn that to "turn on the stove," it must send a *digital command* to the number.matter\_stove\_temp entity in Home Assistant.

This gap is the central technical problem this research will solve. The project will involve *forking* or *modifying* a RoboCasa-like framework 36 to create the Robot Task Simulation (RTS) layer of the **Unified Digital Twin**, enabling it to bind its internal object states to an external data source (the BDT).

### 3.3 Physical Platforms and Real-World Deployment Trends

The deployment of physical robots is a non-trivial undertaking, but industry trends are moving toward this exact form of integration. The 2025 Hannover Messe, for example, highlighted the rise of "Embodied or physical AI" 37, with a clear focus on connecting physical systems to digital platforms. A prominent demonstration involved FANUC robots streaming live machine data directly to SAP's digital platform 38, showing a clear precedent for connecting physical robots to high-level digital systems. This project applies that same concept—Robot-to-Digital-Platform—to the *domestic* smart living environment.

While advanced humanoid robots are emerging 37, a wheeled, general-purpose mobile manipulator with a ROS 2 (Robot Operating System 2) interface is a more practical and robust platform for navigating the retrofitted apartment environment and achieving the project's manipulation goals.

## Part 4: Project Proposal: The Assistive Living Unified Digital Twin (AL-UDT) Laboratory

### 4.1 The Physical Laboratory: A Hybrid Retrofit

The AL-UDT Laboratory will be a physical, 70m² apartment, fully retrofitted for accessibility (e.g., no thresholds, 90cm automated doorways) and instrumented with a three-layer hybrid technology stack.

* **Layer 1: The Backbone (KNX):** A dedicated **KNX-TP Bus** will control all *safety-critical* and *infrastructure-level* building systems. This includes:
  + All ceiling and wall lighting, likely using KNX-DALI gateways for addressable control.
  + HVAC and underfloor heating via KNX valve actuators.
  + Automated doors and window blind motors using KNX shutter/blind actuators.
  + Wired, multi-function sensors (presence, temperature, humidity, CO2) integrated directly onto the KNX bus for maximum reliability.
* **Layer 2: The Flexibility Layer (Matter):** A **Matter-over-Thread** network (with Wi-Fi/Ethernet for high-bandwidth devices) will manage all *user-facing*, *plug-in*, and *assistive* devices. This includes:
  + Smart-plugs for consumer appliances (kettle, toaster, TV).
  + Matter-enabled assistive technology devices, such as a smart pillbox, bed presence sensors, and dedicated fall-detection sensors.
* **Layer 3: The Robotic Workforce:** A **General-Purpose Mobile Manipulator** (e.g., PAL Robotics TIAGo or similar) equipped with a navigation stack (LiDAR, depth cameras), a 6+ DOF arm, and a gripper. The robot will run on a **ROS 2** interface for open-standards communication.

### 4.2 The Digital Twin Architecture (The Core Innovation)

The core novelty of this project is the *software architecture* that unifies the physical lab. This architecture consists of three layers, which are detailed in Table 2.

* **Layer 1: The Building Digital Twin (BDT):** This is a *real-time, state-based model* of the entire home. It will be hosted on a dedicated **Home Assistant** server.1 The BDT will aggregate *every* device, sensor, and actuator from both the KNX bus (via a KNX IP Interface) and the Matter network into a single, unified entity model.4 This BDT will also host dashboards for 3D visualization 3 and predictive analytics for energy and occupancy.4
* **Layer 2: The Robot Task Simulation (RTS):** This is a *physics-based, kinematic model* of the apartment and the robot. It will be built by *forking* or adapting the **RoboCasa** framework.1 This layer simulates 3D space, physics, robot movement, and object manipulation.5
* **Layer 3: The Unified Digital Twin (UDT) (The Novel Contribution):** This is the *bi-directional data-binding layer*, likely implemented using MQTT and dedicated APIs, that synchronizes the BDT and the RTS in real-time.

The function of the UDT is best explained by its two communication pathways:

1. **BDT -> RTS (World-State-to-Sim):** This binding ensures the simulation is a *perfect mirror* of the real world's digital state.
   * When the knx.light.kitchen entity in Home Assistant turns 'on', the UDT binding instantly updates the RTS, and the *light source* in the 3D simulation turns on.
   * When the cover.knx\_living\_room\_blinds entity reports a position of '30%', the UDT binding moves the *articulated 3D blind model* in the RTS to the 30% position.
   * When the binary\_sensor.matter\_bed\_presence entity turns 'on', the UDT binding updates the simulation, and the *3D human model* in the RTS appears in the bed, triggering context-aware robot behaviors.
2. **RTS -> BDT (Sim-Action-to-World):** This binding allows the robot to learn to interact with the *digital world*.
   * The *simulated* robot moves to a *virtual* KNX light switch and performs a "press" action in the RTS.
   * The RTS registers this interaction with its virtual object and publishes a command to the UDT.
   * The UDT translates this into a light.toggle service call in Home Assistant.
   * Home Assistant sends the command to the KNX bus, and the *physical* light turns on.

This UDT architecture creates the ultimate sim-to-real training environment. The robot can be trained 24/7 in a virtual world that is not a static approximation, but a *live, real-time, protocol-level mirror* of the physical home. This **solves the "RoboCasa Gap"**. The robot will correctly learn that to "turn on the stove," it must send a *digital command* to the number.matter\_stove\_temp entity, not just twist a dumb knob.

Furthermore, this enables a new class of **safe, predictive HRI**. Consider a scenario: a resident with dementia turns on the *physical* stove and walks away. The *physical* stove reports its state via Matter to the BDT. The BDT updates the UDT. The *robot's brain* (the UDT) sees the stove.state == 'on' and user.location == 'not\_in\_kitchen' for 10 minutes. This state-based rule violation triggers an autonomous task, and the *physical* robot is dispatched to check on the user and the stove. This is a level of robust, context-aware safety that is currently impossible with disconnected systems.

**Table 2: The Unified Digital Twin (UDT) Data-Binding Schema (Conceptual)**

| **Physical Object/System** | **BDT Entity (Home Assistant)** | **RTS Model (RoboCasa-Fork)** | **UDT Binding Direction** | **Example Task / Safety Check** |
| --- | --- | --- | --- | --- |
| **Automated Hallway Door** | cover.knx\_hallway\_door | robocasa.door\_model\_3 (Articulated) | Bi-directional | **Task:** Robot requests door open via RTS. **Safety:** Robot perceives open path *only if* BDT state confirms position > 90%. |
| **Smart Kettle** | switch.matter\_kettle | robocasa.kettle\_model\_1 (Stateful) | Bi-directional | **Task:** Robot "presses" virtual button in RTS. BDT entity switch.turn\_on is called. *Physical* kettle turns on. |
| **User in Bed** | binary\_sensor.matter\_bed\_presence | human\_model\_1 (In bed pose) | BDT -> RTS | **Task:** Robot's simulation *updates* with user's presence, triggering "good morning" task (e.g., open blinds). |
| **Stove Burner** | number.matter\_stove\_temp | robocasa.stove\_model\_1 (Stateful, visual FX) | Bi-directional | **Task:** Robot learns to set temperature via RTS command, not physical knob. **Safety:** stove.temp > 50 AND user.presence == 'absent' triggers robot check. |
| **Living Room Blinds** | cover.knx\_living\_room\_blinds | robocasa.blinds\_model\_1 (Articulated) | BDT -> RTS | **Context:** Robot's navigation and vision algorithms *adapt* to real-time lighting changes in the simulation, mirrored from the real world. |

### 4.3 The Robotic Integration Layer (RIL)

The "spinal cord" of the physical robot will be a ROS 2 software package designated as the Robotic Integration Layer (RIL). This layer is the bridge between the UDT's high-level logic and the robot's low-level hardware.

* The RIL subscribes to the UDT for high-level goals (e.g., "Goal: prepare\_coffee") and world-state updates (e.g., "State: user.location == 'living\_room'").
* It subscribes to the robot's *physical* sensors (LiDAR, cameras) for real-time local navigation and obstacle avoidance.
* It publishes joint and velocity commands to the physical robot's hardware controllers.

During the *training* phase, the RIL is connected *only* to the UDT, running in a purely simulated loop. During the *deployment* phase, the RIL is connected to the UDT *and* the physical robot, using the UDT as its definitive "world model" and its "command interface" for interacting with the smart environment.

### 4.4 A Multi-Year Research and Implementation Plan

This project is structured as a three-year doctoral research plan, directly analogous to the methodology of the 1 report.1 The plan is divided into six core milestones, culminating in a fully validated UDT framework and a completed PhD thesis.

**Table 3: Multi-Year Project Milestones and Deliverables (AL-UDT Lab)**

| **Milestone** | **Name** | **Description** | **Deliverables** | **Timeline** |
| --- | --- | --- | --- | --- |
| **M1** | **Design & Procurement** | Finalize apartment retrofit blueprints, KNX bus topology, and UDT data-binding schema. Procure all KNX hardware, servers, Matter devices, and the robotic platform. | • Detailed architectural & KNX blueprints.  • UDT data schema document.  • Completed hardware procurement. | End of March 2026 |
| **M2** | **BDT Implementation** | Complete physical apartment retrofit. Install and commission the full KNX bus using ETS software. Install Home Assistant and integrate all KNX and Matter devices. | • A fully built and physically functional assistive living lab.  • A complete, operational **Building Digital Twin (BDT)** in Home Assistant. | End of Sept. 2026 |
| **M3** | **RTS & UDT Development** | Fork the RoboCasa framework. Build the high-fidelity 3D model of the apartment in the simulator. Develop the bi-directional data-binding layer (the UDT) to link the BDT and RTS. | • A functional **Robot Task Simulation (RTS)**.  • The novel **Unified Digital Twin (UDT)** data-binding layer (software). | End of March 2027 |
| **M4** | **Simulated Training** | Connect the BDT and RTS to create the fully functional, live-synced UDT. Define a suite of 20+ assistive tasks. Train the robot's control policies *entirely* within the UDT. | • A set of trained, high-performance policies for assistive tasks.  • A report on UDT-based training methodology. | End of Sept. 2027 |
| **M5** | **Sim-to-Real Deployment** | Deploy the trained policies from M4 onto the physical robot in the physical lab. Conduct extensive robustness testing (e.g., inject network lag, test bus failures, introduce "desynchronization"). | • A fully deployed and physically operational robotic workforce.  • Experimental data on Sim-to-Real transfer and system robustness. | End of March 2028 |
| **M6** | **User Validation & Thesis** | Conduct user-centric studies with a cohort of elderly participants to measure system performance, trust, acceptance, and usability.1 Complete data analysis and submit thesis. | • A completed and approved PhD thesis.  • Published peer-reviewed papers.  • User-study data on HRI and acceptance. | End of Sept. 2028 |

## Part 5: Critical Research Challenges in an Integrated Robotic Home

### 5.1 Compounded Privacy and Security Risks

The proposed Unified Digital Twin represents a data-collection apparatus of unprecedented sensitivity. It aggregates *all* data streams from *all* IoT devices (every light switch, every presence sensor, every smart plug) 1 and *compounds* this with the robot's own rich sensor data (cameras, microphones, and LiDAR) into a single, queryable model.

This creates a *compounded privacy risk*.1 A breach of the UDT would not just reveal a user's habits; it would provide a perfect, time-stamped, 3D-mappable record of *everything* they do, their precise location, their health status (from Matter sensors), and the entire state of their home. This raises legitimate and severe anxieties about data acquisition, potential misuse, and unwanted surveillance.1

**Research Challenge:** This risk necessitates a "privacy-by-design" approach. A core research question will be: How can we apply data minimization and federated learning principles to the UDT? Can the robot be trained on abstracted *state* data (e.g., user.location == 'kitchen') without granting its training algorithm access to the *raw camera feed* that generated that state? The UDT architecture may allow for a "privacy firewall" where the BDT processes raw sensor data locally and shares only high-level, anonymized state changes with the RTS.

### 5.2 Ethical Considerations and User Autonomy

The ethical dilemmas outlined in the foundational report 1 are magnified by this project's capabilities. The question is no longer just "can a robot replace a human companion?" 1, but "what happens when an autonomous, predictive robot *knows* your needs before you do?"

A predictive UDT, which can forecast energy use 15 or user behavior 40, could trigger the robot to act *pre-emptively*. This could be immensely beneficial (e.g., delivering water before a user becomes dehydrated) or profoundly harmful. A system that "over-helps" by pre-emptively tidying, cooking, or assisting could inadvertently reduce the user's personal independence and autonomy, which is the very thing the system was designed to support.1

**Research Challenge:** This project must develop an HRI framework for **negotiated autonomy**. The robot's logic must differentiate between *critical* events (a fall, a fire) where it acts immediately, and *non-critical* predictions (e.g., "you usually have tea at 4 PM"). For non-critical actions, the system must "ask" before acting, providing a clear, accessible interface for the user to grant or deny consent, thereby preserving their agency.

### 5.3 Regulatory and Compliance Frameworks

A system that uses AI to control a physical robot in a human environment is a *classic* "high-risk AI application" as defined by regulatory frameworks like the EU AI Act.1 As such, the AL-UDT Laboratory will be subject to rigorous compliance obligations, including demands for human oversight, transparency, robustness, and granular data governance.1

**Project Opportunity:** The UDT architecture, rather than just being a liability, can be a powerful *solution* for these compliance challenges.

1. **Traceability and Explainability:** The BDT, fed by the immutable state changes from the KNX bus and Matter network, provides a perfect, time-stamped log of all building events. This log can be used to *explain* *why* the robot made a specific decision (e.g., "The robot moved to the kitchen at 10:04 because binary\_sensor.matter\_stove\_presence was 'on' and binary\_sensor.matter\_user\_presence was 'absent' for 10 minutes."). This directly fulfills transparency requirements.
2. **Demonstrable Robustness:** The UDT allows for *provable* safety and robust testing.1 We can *formally verify* in the simulation that the robot's logic is *bound* to the door's *digital state*. This allows us to prove that the robot will *never* attempt to pass through a closed door. This ability to test and validate safety-critical logic within a live-synced digital twin provides a new, powerful method for demonstrating system robustness and satisfying regulatory demands.

## Part 6: Conclusion and Future Work

### 6.1 Summary of Proposed Contributions

This report has proposed the **Assistive Living Unified Digital Twin (AL-UDT) Laboratory**, a novel PhD research project to design, build, and validate a fully integrated smart living environment. This project addresses a critical gap in the current state-of-the-art: the "Sensor-Action Gap" between "action-rich" robotic simulators and "sensor-rich" building automation systems.1

The core contribution is the **Unified Digital Twin**, a bi-directional data-binding layer that synchronizes a *state-based* **Building Digital Twin** (hosted in Home Assistant) 3 with a *physics-based* **Robot Task Simulation** (adapted from RoboCasa).5

This framework, built on a robust and flexible hybrid **KNX-Matter** physical infrastructure, enables the training and deployment of generalist robotic workforces that are truly context-aware, demonstrably safe, and robust to the dynamic, digitally-controlled nature of a modern smart home. This work will produce a validated methodology for sim-to-real transfer and a framework for addressing the complex HRI, ethical, and regulatory challenges of next-generation assistive technology.

### 6.2 Open Research Questions (for Future Work)

The successful implementation of the AL-UDT Laboratory will serve as a foundation for a new generation of research questions:

* **Resilience to Desynchronization:** The UDT's primary weakness is a "lying" twin. What happens when the UDT *desynchronizes* from reality (e.g., a power failure on the KNX bus, or a user *manually* moves a chair, breaking the simulation's model)? Future research must focus on using the robot's *physical sensors* (vision, LiDAR) to detect and correct these desynchronization events.
* **Scalability:** How does this UDT architecture scale? This project models a single apartment. How can the framework be expanded to manage a multi-unit assistive living facility, like those envisioned by the Local+ and MIMO projects, with multiple users and multiple robots?.25
* **HRI for a "Ghost" in the Machine:** This project creates a robot whose actions are often not tied to a user's *immediate* command, but to the *invisible state* of the building's digital twin. How do users perceive such a system? This opens a new frontier in HRI research focused on *explainability*—designing interfaces that can clearly communicate *why* the robot is acting, (e.g., "I am checking the stove because it has been on for 10 minutes and you are in the living room."). This moves beyond simple HRI to a more holistic, *Human-Building-Robot Interaction* paradigm.

#### Works cited

1. 2025 PhD UPB Smart Living Robotic Workforce Research v.1.2.2.pdf
2. RoboCasa | robocasa-web, accessed November 6, 2025, <https://robocasa.ai/>
3. Managing My 3-Level Smart Home with a Digital Twin in Home Assistant using Floorplan, accessed November 6, 2025, <https://community.home-assistant.io/t/managing-my-3-level-smart-home-with-a-digital-twin-in-home-assistant-using-floorplan/867830>
4. Smart Buildings and Digital Twin to Monitoring the Efficiency and Wellness of Working Environments: A Case Study on IoT Integration and Data-Driven Management - MDPI, accessed November 6, 2025, <https://www.mdpi.com/2076-3417/15/9/4939>
5. Overview — RoboCasa 0.2 documentation, accessed November 6, 2025, <https://robocasa.ai/docs/introduction/overview.html>
6. Knx vs matter vs HomeKit : r/homeautomation - Reddit, accessed November 6, 2025, <https://www.reddit.com/r/homeautomation/comments/10hlqss/knx_vs_matter_vs_homekit/>
7. Comparing smart home trends: KNX vs. Matter | Hestia Magazine, accessed November 6, 2025, <https://www.hestiamagazine.eu/comparing-smart-home-standards-knx-vs-matter>
8. KNX & Matter is the best smart home you can build right now, accessed November 6, 2025, <https://www.1home.io/blog/knx-with-matter-is-the-best-smart-home-right-now/>
9. How to Integrate Home Assistant With KNX & ETS - Helge Klein, accessed November 6, 2025, <https://helgeklein.com/blog/how-to-integrate-home-assistant-with-knx-ets/>
10. KNX with Home Assistant as brain - Reddit, accessed November 6, 2025, <https://www.reddit.com/r/KNX/comments/1dis1b6/knx_with_home_assistant_as_brain/>
11. KNX Integration problems - Home Assistant Community, accessed November 6, 2025, <https://community.home-assistant.io/t/knx-integration-problems/648868>
12. Segway Navimow H-series (lawn mower robot) - Home Automation - openHAB Community, accessed November 6, 2025, <https://community.openhab.org/t/segway-navimow-h-series-lawn-mower-robot/156578>
13. denysdovhan/vacuum-card: Vacuum cleaner card for Home Assistant Lovelace UI - GitHub, accessed November 6, 2025, <https://github.com/denysdovhan/vacuum-card>
14. humbertogontijo/homeassistant-roborock: Roborock integration for Home Assistant. This integration uses your devices from the Roborock App - GitHub, accessed November 6, 2025, <https://github.com/humbertogontijo/homeassistant-roborock>
15. A User-in-the-loop Digital Twin for Energy Consumption Prediction in Smart Homes - CEUR-WS.org, accessed November 6, 2025, <https://ceur-ws.org/Vol-3957/AXAI-paper01.pdf>
16. Digital Twins and Machine Learning - Page 2 - 3rd Party - openHAB Community, accessed November 6, 2025, <https://community.openhab.org/t/digital-twins-and-machine-learning/23417?page=2>
17. Digital Twins and Machine Learning - 3rd Party - openHAB Community, accessed November 6, 2025, <https://community.openhab.org/t/digital-twins-and-machine-learning/23417>
18. Overview of the OpenHAB System Architecture. Showing the Eclise... - ResearchGate, accessed November 6, 2025, <https://www.researchgate.net/figure/Overview-of-the-OpenHAB-System-Architecture-Showing-the-Eclise-SmartHome-Core-left-and_fig1_325785698>
19. Minister Pinkwart launches the Living Lab. NRW in Wuppertal - YouTube, accessed November 6, 2025, <https://www.youtube.com/watch?v=HRteikOyrmg>
20. Karsten Voss's lab | University of Wuppertal (Uni-Wuppertal, BUW) - ResearchGate, accessed November 6, 2025, <https://www.researchgate.net/lab/Karsten-Voss-Lab>
21. Competition and Living Lab Platform (Annex 74) Project Summary Report - IEA EBC, accessed November 6, 2025, <https://www.iea-ebc.org/Data/publications/Annex_74_final_report.pdf>
22. Living Lab NRW at the Week of the Environment in Berlin - Bergische Universität Wuppertal, accessed November 6, 2025, <https://www.uni-wuppertal.de/en/news/detail/living-lab-nrw-bei-der-woche-der-umwelt-in-berlin/>
23. Virtual Institute Smart Energy: Smart Home – Co-Benefits and Needs of Private Households, accessed November 6, 2025, <https://wupperinst.org/en/p/wi/p/s/pd/864/>
24. A field study on the effect of building automation on perceived comfort and control in institutional buildings | Request PDF - ResearchGate, accessed November 6, 2025, <https://www.researchgate.net/publication/337873423_A_field_study_on_the_effect_of_building_automation_on_perceived_comfort_and_control_in_institutional_buildings>
25. LOCAL + - Student project - FH Aachen, accessed November 6, 2025, <https://www.fh-aachen.de/en/faculties/architecture/lectures-projects/local>
26. Team LOCAL+ of the FH Aachen University succeeds at Solar Decathlon Europe 2021/22, accessed November 6, 2025, <https://www.linear.eu/en/blog/team-local-of-the-fh-aachen-university-succeeds-at-solar-decathlon-europe-2021/22/>
27. PRESS RELEASE - IEA SHC, accessed November 6, 2025, <https://www.iea-shc.org/Data/Sites/1/media/documents/press/2022-06-17--shc-ises-award-solar-decathlon-2022.pdf>
28. Concept: Sustainable living space for Wuppertal - MIMO - Solar ..., accessed November 6, 2025, <https://mimo-hsd.de/project/concept/>
29. MIMO Düsseldorf, Germany - Solar Decathlon, accessed November 6, 2025, <https://sdeurope.uni-wuppertal.de/en/sde-21/22/teams-projects/mimo-duesseldorf-germany/>
30. Our HDU - MIMO - Minimal Impact Maximum Output, accessed November 6, 2025, <https://mimo-hsd.de/sde21/hdu/>
31. What's the best way to control Home Assistant devices from OpenHAB, accessed November 6, 2025, <https://community.openhab.org/t/whats-the-best-way-to-control-home-assistant-devices-from-openhab/163289>
32. Moving From OpenHAB to Home Assistant - Karyl F. Stein, accessed November 6, 2025, <https://karylstein.com/2025/03/10/moving-from-openhab-to-home-assistant/>
33. RoboCasa: Large-Scale Simulation of Everyday Tasks for Generalist Robots, accessed November 6, 2025, <https://www.roboticsproceedings.org/rss20/p050.pdf>
34. RoboCasa: Large-Scale Simulation of Everyday Tasks for Generalist Robots - arXiv, accessed November 6, 2025, <https://arxiv.org/abs/2406.02523>
35. RoboCasa: Large-Scale Simulation of Everyday Tasks for Generalist Robots - arXiv, accessed November 6, 2025, <https://arxiv.org/html/2406.02523v1>
36. RoboCasa: Large-Scale Simulation of Everyday Tasks for Generalist Robots - GitHub, accessed November 6, 2025, <https://github.com/robocasa/robocasa>
37. Hannover Messe 2025: Mind The Reality Gap - Forrester, accessed November 6, 2025, <https://www.forrester.com/blogs/hannover-messe-2025-mind-the-reality-gap/>
38. Hannover Messe 2025 Review: Takeaways and Event Critiques - JigSpace, accessed November 6, 2025, <https://www.jig.com/blog/hannover-messe-2025-review-takeaways-and-event-critiques>
39. News & Articles - HANNOVER MESSE, accessed November 6, 2025, <https://www.hannovermesse.de/en/news/news-articles/newshub?tag=1232>
40. AI-Powered Digital Twin for Personalized Assistance and Predictive Decision- Making - RSIS International, accessed November 6, 2025, <https://rsisinternational.org/journals/ijrsi/digital-library/volume-12-issue-3/609-617.pdf>