Research on Spatial Agent Based on Spatial Terminalization

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Abstract

With the rapid iteration of artificial intelligence, Internet of Things, and spatial computing technologies, the implementation of cutting-edge applications such as smart homes, embodied AI, and digital twins relies heavily on the deep integration of physical spaces and hardware devices. Over two decades of development in the smart home industry has demonstrated that the decoupling between physical spaces and hardware is the underlying root cause restricting industry growth, directly leading to systemic issues such as fragmented hardware ecosystems, high deployment and operation costs, and poor user interaction experiences. To address these challenges, this paper proposes the "spatial terminalization" theory, which takes indoor spaces with independent property rights as basic intelligent units. It designs a spatial hardware connection system centered on the spatial bus, establishing unified hardware connection specifications, data control mechanisms, and spatial coordinate systems, to drive the evolution of physical spaces from passive containers into integrated habitation intelligent terminals. The proposed architecture is inferred from practical engineering observations to have broad adaptability for most indoor residential layouts and hardware-connecting scenarios. The design targets cross-brand hardware interoperability and potential reduction in system-level hardware overhead. This work establishes a standardized distributed connection foundation for heterogeneous hardware, mitigates ecosystem barriers introduced by individual vendors, and offers theoretical support for multi-party collaborative spatial-intelligence system construction. This paper presents the complete architectural design and preliminary universality analysis, and discusses directions for follow-up technical validation and potential practical deployment.

Key words: Spatial Agent; Spatial Terminalization; Spatial Bus; Smart Home; Power Line Communication; Spatial Coordinate System; Spatial Intelligence

1 Introduction

The development of the Internet has undergone two disruptive paradigm revolutions: the personal computer Internet (Internet 1.0) in the 1990s reconstructed the global information connection and sharing paradigm through digital technology [1]; the mobile Internet (Internet 2.0) in the early 21st century extended connection capabilities to individual life scenarios through smartphones, completely reshaping human behavior patterns and interaction methods [2]. The common essence of these two revolutions is that independent terminal devices have always been the main subject of connection, while physical space only exists as a static container for carrying devices.

Currently, with clustered breakthroughs in technologies such as artificial intelligence, Internet of Things, spatial computing, and digital twins, the Internet is moving toward a third paradigm revolution with spatial intelligence as its core [3]. From Apple’s exploration of spatial computing terminals with Apple Vision Pro [4], to the systematic construction of "Spatial Intelligence" theory by Fei-Fei Li’s team [5], to the large-scale application of digital twin technology in the construction field [6], explorations in both industry and academia point to the same trend: the next generation of the Internet will be deeply embedded in physical space, making space itself the core subject of connection, computing, and interaction.

However, the current relationship between physical space and hardware devices still presents a fragmented state of decoupling, discreteness, and stacking: isolated hardware has redundant functions and poor cross-device collaboration, forming an ecological dilemma of "low intelligence and high redundancy". This dilemma is particularly prominent in the smart home field: different brand manufacturers build ecosystem barriers with proprietary technology stacks, multi-application control processes are cumbersome, engineering integration is highly complex and excessively costly, and user experience and system efficiency lag significantly [7]. The implementation of cutting-edge technologies such as embodied AI, metaverse, and digital twins cannot be separated from two core carriers: physical space and hardware devices. Therefore, it is necessary to re-examine the positioning of physical space from the underlying logic, extract universal connection laws from diverse spatial structures, integrate all hardware resources with space as the basic unit, and build a globally coordinated spatial-level intelligent terminal system.

Achieving spatial terminalization faces six core technical challenges: first, the standardized and fixed design of the bus position; second, the balance between simplicity and flexibility of connection methods; third, the unified design of the spatial core anchor point (which needs to carry the functions of coordinate origin, control center, power supply center, and network center simultaneously); fourth, the universality of the solution for diverse apartment layouts; fifth, the non-intrusive deployment method; sixth, electromagnetic interference suppression for power line communication. In response to these challenges, this paper constructs a complete spatial agent architecture, transforming indoor spaces into standardized hardware connection platforms that support fair access of hardware from all brands as functional components of the spatial terminal.

The core contributions of this paper include:

(1) Proposing the "spatial terminalization" theory, defining indoor physical space as the next-generation Internet terminal form, and providing a new theoretical perspective for the physical implementation of spatial intelligence and embodied AI;

(2) Designing the complete architecture of the "spatial agent," including core components such as the spatial bus, spatial origin, central control cabinet, and hardware connection system, realizing full-stack unification of power supply, communication, wiring, and ports;

(3) Constructing a standardized spatial coordinate system, realizing the mapping between local spatial coordinates and world geodetic coordinates, and providing a unified physical space framework for embodied AI and world models;

(4) Verifying the universality of the spatial bus based on engineering practice data, and validating the adaptability of the solution in different apartment layout scenarios.

2 Core Concepts and Theoretical Foundations

2.1 Spatial Terminalization

Spatial terminalization refers to the process of deeply coupling physical space and hardware devices through a third-party "spatial hardware connection system" to form an integrated intelligent terminal. This process takes the physical boundary of a single space as the hardware connection framework, and consists of the spatial origin, the spatial hardware connection system, and the central control cabinet, which uniformly standardizes the connection methods, spatial coordinate system, and data control mechanism of whole-house intelligent hardware.

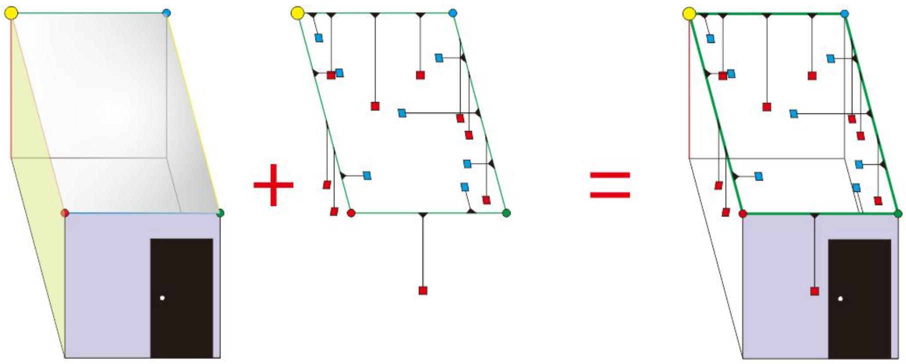
Spatial terminalization has four core characteristics:

(1) The main subject of connection shifts from home appliances to the housing space itself;

(2) Human-computer interaction shifts from external terminal control to natural interaction inside the space;

(3) Soft furnishings and home appliances inside the terminal are transformed into functional components and input/output devices of the terminal;

(4) It has a globally unified data control center.



2.2 Connotation Analysis of Spatial Intelligence

In the field of artificial intelligence, the definition of spatial intelligence proposed by Fei-Fei Li's team has benchmark academic value. Its core viewpoint states that spatial intelligence is the underlying comprehensive ability of embodied AI to complete 3D geometric perception, physical rule understanding, and spatial relationship reasoning in a 3D spatiotemporal environment, and to transform physical scenarios through active interaction. It is the core intelligent foundation connecting machine perception, spatial imagination, and physical action [5]. This definition centers on agents, focusing on the subjective cognition of agents toward physical space, and belongs to the category of endogenous spatial cognition and behavioral capabilities of agents.

This paper proposes a complementary interpretive perspective: the virtual space system constructed by spatial intelligence exists independently of embodied AI, possesses objectivity and absoluteness, and is a space system with real-time synchronization between virtual and reality. Spatial intelligence has independent software systems, hardware systems, and absolute coordinate systems, with 3D geometric perception and spatial hardware control capabilities, but does not possess cognitive abilities such as physical rule understanding and spatial relationship reasoning. It forms a functionally complementary and mutually independent relationship with embodied AI.

Research on whole-brain simulation of digital fruit flies provides empirical support for this theoretical perspective: the study integrates the FlyWire whole-brain digital brain, the NeuroMechFly high-precision virtual body, and a virtual physical environment, and realizes the autonomous emergence of biological instinctive behaviors of digital fruit flies without data training or manually preset behavior scripts. This experiment confirms that the virtual physical environment is a third-party system independent of the digital brain and virtual body, and does not change due to the observation behavior of agents. Based on this paradigm, a theoretical analogy can be established: the digital brain corresponds to the core cognitive system of artificial intelligence, the virtual body corresponds to the execution carrier of embodied AI, and the virtual physical scenario corresponds to the "spatial intelligence" system proposed in this paper. Different from traditional definitions, the spatial intelligence proposed in this paper does not participate in the cognitive reasoning and behavioral decision-making of agents. Its core essence is to take space as the main body, rely on the spatial coordinate system and software-hardware architecture, build an objective, stable, and interactive digital physical space, and provide basic scenario support for various artificial intelligence and embodied AI applications.

2.3 Comparative Analysis of Intelligent Terminal Form Evolution

From the PC Internet to the spatial Internet, terminal forms, connection methods, and value logic have undergone systematic changes. The specific comparison is shown in Table 1.

Table 1 Comparison of Intelligent Terminal Evolution

Comparison Dimension	PC Internet	Mobile Internet	Spatial Internet

Connection Subject	Computers	Smartphones	Space (Intelligent Terminal)
Network Characteristics	Fixed access	Mobile access	Fixed space coverage
Operation Position	Desktop operation	Handheld operation	Global interaction inside the terminal
Access Method	Wired (address identification)	Wireless (location identification)	Wired + wireless (address + location dual identification)
Computing/Data Deployment	Local computing / local data	Cloud computing / cloud data	Local-first, cloud collaboration
Human-Computer Interaction	Mouse, keyboard	Touch screen	Body movements, voice, multimodal interaction
Value Manifestation	Information sharing	Mobile application services	Spatial intelligence applications
Typical Applications	Websites, email	Mobile payment, navigation	Smart home, embodied AI
Address System	IPv4	IPv4 + IPv6	IPv6 + spatial origin + physical address + GNSS coordinates

3 Related Research and Analysis of Industrial Pain Points

3.1 Research Status of Smart Home Connection Technology

Smart home is the earliest application direction to explore the relationship between space and hardware connection [8]. Existing research mainly focuses on three levels: communication protocol optimization, device interconnection, and edge computing architecture. At the communication protocol level, wired bus technologies such as KNX and RS-485 are maturely applied in the building automation field [9], wireless technologies such as ZigBee, BLE, and Wi-Fi are widely deployed in consumer-grade smart homes [10], and the introduction of the Matter protocol has further promoted cross-brand interconnection at the application layer [11]. At the system architecture level, open-source platforms such as Home Assistant realize unified management of multi-protocol devices through software adaptation [12]. At the edge computing level, existing research has explored architecture models for device collaboration and data processing through local gateways [13].

However, existing research and industrial solutions all focus on device-level connection optimization, and have not solved the core problem of space-hardware decoupling from the underlying spatial architecture level, resulting in the industry always facing the fragmentation dilemma.

3.2 Root Cause Analysis of Underlying Industrial Dilemmas

3.2.1 Structural Contradiction of Mismatched Power Supply Standards

The global civil power supply standard is unified as alternating current (AC), with two mainstream standards: AC 220–240 V/50 Hz and AC 100–120 V/60 Hz [14]. Electrical equipment is divided into AC and DC types, and common DC standards include six types: DC 5 V, DC 9 V, DC 12 V, DC 24 V, DC 36 V, and DC 48 V. There is no unified indoor DC power supply standard worldwide.

With the maturity of semiconductor technology and DC brushless motor technology, most indoor intelligent appliances have adopted DC power supply [15]. The single AC power supply standard results in all DC appliances requiring independent power adapters, bringing problems such as increased cost, rising energy consumption, enlarged volume, and reduced aesthetics, forming a structural contradiction of mismatched power supply and consumption standards.

3.2.2 Mismatch Between Static Wiring and Dynamic Demand

Current home decoration generally adopts the concealed wall wiring mode. Line points, layout positions, cable specifications, and interface types are constructed at one time during the decoration stage, which is a static and fixed wiring solution [16]. With the iteration of intelligent technology and changes in user demand, problems such as insufficient reserved points, unreasonable positions, and incompatible interfaces often arise when adding devices, replacing product categories, or upgrading systems. Line renovation requires destructive wall construction, with long construction periods and high costs, and will damage the original decoration appearance.

The concealed wall mode strongly couples the wiring system with the building structure, making it impossible to upgrade or transform independently, and making cable aging and fault troubleshooting difficult. Meanwhile, mixed laying of strong current, weak current, and communication lines is prone to signal interference, affecting the communication quality and control accuracy of intelligent devices [17]. The static and fixed wiring mode fundamentally conflicts with the core demands of smart homes for dynamic iteration and flexible expansion.

3.2.3 Fragmentation of Computing and Control Architecture

The current smart home industry generally adopts the architecture model of "distributed computing, isolated storage, and fragmented control", lacking a unified whole-house computing, storage, and control system, which is one of the core reasons for fragmented experience [18].

This architecture has four drawbacks:

(1) Waste of computing resources: simple control tasks are dispersedly executed on each terminal device, making it impossible to realize centralized scheduling and efficient utilization of

computing power;

(2) Data island problem: user behavior and device operation data are stored separately on different brand platforms, making global integration and in-depth analysis impossible, and it is difficult to support high-level artificial intelligence decision-making [19];

(3) Fragmented control experience: users need to install multiple brand applications, cross-brand scenario linkage docking is complex and has high response delay;

(4) Difficult system upgrade: different devices have inconsistent upgrade rhythms, old devices cannot receive update support, and have short life cycles.

3.2.4 Lack of Unified Hardware Connection Standards

The industry has long tried to solve interconnection problems by unifying device-layer communication standards, but has never touched the underlying framework of hardware connection. Cross-brand protocols such as Matter only realize communication language interconnection at the application layer, and do not solve underlying hardware connection problems such as physical interfaces, power supply specifications, and wiring methods [11]. Devices of different brands still cannot realize designed to achieve plug-and-play capability and interchangeable compatibility at the hardware level. Protocol unification only at the application layer cannot solve the problem of underlying hardware fragmentation, and the overall redundancy of the system continues to increase.

The lack of unified hardware connection standards is essentially the result of commercial interest games: manufacturers build ecosystem barriers through exclusive interfaces and protocols to lock in users and markets, resulting in scattered industry resources and making it difficult to promote underlying technological breakthroughs and standard unification.

4 Core Architecture Design of the Spatial Agent

A spatial agent is an integrated intelligent terminal composed of a main space and sub-spaces networked together, with an indoor space with independent property rights as the basic unit. A sub-space consists of physical space and a hardware connection system; a main space consists of five parts: physical space, central control cabinet, hardware connection system, spatial origin, and AI butler (AI Agent). The overall structure is shown in Table 2.

Table 2 Composition Structure of the Spatial Agent

<table>
<tr><td rowspan="3">Spatial Agent</td><td colspan="4">Main Space (1 unit)</td><td colspan="2">Sub-spaces (N units)</td></tr>
<tr><td rowspan="2">Physical space</td><td>Spatial Origin</td><td>Central Control Cabinet (AI Butler)</td><td>Hardware Connection System</td><td rowspan="2">Physical space</td><td>Hardware Connection System</td></tr>
<tr><td colspan="3">Hardware connection carrier of the main space</td><td>Hardware connection carrier of sub-spaces</td></tr>
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4.1 Spatial Hierarchy: Main-Sub Space Topology and Bus Connection

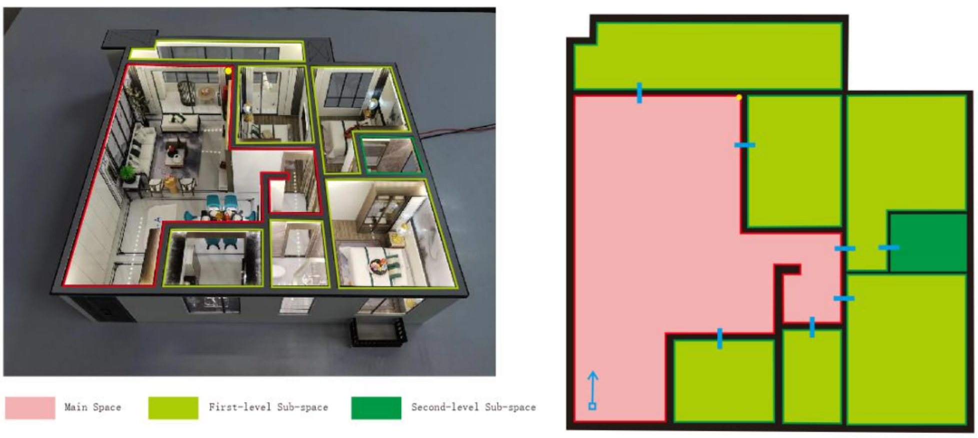
This paper defines indoor physical spaces with independent property rights as property units, which usually consist of one or more functional areas. Based on spatial topological relationships, a hierarchical spatial system is established:

A property unit consisting of only a single area is called a main space;

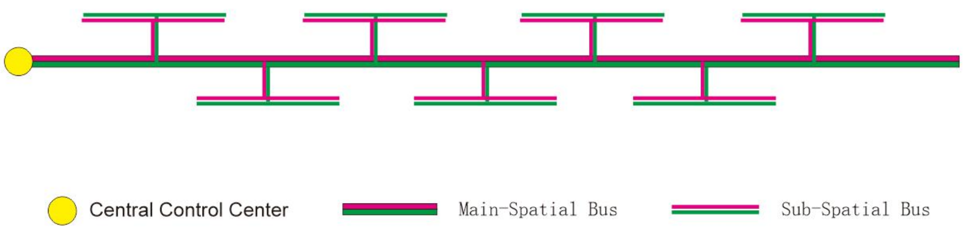
Multi-area property units adopt the "main space + sub-space" hierarchical model. The main space is the core space where the main entrance and exit are located. Sub-spaces are divided into levels 1 to N according to topological relationships: those directly connected in parallel to the main space are level 1 sub-spaces, those connected in series after level 1 sub-spaces are level 2 sub-spaces, and so on.

The spatial bus undertakes both hardware access and space connection functions: it is both the physical carrier of space boundaries and the core medium for interconnection between adjacent spaces. The buses of adjacent spaces can be directly drilled through without additional wiring, realizing low-cost networking of spaces.

Note: The main spaces and sub-spaces mentioned in this study refer to physical spaces where the spatial bus can be installed; spaces that do not meet installation conditions are not included in the statistics.



"Spatial Agent" Topology



4.2 Coordinate Anchor: Spatial Origin and Coordinate System

The spatial origin is the core benchmark anchor of global spatial rules. Its standard deployment position is at the corner diagonally opposite the main entrance and exit of the main space; if the main entrance is located in the middle of the wall, the left corner is preferred. When coupled with the spatial bus, the spatial origin undertakes eight core functions:

(1) Origin of the spatial coordinate system (0, 0, 0);

(2) World coordinate conversion center;

(3) Starting point of the spatial bus;

(4) Data processing center area;

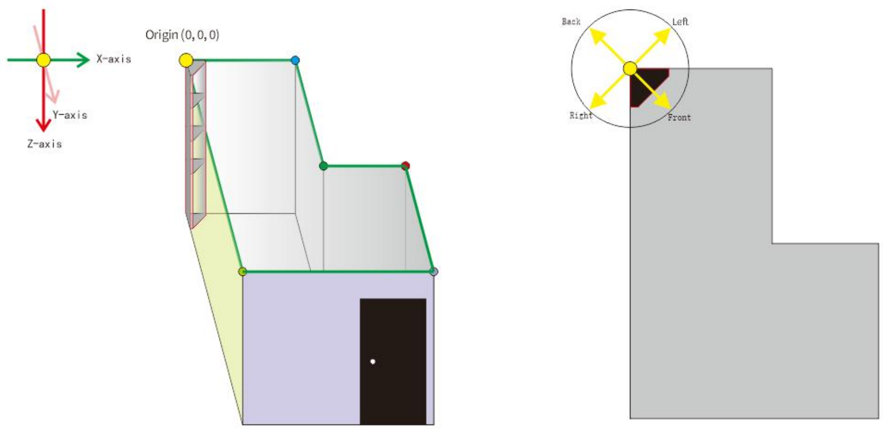
(5) Power supply center area;

(6) External network connection node;

(7) Human-computer interaction center area;

(8) Spatial visual observation benchmark point.

Spatial coordinates, world coordinates, spatial orientation, and direction are all based on the space itself, corresponding to constant absolute values in the physical world, and do not change with the movement of humans or agents. This benchmark system endows space with an independent fourth-party attribute, connects the real world and the virtual physical world, and supports two-way data interaction with embodied agents.



4.2.1 Local Spatial Coordinate System

After determining the spatial origin $O(0,0,0)$, a global spatial coordinate system (x, y, z) is established according to the right-hand rule: the x-axis extends along the starting end of the main space bus, the y-axis extends along the ending end of the main space bus, and the z-axis is the height direction of the global space. After the establishment of the spatial coordinate system, all positions within the spatial agent have unique coordinate codes, which are the core foundation for spatial positioning and spatial perception.

The relative positional relationship between a local spatial point (x, y, z) and the spatial origin $O(0, 0, 0)$ can be expressed as:

$$\vec{OP} = x \cdot \boldsymbol{e_x} + y \cdot \boldsymbol{e_y} + z \cdot \boldsymbol{e_z}$$

where $\boldsymbol{e_x}$, $\boldsymbol{e_y}$, $\boldsymbol{e_z}$ are the three orthogonal unit vectors of the local coordinate system.

4.2.2 World Geodetic Coordinate System Mapping

The spatial origin simultaneously anchors the world geodetic coordinate system (longitude λ, latitude ϕ, altitude h), so that any point in space has a unique, objective coordinate identifier that can interoperate with the Global Navigation Satellite System (GNSS) [20]. This coordinate system does not rely on agent perception, is based on physical anchors, and naturally belongs to the same benchmark framework as systems such as GPS and Beidou. It can realize two-way coordinate conversion and data intercommunication through affine transformation, providing underlying support for cross-space intelligent collaboration and data flow.

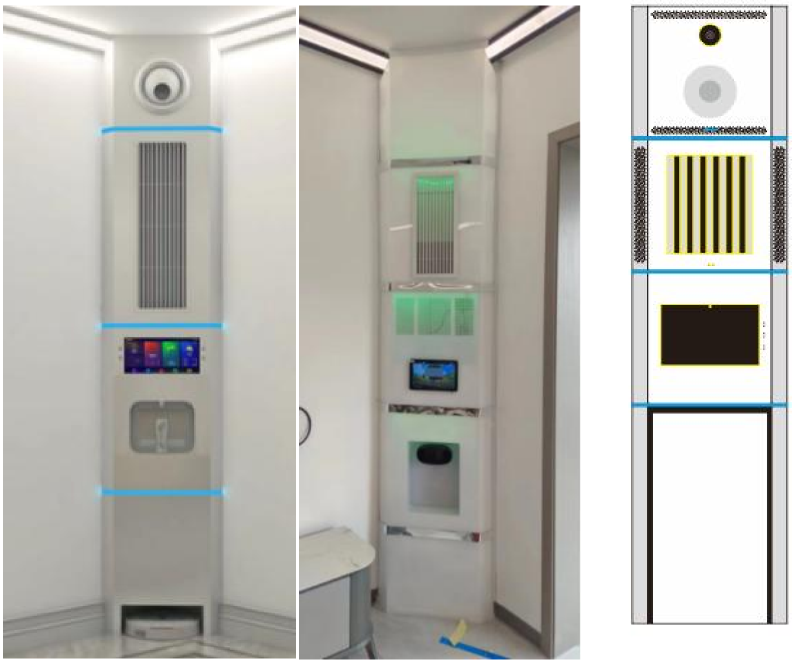
4.2.3 Spatial Orientation and Direction Specifications

Spatial orientation adopts a unified judgment standard: when an observer stands directly in front of the central control cabinet, faces the main entrance, and looks outward horizontally, the facing direction is the standard orientation of the space, which is a unified reference connecting humans and machines, and bridging indoor and outdoor spaces.

Spatial direction is not based on human subjective orientation, but takes the midline of the central control cabinet's orientation as the forward benchmark to delimit left and right directions: 0–45 to the left of the front is the left side of the space, and 0–45 to the right is the right side of the space. The standardized spatial direction system provides a concise and unified language carrier for human-machine spatial information interaction.

4.3 Central Unit: central control cabinet

The central control cabinet is a hanging column-type four-layer functional system, consisting of four modules: (1) Central control host (core essential module); (2) Air conditioning and circulation system; (3) Energy storage system (including identity verification module); (4) Embodied AI base. The central control cabinet is deployed at the core of the main space hardware connection system, serving as the intelligent hub of the entire spatial agent and the only access point for external network connections. This paper focuses on the analysis of the central control host module, and the remaining layers are reserved for future expansion.



Note: The two figures on the left show the design drawing and Photograph of the early-stage experimental prototype of the previous- generation experimental prototype; the one on the right is the design drawing for this study.

4.3.1 Central Control Host

The spatial agent needs to reserve power cables and optical fibers (or network cables) in advance to the position of the central control host, as the global energy and data transmission channel. The central control host includes six subsystems:

(1) Power supply system: divides the total power cable into five independent circuits, each connected to an air circuit breaker, corresponding to the AC power supply track, broadband DC power supply track, narrowband DC power supply track, central control cabinet power supply (excluding the energy storage system), and energy storage system power supply;

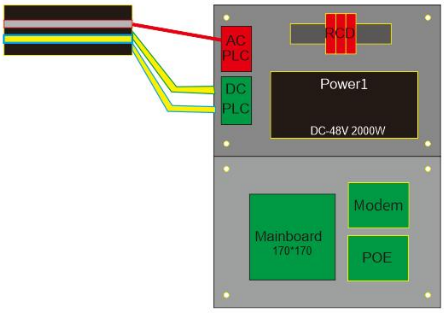
(2) Data transmission system: includes three independent channels, namely 220V AC power line communication (AC-PLC), 48V DC broadband power line communication (DC-PLC broadband), and 48V DC narrowband power line communication (DC-PLC narrowband). Broadband PLC provides transmission rates from 100 Mbps to Gigabit level, used for network, video, and display devices; narrowband PLC is used for instruction transmission of sensors and control devices [21];

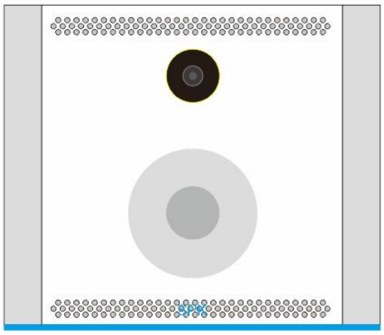
(3) Computer system: undertakes data processing and hardware control functions. The edge computing unit can be equipped with an AI butler and a local large language model, and ultra-high-performance configurations can serve as computing power nodes to provide external services;

(4) Network system: Gigabit fiber access with Wi-Fi routing to achieve global network coverage;

(5) Storage system: independently deploys Network Attached Storage (NAS) as a storage center for personal data, audio-visual data, and work data;

(6) Human-computer interaction system: integrates cameras, microphones, and speakers as basic interaction sensors.





4.3.2 Extended Function Modules

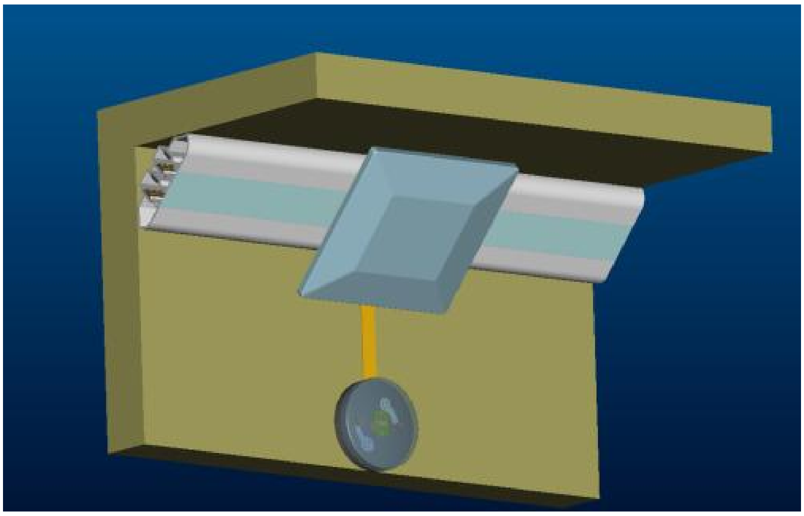
Air conditioning and circulation system: integrates air conditioning, liquid cooling heat dissipation, and dual air circulation functions. The liquid cooling system is specially designed for heat dissipation of high-computing-power units, and the air conditioner is used for fine-tuning ambient temperature. The two share an outdoor heat dissipation host; dual air circulation realizes internal and external air conditioning and purification.

Energy storage system and identity recognition system: ensures global power supply stability. It is externally equipped with a touch screen and identity recognition modules such as fingerprint, face, and voiceprint, and various high-authority applications are authorized here.

Embodied AI base: provides basic support such as automatic homing, cleaning, charging, and garbage collection for embodied devices such as sweeping robots and robotic arms.

4.4 Connection Carrier: Hardware Connection System

The hardware connection system is the implementation carrier of the spatial bus, consisting of four core units: (1) Spatial bus; (2) Branch box; (3) Branch wiring; (4) Branch port.



4.4.1 Spatial Bus

The spatial bus is a track-type hardware connection bus embedded in the indoor crown molding position. It forms a continuous closed ring structure along the junction of the wall and ceiling, supports vertical access of all non-ground hardware connection ports, and realizes multi-standard power supply and communication through power line communication technology. It is a designed to achieve plug-and-play capability global connection foundation.

The spatial bus has five core characteristics:

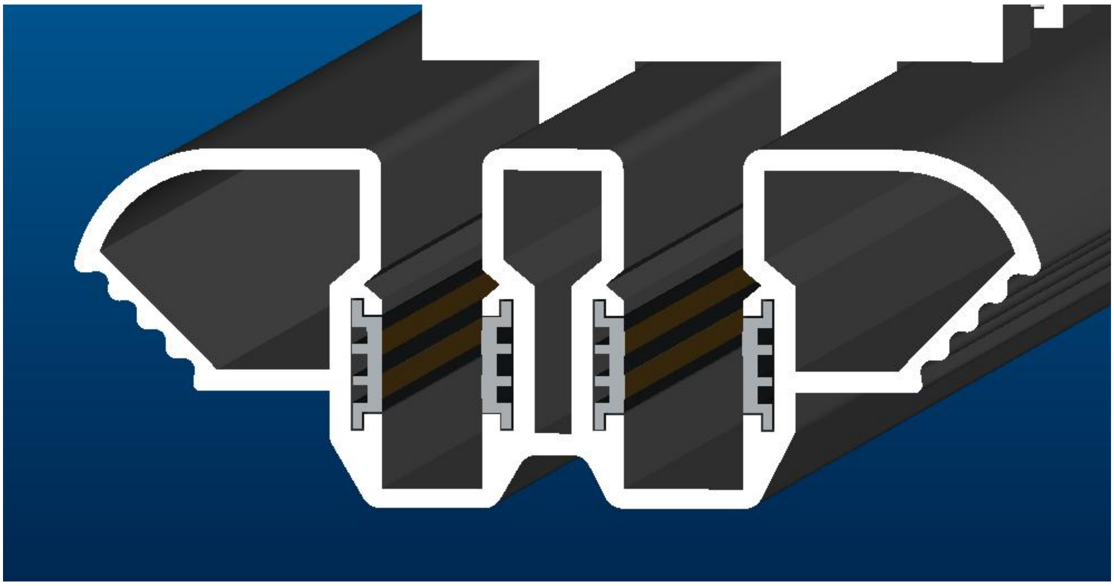
Dual standards: adopts dual-track slots, provides AC and DC dual power supply systems, and the number of track paths can be expanded according to demand;

Dual topologies: naturally forms a ring bus structure. The topology can be switched between ring topology and bus topology through opening and closing devices to adapt to different electrical characteristic requirements [22];

Dual frequency bands: integrates broadband power line communication (10 Mbps–1000 Mbps, for high-speed communication) and narrowband power line communication (10 Kbps–2000 Kbps, for control instructions) [23];

Dual attributes: has both building decoration attributes and electrical connection attributes. The track design does not affect the decoration and concealing function of the crown molding, and is unobtrusive when surface-mounted;

Global coverage: the closed ring structure realizes seamless coverage of the entire space.



4.4.2 Branch Box

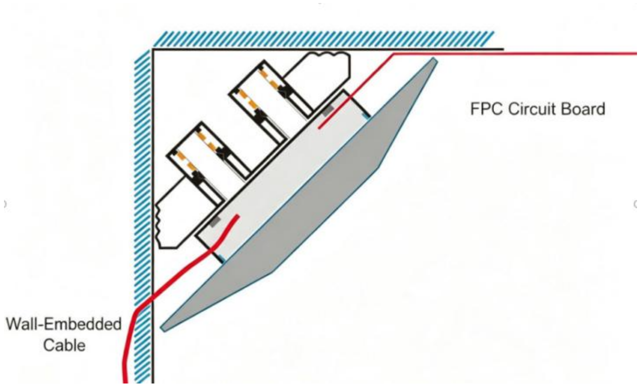
A branch box is a plug-in component that obtains power and signals from the spatial bus, which can extend to the ceiling or wall. According to the combination of track slot types and connection directions, a total of five plug-in components are provided, with decorative covers to conceal the connection interfaces. The branch box type matrix is shown in Table 3.

Table 3 Branch Box Type Matrix

Track Type	Ceiling Direction	Wall Direction	Wall-Ceiling Bidirectional
Low-voltage DC (narrow slot)	Narrow slot upward	Narrow slot downward	Dual-slot bidirectional
High-voltage AC (wide slot)	Wide slot upward	Wide slot downward	

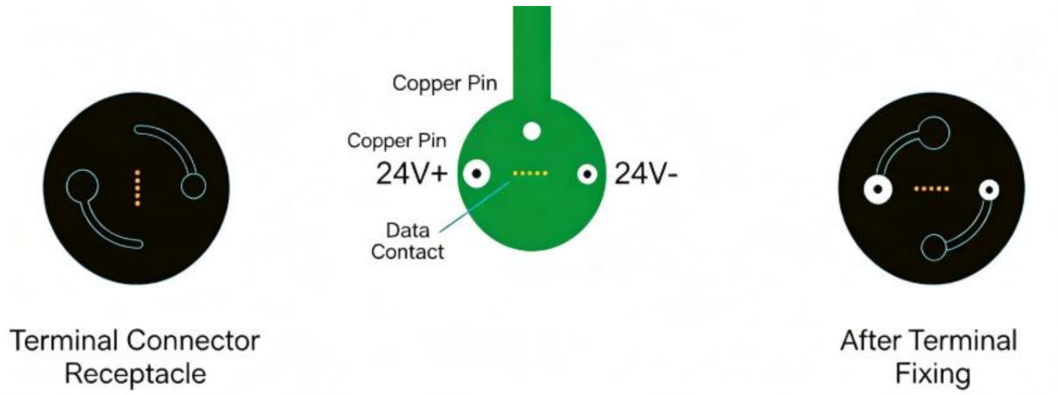
4.4.3 Branch Wiring

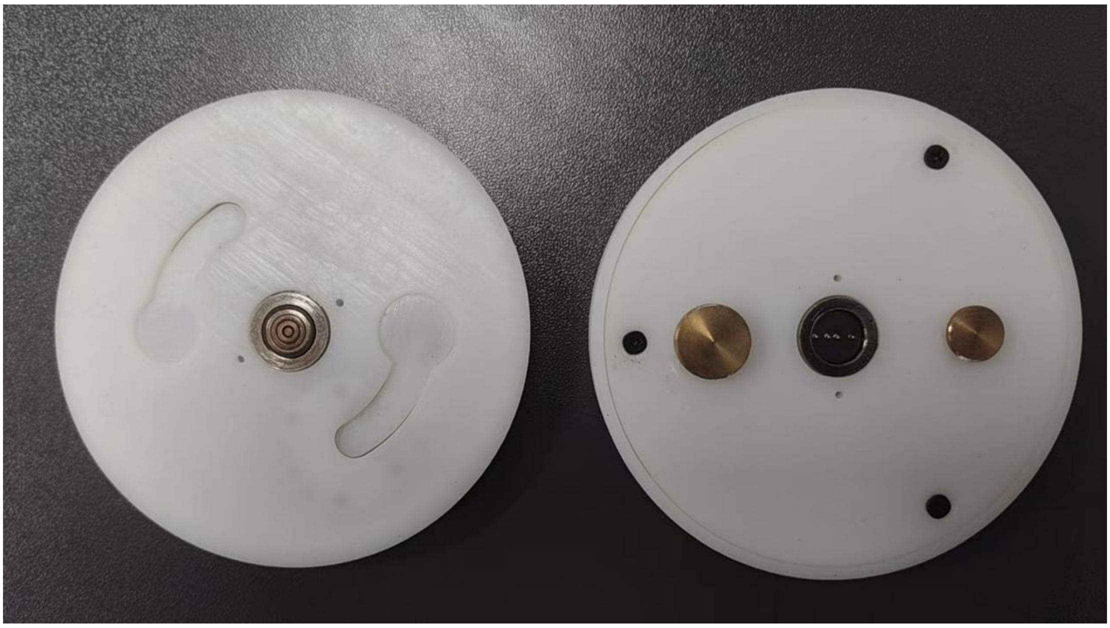
For low-voltage DC scenarios, this paper proposes a wall-mounted Flexible Printed Circuit (FPC) wiring solution. The FPC flexible board is only 0.5 mm thick and can be bent freely. It does not require wall slotting or drilling. After being pasted on the wall, it can be covered with wall cloth or leveled with paint. There is no risk of electric shock, and the installation is simple and safe [24]. AC branch wiring still adopts traditional pre-embedding technology, which is compatible with existing building codes.



4.4.4 Branch Port

To support FPC DC wiring, this paper designs a three-in-one surface-mounted base panel: no wall drilling is required, and power supply, signal transmission, and equipment fixation are realized simultaneously. The panel is only 8 mm thick, adopts a rotary locking structure for power intake. Insert and rotate clockwise to complete the connection; with an anti-reverse insertion design, taking into account operational convenience and aesthetics.





4.5 Spatial Native AI Butler

The AI butler consists of a Large Language Model (LLM), an AI Agent, and a human-computer interaction system. The LLM supports local private deployment or cloud access, and the AI Agent is deployed on the local edge computing unit. The system has long-term memory and voiceprint recognition capabilities, supports Model Context Protocol (MCP) access, and a personalized knowledge base; it can realize human-computer interaction and hardware control through voice and body movements, and supports multi-device collaboration to execute scenario-based instructions.

The system is equipped with a unified mobile application for remote control, and supports preset multi-scenario modes, including tutoring mode, parenting mode, health care mode, elderly care mode, romantic mode, e-sports mode, work mode, sleep mode, etc.

5 Implementation of Core System Functions

5.1 Dual-Standard Power Supply System

The global space adopts an independent dual-standard multi-path power supply architecture. Under the track-type bus architecture, the cost increment of this solution is extremely low, while greatly improving power supply flexibility and reducing electromagnetic interference between paths.

The system takes the power supply end of the central control host as the main control unit, and configures independent air circuit breakers for the AC power supply path (AC 110 V/AC 220 V), broadband DC power supply path (BB-DC 48 V), narrowband DC power supply path (NB-DC 48 V), central control cabinet, and energy storage system, respectively, realizing independent control of each circuit.

The dual-standard power supply system is compatible with traditional and future hardware requirements: traditional high-power home appliances adapt to the AC power supply track and can be used without modification; new intelligent hardware adopts native DC adaptation design, directly matching the DC 48 V power supply track, eliminating the need for external power adapters.

5.2 Multi-Channel PLC Communication System

Traditional pain points of deploying Power Line Communication (PLC) indoors include: poor stability due to electromagnetic noise interference, high operation and maintenance difficulty of traditional wiring, and incompatibility of PLC modules from different manufacturers [25]. The spatial hardware connection system solves the above problems from the architecture level: multi-path design physically isolates electromagnetic interference, and the surface-mounted bus and designed to achieve plug-and-play capability interfaces greatly reduce operation and maintenance difficulty, and the globally unified PLC module eliminates compatibility problems.

The system adopts a "wireless + wired" integrated communication solution: AC appliances use Bluetooth communication, Internet access uses Wi-Fi, and wired connections uniformly adopt PLC technology. The three technologies operate independently. Among them, PLC is divided into two independent channels: broadband and narrowband, which adapt to high-speed and low-speed device requirements respectively.

PLC is selected as the core communication method for DC devices because of its strong scenario adaptability: under the spatial terminalization architecture, device communication is transformed into internal bus communication. Traditional buses such as I2C, SPI, and UART have limited transmission distance (about 0.5 m) and cannot adapt to whole-house scenarios; buses such as CAN and RS-485 require twisted-pair wiring, which has poor adaptability to the track-type architecture. PLC technology can realize long-distance (over 100 meters) and high-rate data transmission without additional communication cables, and is highly compatible with the track-type architecture of the spatial agent [26].

The unified communication architecture ends the disorderly competition of communication protocols: currently, hardware manufacturers integrate multiple types of communication protocols in basic devices to improve compatibility, which is ineffective internal friction, pushing up device cost, volume, and energy consumption. Under the spatial terminalization architecture, hardware manufacturers can focus on product quality upgrading, cost optimization, and user experience improvement, fundamentally solving the problem of poor interconnection of multiple ecosystems in smart homes.

5.3 Hierarchical Wiring System

The spatial hardware connection system divides whole-house wiring into two categories: bus and branch lines, reconstructing the certainty of the wiring system. A single spatial area is only equipped with one fixed bus. The bus position is not affected by changes in device points, and has fixity, regularity, and predictability, making the power supply and communication connection of whole-house hardware standardized, quantifiable, and predictable.

The system adopts two types of branch wiring modes: AC branches follow the traditional pre-embedding technology and are compatible with existing building codes; DC 48 V DC branches adopt the FPC wall-pasting solution, which does not require slotting construction. The combination of track bus and DC branch lines realizes designed to achieve plug-and-play capability at any point in the whole house, greatly improving deployment flexibility and adaptability.

5.4 Integrated Connection Port

Relying on the standardized power supply, wiring, and communication systems, the system realizes the full unification of terminal connection ports. The integrated wall panel synchronously transmits power and communication signals through FPC, and can be quickly installed only with screw fixation. The panel adopts a three-in-one integrated design of "power supply, communication, and equipment fixation". When connecting the device, one plug and one twist can complete the whole process of connection, without manual network configuration or account verification, truly realizing hardware designed to achieve plug-and-play capability.

This design completely eliminates the external long-tail cables of devices, realizes a minimalist layout of home hardware, and eliminates material waste and potential safety hazards caused by cable redundancy.

6 Comparison of Mainstream Solutions and Advantage Analysis

6.1 Comparison of Wired Connection Solutions

6.1.1 KNX Bus

KNX is an open standard in the field of building automation, supporting multiple physical media and having cross-manufacturer interoperability. However, it relies on dedicated twisted-pair pre-embedding, and later renovation requires wall construction. The unit price of equipment is high, and system configuration requires professional engineers. It is essentially designed for commercial buildings, and has significant shortcomings in economy and ease of use in residential scenarios.

6.1.2 RS-485 Bus

RS-485 uses differential signal transmission, supports multi-node cascading, and has a communication distance of up to 1200 meters. It is widely used in the field of industrial control. However, it requires independent twisted-pair wiring, lacks unified application standards at the protocol layer, and devices from different manufacturers are difficult to achieve semantic-level interoperation. Moreover, it does not have power supply capacity and cannot solve the problem of mismatched power supply standards.

6.1.3 CAN Bus

CAN bus has high real-time performance and strong anti-interference ability, and is maturely applied in the automotive electronics field. However, it also requires dedicated twisted pairs and has poor adaptability to the track-type architecture; the number of nodes and communication rate are limited by the bus load, making it difficult to support the access of hundreds of heterogeneous devices in the whole house.

6.1.4 Ethernet (Including PoE)

Ethernet has the advantages of high bandwidth and low latency, and PoE technology can realize power supply through network cables. However, it requires independent pre-embedded network cables, the amount of cables increases linearly with the number of devices, and the construction cost is high; PoE power supply power is limited and cannot drive high-power home appliances; the central switch increases the complexity of the system and fault points.

6.2 Comparison of Wireless Connection Solutions

6.2.1 Wi-Fi

Wi-Fi has a low deployment threshold and high user awareness. However, it adopts a star topology. When the number of devices exceeds 20–30, channel congestion and delay increase significantly; each device requires an independent power supply, which cannot solve the problem of adapter redundancy; its power consumption is high, making it unsuitable for low-power sensor nodes. Wi-Fi is essentially an Internet access protocol, not a dedicated device control protocol.

6.2.2 ZigBee

ZigBee adopts Mesh networking, with low power consumption and large node capacity, suitable for sensors and switch devices. However, it requires an independent gateway, and gateways of different brands are incompatible with each other, forming a paradox of "unified protocol, fragmented ecosystem"; its communication distance is short and relies on relay nodes to expand coverage. It only solves the connection at the communication layer, and does not touch the problems of power supply and physical interfaces.

6.2.3 Bluetooth (BLE)

Bluetooth Low Energy (BLE) chips have low cost and simple pairing procedures, and are widely used in near-field control scenarios. However, its communication distance is short, wall penetration attenuation is severe, mesh networking capability is not yet mature, and the reliability of large-scale device collaboration is insufficient.

6.2.4 Z-Wave

Z-Wave adopts the Sub-GHz frequency band, with better wall penetration than ZigBee and BLE, and high stability of Mesh networking. However, it is a semi-closed protocol, with highly concentrated chip supply and certification systems, limited ecological openness, and narrow coverage of device categories.

6.2.5 Matter Protocol

The Matter protocol was launched by the Connectivity Standards Alliance (CSA), aiming to realize cross-brand device interoperability through a unified application layer. However, its unification only stays at the software communication level, and does not involve underlying specifications such as power supply, wiring, and physical interfaces. Users still face fragmented experiences such as multi-application control, multi-gateway docking, and cumbersome network configuration.

6.3 Comprehensive Comparative Analysis

The multi-dimensional comparison of wired, wireless solutions and the spatial terminalization solution is shown in Table 4.

Table 4 Comprehensive Comparison of Mainstream Connection Solutions

Comparison Dimension	Wired Solutions (KNX/RS-485/CAN/Ethernet)	Wireless Solutions (Wi-Fi/ZigBee/BLE/Z-Wave/Matter)	Spatial Terminalization Solution
Connection Level	Device-level (single-point communication)	Device-level (single-point communication)	Spatial-level (full-stack unification)
Power Supply Mode	Independent power supply, requiring extra power cords or adapters	Independent power supply, requiring extra power cords or adapters	Native bus power supply, dual AC/DC standards, adapter-free
Communication Mode	Dedicated cables (twisted pair/network cable)	Electromagnetic waves (2.4 GHz/Sub-GHz)	PLC (broadband + narrowband), power supply, and communication on the same cable
Wiring Mode	Pre-embedded pipelines, one-time construction, renovation requires wall breaking	Wiring-free (devices still need independent power supply lines)	Crown molding surface-mounted bus + FPC wall branch lines, slot-free, adjustable
Connection Port	Dedicated interfaces, not unified across brands	No physical port concept (power supply interfaces are not unified)	Three-in-one surface-mounted panel, one plug and one twist, designed to achieve plug- and-play capability
Compatibility	Compatible within the protocol, not compatible across protocols	Compatible within the protocol, fragmented across brand ecosystems	Globally unified connection rules, brand-independent, designed to achieve plug- and- play capability
Construction Complexity	High (requires professional design and pre-embedded construction)	Low (wiring-free)	Low (surface-mounted bus + wall FPC, standardized assembly)
Later Renovation	Extremely difficult (destructive wall construction)	Devices are replaceable, power supply points are limited	Flexible (fixed bus, branch ports can be freely added or removed)
Device Cost	High (dedicated cables + interface modules)	Medium (low communication module cost, redundant adapters)	Low (eliminates communication modules, adapters, and redundant cables)

User Experience	Requires professional debugging, high operation threshold	Multi-App control, cumbersome network configuration, unstable linkage	designed to achieve plug - and- play capability, no network configuration required, unified management
Data Management	Decentralized (each system is independent)	Decentralized (each brand cloud platform is independent)	Centralized (unified management by the central control cabinet)
Pre-design Requirement	Requires advance design	Requires advance design	No special design required
System Energy Consumption	High (high redundancy)	High (high redundancy)	Low (low-redundancy architecture)
Deployment Intrusiveness	Intrusive	Non-intrusive	Non-intrusive

6.4 Special Solution Comparison

6.4.1 Comparison of Power Line Communication Solutions

The comparison between existing PLC solutions and the spatial terminalization PLC solution is shown in Table 5.

Table 5 Comparison of Power Line Communication Solutions

Comparison Dimension	Existing PLC Solutions	Spatial Terminalization PLC Solution
Connection Level	Device-level (single-point communication)	Spatial-level (full-stack unification)
Power Supply Relationship	Single power supply standard, relying on existing power lines	Dual AC/DC standard multi-track power supply
Wiring Specification	No unified wiring rules, passively limited	Unified wiring rules, predictable and unrestricted
Port Characteristics	Traditional interfaces, passively limited positions	Unified interfaces, flexible configuration
Stability	Unstable and uncontrollable (random home grid topology)	Stable and controllable (fixed grid topology, multi-path isolation of interference)
Hardware Cost	High (low intelligence, high redundancy)	Low (unified management, reduced redundancy)

Detection and Maintenance	Difficult (complex lines, high construction difficulty)	Easy (simple lines, easy maintenance for surface mounting)
Management Architecture	Decentralized (each device is independent)	Centralized (unified management by the central control cabinet)
Electromagnetic Interference Isolation	Not supported	Supported
Third-party Ecological Access	Difficult	Standardized access support

6.4.2 Comparison of Software Hub Solutions

Home Assistant (HA) is a mainstream open-source smart home automation platform that supports integration with over 3000 brands and protocols. Its comparison with the spatial terminalization solution is shown in Table 6.

Table 6 Comparison between Home Assistant and Spatial Terminalization Solutions

Comparison Dimension	Home Assistant Solution	Spatial Terminalization Solution
Positioning Level	Software hub (application layer integration)	Hardware connection foundation (physical layer + data layer unification)
Core Problem Solved	Software interoperability of cross-brand devices	Full-stack hardware unification of power supply, communication, wiring, and ports
Rule Maker	Each brand hardware defines its own, HA passively adapts	Unified regulations by the spatial bus, brands actively follow
Power Supply Mode	Not involved (devices still need their own adapters)	Native bus power supply, dual AC/DC standards, adapter-free
Wiring Mode	Not involved (relying on existing lines or separate wiring)	Crown molding surface-mounted bus + FPC wall branch lines, unified specifications
Connection Port	Not involved (customized by each brand)	Unified port, designed to achieve plug- and- play capability

Deployment Threshold	Extremely high (requires IT skills, self-operation and maintenance)	Extremely low (standardized assembly, no professional debugging required)
Applicable Objects	Technology enthusiasts, geek groups	All users (including non-technical users)

In summary, none of the existing smart home solutions have fundamentally solved the two core problems of wiring and central control. The essence of wiring is to realize the unified bearing of power supply and communication, and the essence of central control is to realize global management and scheduling. Both are the underlying core of hardware connection. The spatial bus architecture reconstructs the connection system from the spatial level, which is a systematic solution to the above problems.

7 Rationality Demonstration and Universality Verification

7.1 Rationality Demonstration of Distributed Collaborative Architecture

The essential difference between smart homes and spatial agents is the difference between a combination of independent intelligent hardware and distributed heterogeneous hardware collaboration. This section provides a four-dimensional demonstration that the distributed heterogeneous collaborative architecture will eventually replace the isolated independent hardware combination.

7.1.1 Hardware Boundary Constraints: Trade-off Between Computing Power, Power Consumption, and Volume

The computing power, sensing, and power supply capabilities of any independent intelligent hardware are constrained by the physical boundary of the device body. Integrating full-category sensing and computing capabilities will lead to an exponential increase in chip power consumption, heat dissipation, and structural costs [27]. The distributed architecture realizes computing power splitting: high-computing AI units are responsible for decision-making, micro low-power sensors are responsible for perception, and actuators are responsible for actions. Each performs its own duties, and the overall power consumption and cost are much lower than those of an all-in-one single machine. Meanwhile, sensing devices need to be deployed at the point where events occur. A single central robot cannot cover all areas of the whole house, and isolated hardware can only collect local information, unable to form a global perspective, and high-level intelligent decision-making lacks data support.

7.1.2 Compatibility Defects of Isolated Hardware Combinations

Independent hardware of different brands and generations have incompatible communication protocols and data formats. Each new type of device requires separate development of docking procedures. The core of the distributed heterogeneous architecture is a universal scheduling gateway. One adaptation layer can be compatible with various heterogeneous protocols such as BLE, Matter, PLC, CAN, and Ethernet [28], can reuse existing hardware without full replacement, and has significantly better adaptation and scalability than isolated hardware stacking.

7.1.3 Full Life Cycle Cost Advantage

All-in-one isolated hardware has a high unit price, and the overall investment in whole-house deployment is high. The distributed solution deploys low-cost dedicated sensors and execution terminals on demand, and only builds one central scheduling system, resulting in lower total hardware procurement costs. In terms of iteration and upgrade, adding linkage functions to isolated hardware requires firmware upgrades one by one, and old devices are directly eliminated; distributed collaboration only requires upgrading the upper-layer scheduling algorithm and gateway strategy, and the underlying terminals can continue to be reused, greatly improving iteration efficiency.

7.1.4 Security and Compliance Advantages

The distributed architecture can realize edge hierarchical processing: sensitive local data is computed locally at the terminal and not uploaded if unnecessary; global policies are uniformly managed by the gateway [29]. Isolated hardware is connected to the network separately, and each device requires independent security protection, with more vulnerability points and greater management difficulty.

In summary, physical space hardware is naturally heterogeneous, and perception naturally requires distributed deployment. Global intelligence must rely on cross-device data collaboration. Isolated independent hardware is a local optimal solution for single-point capabilities, while the distributed heterogeneous collaborative architecture with central scheduling is a global optimal engineering solution when scenario complexity increases. The four logics of technology, cost, compliance, and industrial ecology jointly determine that it will inevitably become the main form of next-generation intelligent terminals.

7.2 Universality Verification of the Spatial Bus

The core of the universality of the spatial agent lies in the universality of the spatial bus, whose core basis is the geometric law of indoor spaces: more than 90% of indoor spaces worldwide are cuboid or cuboid composite structures [30], all following the geometric law of "opposite faces parallel, adjacent faces perpendicular," and the crown molding is a natural continuous closed carrier.

For irregular spaces, the solution has corresponding adaptation capabilities:

1. Uneven ceiling (arc-shaped, sloped roof attics): the spatial bus can be installed by adding a false ceiling to achieve a plane transition;

2. Polygonal spaces (pentagons, hexagons): adjusting the bus cutting angle can achieve seamless connection without affecting normal installation;

3. Dislocated and missing-face spaces (split-level, high-ceiling LOFT/duplex): not installing the bus on the missing side does not affect the overall system operation;

4. Non-vertical wall spaces (trapezoidal, curved, cylindrical, spherical, triangular): partition enclosures need to be added to form a flat installation surface, and the engineering complexity is relatively high.

Empirical insights for universality are drawn from the experimental prototype of crown-molding-mounted spatial bus. The research team accumulated installation experience across over 500 indoor sites with a total deployed prototype length exceeding 6000 meters in Guangdong, China. Among these sites, finished apartments constituted 55%, rough-in apartments 20%, retrofitted dwellings 15%, and commercial premises approximately 10%.

Inferred from geometric characteristics of indoor building structures and the above-mentioned prototype deployment experience, the spatial-bus concept exhibits broad applicability for indoor environments. Approximately 90% of indoor rooms follow cuboid or composite-cuboid geometric forms, while the remaining 10% belong to non-standard layouts. Many non-standard layouts can be adapted via minor structural adjustments. Only highly irregular building forms impose substantial constraints on deployment. On this empirical basis, the concept is estimated to be applicable for the vast majority of indoor apartment layouts.

7.3 Design of Subsequent Verification Schemes

The current architecture is in the conceptual verification stage, and systematic verification will be carried out from two dimensions in the future:

1. Bus connection range simulation verification: it is planned to conduct hardware wiring simulation on 500 indoor space areas through system simulation to verify the effectiveness and coverage of the bus connection range;

2. Hardware connection performance test: including dual-standard AC/DC connectivity test, broadband data transmission performance test, device control response test, narrowband connection stability test, and signal anti-interference test.

8 Implementation Effects and Application Value

8.1 Full-Link Anti-Entropy Increase Effect

The essence of hardware cable redundancy, interface redundancy, and communication module redundancy is system entropy increase caused by the disconnection between space and hardware. The spatial agent adopts the full-life-cycle anti-entropy increase design concept, realizing system simplification in the whole link:

Hard decoration wiring stage: The conceptual design aims to eliminate a series of conventional construction steps including on- site measurement, scheme design, wall slotting, pipeline threading, point opening, and landfill repair;

Hardware terminal level: stripping independent computing units such as processors, controllers, and memories, simplifying various wired interfaces, eliminating wireless communication modules and external power adapters, eliminating drilling and fixing processes, and removing power cords and signal cables;

User use stage: no device network configuration, search and pairing required, no need to download multiple applications or register multiple accounts.

From the system level, this design can reduce hardware volume, reduce energy consumption, and reduce advertising implantation and functional restrictions on terminal screens. The anti-entropy increase design not only simplifies the operation process, but also greatly reduces costs and the threshold for intelligent access.

Note: The "anti-entropy increase" referred to in this paper specifically refers to the reduction of system redundancy and the improvement of overall orderliness.

8.2 Full Life Cycle Implementation Effects

The spatial agent This conceptual architecture intends to transform the paradigm of traditional customized smart-home engineering toward standardized modular assembly workflows., reducing the threshold for implementation and use from the full life cycle.

Early deployment level: Traditional smart homes require multiple processes such as on-site survey, customized design, pre-embedded construction, and installation debugging, with high costs and strong randomness. Relying on standardized connection rules, the wiring length and device points of the spatial agent can be predicted in advance, and support flexible adjustment in the later stage, realizing the transformation from "high-cost customized engineering" to "lightweight standard assembly".

Mid-term use level: Traditional intelligent hardware has problems such as cumbersome debugging, messy cables, and complex operations. The spatial agent adopts an integrated designed to achieve plug-and-play capability logic. After the device is connected, power supply, network access, and fixation are completed simultaneously, eliminating the network configuration and debugging process, and realizing the dual improvement of use efficiency and spatial aesthetics.

Later operation and maintenance level: Under the traditional embedded installation mode, hardware iteration and pipeline replacement are difficult, which is easy to cause decoration damage and resource waste. The spatial agent adopts a modular, replaceable architecture. Functional modules can be independently disassembled and iterated without destructive construction, greatly reducing long-term operation and maintenance costs and ensuring the sustainable upgrading of the intelligent system.

8.3 Industrial Ecological Value

The spatial agent builds a non-intrusive intelligent ecological community: its architecture is physically and logically decoupled from the traditional electrical architecture. The two are misaligned and coordinated without conflict. High-power traditional home appliances can be retained in the original architecture to isolate harmonic interference and ensure the stability of the new system. Traditional smart home products can exist as non-standard systems in the space for a long time without conflict.

Standardized underlying connection specifications proposed in this work may provide reference for future household-equipment design optimization regarding form factor, cost, functionality and power consumption. The proposed non-intrusive architectural paradigm exhibits adaptability for multiple building conditions including rough-in, finished and retrofitted residences across different building life-cycle stages. Furthermore, the unified spatial-coordinate framework supplies fundamental spatial semantics for emerging applications such as digital twins and embodied AI, supporting millimeter-scale virtual-physical mapping, cross-modal perception and global path-planning for intelligent agents.

The unified spatial coordinate system provides the underlying "spatial language" for cutting-edge applications such as the metaverse, digital twins, and embodied AI. By establishing unique coordinates and absolute positional relationships of spatial elements, logical errors caused by ambiguous spatial semantics can be avoided, enabling virtual-real interaction to reach millimeter-level accuracy, supporting high-level applications such as cross-modal perception, global path planning, and accurate behavior prediction, and promoting the human-machine-object integrated intelligent space to a higher level of development [31]. The implementation of world models and autonomous intelligence also relies on a standardized physical space framework as support [32][33].

9 Conclusion and Prospect

This paper systematically proposes the "spatial terminalization" theory and the "spatial agent" architecture design. The core achievements include three levels:

1. Theoretical level: proposing the concept of spatial native Internet, defining indoor physical space with independent property rights as the next-generation Internet terminal form, establishing a complete conceptual framework, and providing a new theoretical perspective for the physical implementation of embodied AI and world models;

2. Architectural level: designing a complete spatial agent architecture with the spatial bus, spatial origin, central control cabinet, and hardware connection system as the core, realizing full-stack unification of power supply, communication, wiring, and ports;

3. Engineering level: Drawing upon multi-site deployment experience of the crown-molding-mounted experimental prototype, this work provides preliminary analysis showing broad potential applicability of the spatial-bus concept for most indoor layouts.

Future work will focus on three directions: first, completing large-scale simulation verification of the bus connection range; second, carrying out systematic hardware tests of dual-standard connectivity, broadband transmission, device control, narrowband connection, and signal stability; third, promoting the formulation of industry standards and industrialization of the spatial bus.

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