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Enabling smart campus indoor spaces through spatial modeling with the IMDF Platform

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ABSTRACT

Smart campus is developed to deliver intelligent, user-centric services by leveraging IoT and big data to optimize the management of resources, spaces, and campus-wide activities. Its architecture relies on three core technological pillars: (1) Internet of Things (IoT) for collecting real-time data from the physical environment, (2) cloud computing for processing and storing both spatial and non-spatial data at scale, and (3) intelligent analytics that apply machine learning and data mining for automated decision-making and anomaly detection. Among these, spatial data, especially indoor spatial data, plays a vital role in enabling services such as indoor navigation, resource allocation, and environmental monitoring. However, the lack of standardization and poor interoperability with IoT systems remain key barriers to the effective use of indoor spatial data. To overcome this, this paper proposes a unified approach that leverages the Indoor Mapping Data Format (IMDF) as part of the spatial data infrastructure (SDI) for smart campuses. By integrating IMDF with the OGC SensorThings API, referred to as the digital nervous system (DNS) in a smart campus architecture, the approach helps build a flexible, real-time responsive indoor mapping system. This solution aims to standardize and optimize the connection between IoT data and indoor maps, thereby improving user experience and operational efficiency of smart campuses.

1. INTRODUCTION

A smart campus integrates intelligent technologies to enhance teaching and learning efficiency while optimizing resource and environmental management within the campus. These systems provide IT services that support automation and real-time monitoring, spanning academic activities to infrastructure management (Muhamad et al., 2017). The smart campus architecture is built on three core components: (1) Internet of Things (IoT), which collects real-time data from environmental sensors, electrical devices, and user behavior to link the physical world with digital models (Ye et al., 2024), (2) Cloud computing, which stores and processes large-scale data by integrating spatial data, such as maps and locations, with non-spatial data, including academic records and administration (Liu & Wang, 2024) and (3) Intelligent analytics, which employs machine learning to extract insights and automate decision-making. Among these core components, spatial data plays a critical role in visualization and enhancing user experiences by supporting navigation, space management, and environmental monitoring. While outdoor spatial data is supported by mature platforms like Google Maps and OpenStreetMap, indoor spatial data faces challenges such as lack of standardization, difficulty integrating with IoT, and limited real-time information (Muhamad et al., 2017). Besides, current indoor systems are frequently isolated and lack integration, hindering navigation and device monitoring capabilities.

To address the aforementioned challenges related to indoor spatial data, the proposed smart campus architecture incorporates the IMDF platform as a key component. This platform was developed as part of the authors' research on IoT system integration in indoor environments (Sharma et al., 2020). It is based on the Indoor Mapping Data Format (IMDF) (Apple Inc., 2021; OGC, 2025a), a standard for representing indoor spatial data, developed by Apple and officially recognized by the Open Geospatial Consortium (OGC) - an international organization responsible for developing and maintaining open geospatial standards to ensure interoperability across systems (OGC, 2025b). The IMDF platform resolves these challenges thanks to its standardized data model and API for managing indoor spatial data. Its design facilitates integration with IoT systems for better coordination between spatial and sensor data. In this way, it acts as the spatial backbone of the smart campus, also aiding in the connection of spatial and non-spatial information.

In this context, this paper presents the practical implementation of the IMDF platform within indoor smart campus environments. The core content is detailed in the section IMDF-Based Indoor Smart Campus, which is structured into three main parts: (1) A generalized architecture for indoor smart campuses, (2) The IMDF platform as a standardized indoor spatial data infrastructure and (3) The integration of the IMDF platform with the Digital Nervous System (DNS) enabling seamless coordination between spatial data and IoT systems. The section that follows demonstrates how the IMDF platform has been practically implemented at Can Tho University, supporting real-time device monitoring, space management, and interactive visualization of indoor IoT infrastructure in a real-world smart campus scenario.

2. RELATED WORKS

2.1. Smart Campus

A smart campus is a miniaturized smart city model within university campuses, where information and communication technologies, IoT systems, and data services are integrated to optimize management, enhance sustainability, and improve user experience. Based on the research presented in Towards a Novel Architecture of Smart Campuses Based on Spatial Data Infrastructure and Distributed Ontology (Hoang et al., 2021), the three key principles of smart campus include distributed ontology, service-oriented architecture (SOA), and spatial data infrastructure (SDI). The proposed architectural solution integrates two groups of IT systems: local enterprise information systems (EISs) that manage non-spatial data, and SDI that processes spatial data, using WFS (Web Feature Service) (OGC, 2025c) to provide spatial data, Domain-based web service (DWS) to process non-spatial data and bind semantic meaning to distributed ontology, creating a flexible foundation that is easy to deploy in complex environments. According to (Xuan et al., 2024), the Digital Nervous System (DNS) model inspired by the human nervous system is introduced, applying the OGC SensorThings API standard to uniformly manage sensors and actuators. This model helps smart campuses achieve self-recovery and become the system that processes and circulates sensor signals (Xuan et al., 2024).

In summary, smart campus architecture now has a solid foundation with two core components: real-time sensor data systems and spatial data infrastructure. Among these, the Digital Nervous System (DNS) through SensorThings API has completed the sensor data processing and distribution aspect (Xuan et al., 2024), while spatial data infrastructure still needs further development to serve as the architectural backbone, supporting spatial organization, entity linking, and overall system completion (Hoang et al., 2021).

2.2. Indoor data and IMDF

Spatial data issues are becoming increasingly important on smart campuses due to the need for accurate and efficient infrastructure monitoring and management. Spatial data is divided into two main types: outdoor and indoor, where indoor space - such as building layouts, corridors, functional rooms, and internal routes - requires specialized solutions. Many studies have developed digital interior maps for universities to support positioning and navigation within buildings by converting CAD data into graphical models and storing them as graphs for routing algorithms (Świtalski & Salamończyk, 2023), as well as indoor space management systems based on Building Information Modeling (BIM), combining space usage analysis and improved A* algorithms to provide smooth and intuitive navigation on mobile devices (Ma et al., 2020).

The indoor data lifecycle includes: (1) collection, (2) management, (3) sharing, and (4) analysis-service exploitation, where the indoor spatial data model serves as the theoretical foundation for organizing and connecting topological entities (Kang & Li, 2017). IFC and CityGML (OGC, 2021) provide 3D formats but lack detailed descriptions of internal topological connections, while IndoorGML is strong in navigation network and topological models but not yet optimized for visualization and mobile integration (OGC, 2021). In this context, Indoor Mapping Data Format (IMDF) emerges as a comprehensive solution with a simple geometric representation (GeoJSON), clear layer structure (venue, unit, level, amenity, anchor, etc.), mobile-friendly design compatible with modern mapping ecosystems, and easy integration with SensorThings API to create a "Digital Nervous System" for a smart campus.

2.3. SensorThings API

SensorThings API is an open standard by the Open Geospatial Consortium, providing a unified, geospatially-enabled approach to connect IoT devices, data, and applications on the Web, comprising two main functions: Sensing and Tasking (OGC, 2025b). The Sensing part defines a data model with key entities such as Thing, Sensor, Datastream, and Observation, which collectively support the observation and retrieval of real-world data from sensors. In contrast, the Tasking part models TaskingCapability (device execution capabilities) and Task (instructions sent to devices), enabling the remote control and actuation of IoT devices. At Can Tho University, SensorThings-API (CusC, 2025) has been implemented with both parts, enabling the system to self-adjust and respond quickly to environmental events (Xuan et al., 2024). This standard follows REST architecture, uses an efficient JSON format, and supports MQTT (Light, 2017) for lightweight and flexible data transmission (Liang et al., 2021; Liang & Khalafbeigi, 2019). Due to its high degree of standardization and flexible integration with other services, the SensorThings API has played a fundamental role in smart campus solutions (Xuan et al., 2024).

3. IMDF-BASED INDOOR SMART CAMPUS

3.1. Generalized indoor smart campus architecture

In a smart campus, the physical infrastructure and information systems coexist and work in synergy to support the overall management and operation of the campus. The physical infrastructure encompasses the entire campus space, including academic buildings and internal facilities, along with a network of wireless sensor devices (WSN/IoT) deployed to collect real-time data on environmental conditions, activity levels, and resource usage. On the other hand, information systems play a critical role in digitalizing administrative processes and coordinating operations across the physical infrastructure. These systems may include services such as classroom management, equipment status tracking, environmental monitoring, energy coordination, and data analytics to support decision-making.

To ensure seamless connectivity and synchronization between the physical infrastructure and supporting information systems, a three-layer system architecture has been proposed for smart campuses: (1) Sensing and IoT Layer (WSN/IoT Layer): This layer comprises IoT sensors and wireless sensor networks (WSNs) (Matin & Islam, 2012) responsible for collecting real-time field data. It is designed to accommodate a wide range of communication technologies, such as LoRa, Wi-Fi, and Zigbee, depending on transmission distance requirements. (2) Core Services Layer: This layer provides essential services for collecting, managing, and retrieving real-time data from sensing devices, as well as managing spatial data models for campus infrastructure. It acts as the digital backbone for the campus's operational data. (3) Integration Layer: Serving as the interface between subsystems, this layer integrates data from the core services and delivers end-user applications. It enables intelligent monitoring, control, and management across various campus operations (Figure 1).

In the specific implementation of this architecture at Can Tho University, the Indoor Mapping Data Format (IMDF) platform plays a critical role within the Core Services Layer, particularly in managing spatial data. IMDF organizes spatial information using a structured data model based on the IMDF standard and supports spatial visualization, enabling users to better interpret and respond to spatial data through interactive maps and interfaces via the IMDF API.

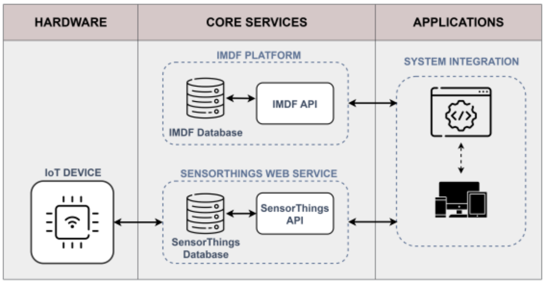

Figure 1. Architecture of the smart campus system or indoor spaces

Furthermore, since the Core Services Layer also incorporates SensorThings API for managing and retrieving sensor data—an essential component of the smart campus's Digital Nervous System (Xuan et al., 2024), the IMDF platform can be flexibly integrated with SensorThings. This integration enables intuitive and efficient real-time sensor data visualization, supporting campus-wide monitoring and decision-making.

The subsequent sections of this paper will explore the practical application of the IMDF platform within the smart campus architecture as outlined above.

3.2. IMDF platform as an essential component of spatial data infrastructure

Emerging intelligent systems increasingly demand seamless human–digital system interaction. Within any organization or enterprise, a wide range of data infrastructure services exists across diverse domains. These services often provide raw data with limited semantic context, raising the critical question: how can such data be interpreted and interacted with in an intuitive and meaningful way? The Indoor Mapping Data Format (IMDF) is identified as a key solution to this challenge.

According to the Open Geospatial Consortium (OGC), IMDF provides a generalized yet comprehensive data model for representing any indoor space, serving as a foundation for navigation, orientation, and spatial awareness (OGC, 2025a). This standard defines how indoor spatial objects are modeled, including their properties and interrelationships, enabling simulation and visualization of indoor environments ranging from small buildings to large-scale urban. Building upon this specification, we have designed an IMDF data model and developed an IMDF-platform that delivers standardized indoor spatial data to external systems. This allows seamless integration and utilization of indoor geospatial information in broader smart applications, particularly in smart campus environments (Figure 2).

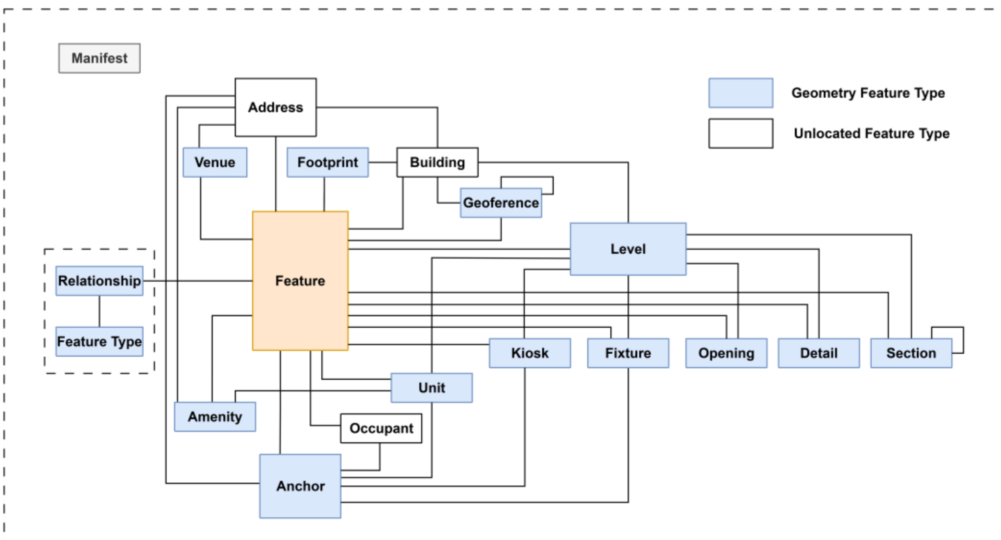

Figure 2. Spatial data model based on the IMDF standard

Following a service-oriented architecture, IMDF-based data can be served through RESTful APIs, providing standardized spatial data services that act as a visualization layer for information systems and enabling a semantically enriched representation of indoor environments. IMDF may be integrated into intelligent systems to support three key application scenarios: (1) As a static model derived from real-world physical entities, facilitating spatial awareness and enabling exploration, navigation, and orientation—for example: campuses, buildings, floors, classrooms, furniture, and devices, (2) As a spatial framework for linking and visualizing non-spatial data, allowing users to access semantically enriched, real-time information associated with spatial objects. For instance, querying how many occupants a classroom can hold or which subject is being taught at a specific time, (3) As a semantic-enhanced interface layer for IoT systems. While most IoT platforms focus on real-time sensing and control, they often lack spatial awareness—for example: Where is the device installed? Which object is being monitored?

Through RESTful APIs, the IMDF platform enables campuses to spatially anchor their digital services and facilitates integration of physical infrastructure with virtual systems. The following section discusses how IMDF can be integrated with other standalone services to construct a user-centric, semantically enriched, and intelligent system.

3.3. Integration of the IMDF platform and the digital nervous system (DNS)

As aforementioned, the Digital Nervous System (DNS) based on the OGC SensorThings API serves as the core of a smart campus system, enabling real-time monitoring, automated control, and intelligent decision-making. However, while these functions are crucial, a truly effective smart campus must remain human- and community-centric. A system with only the DNS may be "intelligent," but it is not yet "complete"—lacking intuitive, user-friendly interaction. Just as the human body requires not only a nervous system but also a skeletal framework for structure, the IMDF (Indoor Mapping Data Format) serves as a spatial backbone that enhances semantic understanding and spatial awareness when combined with the DNS.

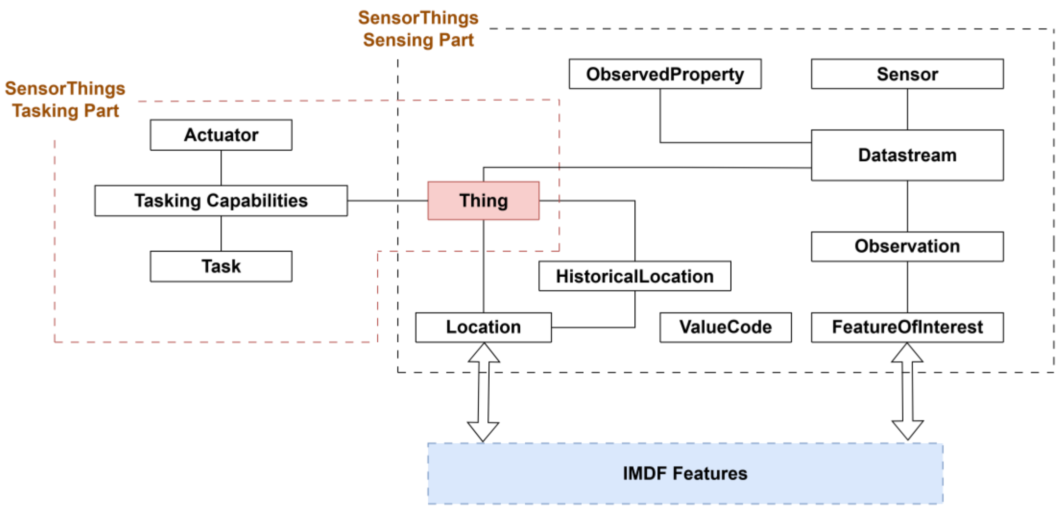

Figure 3. Integrated Model between the IMDF Platform and the SensorThings API

In SensorThings, the "Thing" is the central entity being observed—either physical or abstract—connected to sensors or data sources (Liang et al., 2021). For example, an indoor air quality station that monitors CO2 and PM2.5 levels is modeled as a "Thing" with associated components such as Location (where it is) and FeatureOfInterest (what it observes). However, these spatial descriptors are often limited in semantic richness, particularly in complex indoor environments involving numerous heterogeneous physical objects.

IMDF addresses this gap by providing a structured spatial model with rich semantic relationships between features. It allows the system to more fully answer the questions: what is being measured, for whom, where, and for what purpose. The proposed architecture maps SensorThings' spatial components (Location, FeatureOfInterest) to corresponding IMDF features via RESTful APIs, enabling a semantically enhanced and spatially aware smart campus environment (Figure 3).

4. APPLICATION

The IMDF platform is regarded as a core infrastructure component in smart campus systems, particularly in modeling indoor spaces. Although inherently static, IMDF offers a lightweight, JSON-based data structure that facilitates the development of flexible, RESTful APIs, making it easy to integrate and extend (Table 1). This paper proposes the integration of IMDF with the "Digital Nervous System", a system based on the OGC SensorThings API, to create an interactive and visual platform capable of mapping and interacting with physical entities in real time.

The system is prototyped at Can Tho University through the research project "A Microservice-Based Architecture for IoT Systems Integration on Indoor Mapping Platforms" conducted by the authors. As previously outlined, the proposed system architecture also comprises three layers:

– Hardware Layer: This layer employs IoT technologies, including wireless sensor networks utilizing Mesh network architecture to ensure reliable data transmission in complex environments such as buildings or large campuses.

– Core Services Layer: This layer manages indoor spatial data using the IMDF platform and processes both real-time sensor observations and IoT device metadata through the OGC SensorThings API (Table 2). IMDF acts as the structural backbone, offering a domain-specific data model that captures not only the geometry of indoor spaces but also their semantics via functional labels and classifications, enabling contextual understanding of each area. The SensorThings API provides a standardized framework for observing sensor data (via the Sensing part) and issuing control commands to devices (via the Tasking part). In our prototype, the system monitors air quality, including PM2.5 levels, and can respond intelligently—for instance, by forecasting pollution trends or automatically activating air filtration systems in real time.

Table 1. Output sample of IMDF

Data values	Description
{	
"**id**": "5f7c0d66-1d1a-49cf-8c80-74b72cd18a09",	Identification
"**type**": "Feature",	Feature type
"**feature_type**": "unit",	IMDF feature type
"**geometry**": {	Geometry attribute
"**type**": "Polygon",	Geometry data type
"**coordinates**": [[[11774149.11892,1122434.23729], [11774153.123175,1122438.8592323], [11774166.898972,1122426.7679628], [11774162.894717,1122422.1460236], [11774149.11892,1122434.23729]]]	Geodesic coordinates
},	
"**properties**": {	
"**category**": "room",	Feature category
"**name**": {	Feature instance name
"**en**": "FACULTY OF SOFTWARE ENGINEERING" },	
"**alt_name**": {	Alternative name
"**en**": "FSE"	Language tag attribute
},	
"**display_point**": {	Display point geometry
"**type**": "Point",	
"**coordinates**": [1122429.365,11774159.347]},	
"**level_id**":"c8c333cd-764b-49c8-aae0-34628489b209"	ID of the related feature
}}	

Table 1 demonstrates a sample of Unit feature data from IMDF. Through the API GET request "http://api-host/api/v1.0.0/units/5f7c0d66-1d1a-49cf-8c80-74b72cd18a09", we define the room as a Unit feature, determined by its category properties. By using geometry attributes, we can visualize the polygon on a map with the real coordinates of a specific object.

Table 2. SensorThings API observation output with IMDF feature

Data values	Description
{	
"**id**": 214296,	Identification
"**result**": [23.5],	Observed Value
"**resultTime**": "2024-11-07 14:02:49",	Observation Time
"**FeatureOfInterest**": {	Object Being Observed
"**id**": 1,	Identification
"**name**": "FACULTY OF SOFTWARE ENGINEERING",	Object name
"**description**": "A observed feature of interest",	Object Description
"**encodingType**": "application/vnd.geo+json",	Encoding type
"**properties**": {	
"**feature_id**":"5f7c0d66-1d1a-49cf-8c80-74b72cd18a09"	Feature ID mapping to an IMDF feature
}}}	

Table 2 illustrates the integration between IMDF features and the SensorThings API, where datastreams are linked to a Unit feature in order to establish the relationship between the sensor measurements and the physical object being observed.

– Integration and Visualization Layer: This layer provides comprehensive spatial awareness and visualization for the IoT system (Figure 4). The web-based platform includes a dashboard for real-time monitoring, offering an intuitive visual representation of sensor data (Figure 5).

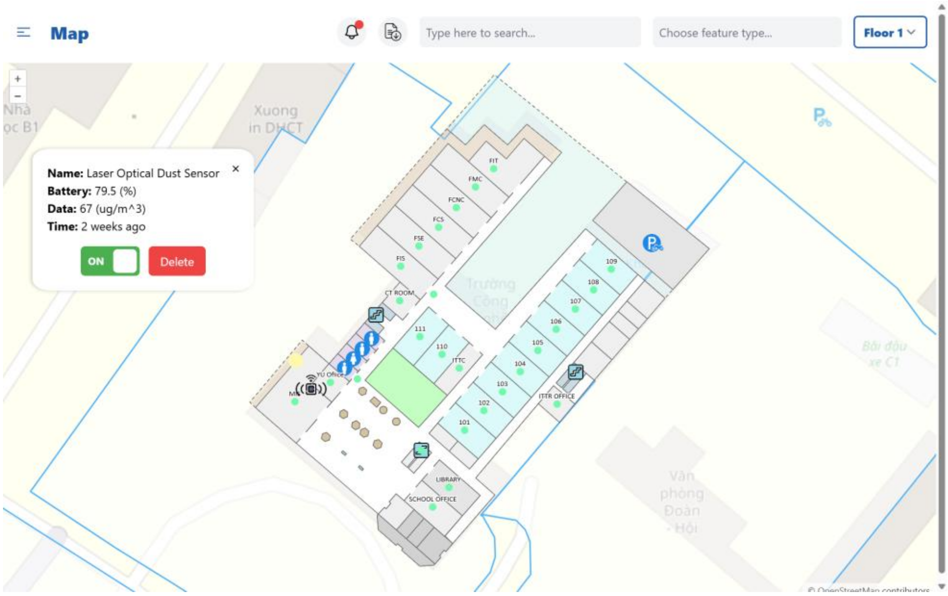

Figure 4. A digital indoor spatial model with real–virtual interaction capabilities

Figure 4 represents physical indoor spatial objects as interactive virtual objects on the map

Previous work has demonstrated that the OGC SensorThings API performs well in real-world IoT deployments. For example, Huang & Wu (2016) developed an interoperable application extending SensorThings API to support tasking capabilities across diverse devices, showing that the standard can support integration with heterogeneous hardware without prohibitive overhead (Huang & Wu, 2016). Wageningen University & Research (2020) used SensorThings API at the core of sensor-to-decision workflows in environmental monitoring projects dealing with multiple sensor types and large volumes of time-series data (Wageningen University & Research, 2020). More recently, de Sousa et al. (2024) showed that SensorThings API can manage semantic richness and linked data in large use-cases like soil data collection (de Sousa et al., 2024). These prior studies suggest that our architecture, which builds upon SensorThings and IMDF standards, has a strong foundation for achieving acceptable performance. While we have not yet conducted quantitative measurements of latency, throughput, or resource usage in our specific smart campus context, we expect similar behavior given our system's modular three-layer design and the proven performance of its components in related work.

Figure 5. Real-time sensor data dashboard for indoor environmental monitoring

The dashboard provides a graphical representation of data collected from indoor sensors via SensorThings API

5. CONCLUSION

In conclusion, this study proposes an integrated solution in which the Indoor Mapping Data Format (IMDF) is adopted as a component within the spatial data infrastructure (SDI) of a smart campus architecture. By integrating the OGC SensorThings API, the system supports both sensing and tasking capabilities, while enabling indoor spatial visualization based on IMDF. The proposed solution delivers three core values: (1) A comprehensive architecture for smart campus systems in indoor environments, enabling the integration of spatial, sensing, and control components, (2) The generation of digital models for indoor spatial objects derived from the physical environment, and (3) The combination of real-time monitoring and responsive control with enhanced visualization and semantic support.

The system was implemented at Can Tho University, demonstrating both feasibility and scalability. Its modular nature allows for easy integration and extensibility, paving the way for potential deployment in larger-scale smart city environments. Future work will focus on the integration of non-spatial services into the IMDF-based framework to optimize system-wide semantic representation, as well as the incorporation of machine learning models to address various challenges such as optimal device placement, intelligent alerting, and decision-making.

CONFLICT OF INTEREST

The authors have no competing interests to declare that are relevant to the content of this article.

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