Service and application under cyber physical system: information integrating and sharing for smart buildings and facilities in real-time

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Abstract

To achieve a more efficient and economical use of resources while providing a safe and comfortable environment for occupants, smart buildings are designed or retrofitted to progressively integrate future technological developments based on existing, widely used technologies. Cyber-physical systems (CPS), controlled or monitored by computer-based algorithms, can seamlessly connect digital and physical spaces to improve the adaptability, autonomy, efficiency, functionality, reliability, security, and availability of smart buildings.

In a smart building with CPS, people perform various interactivities, and in addition, multiple autonomous/non-autonomous heterogeneous facility/devices are connected to a control network, and each usage/generated data is stored in its database. The collection pattern and structure of such a database must be understood by both humans and machines for the realization of smart buildings.

We model the database of the CPS with an ontology semantic system to improve the interoperability of applications and system services. The CPS-oriented ontology designed in this study focuses on integrating information from both temporal/spatial dimensions, as well as the event processing strategies they support, and establishes an ontological framework with representative background knowledge. For data and connections with different conditions and functions, the knowledge graph built based on this ontology describes them as entities in different domains and as relationships between entities. It serves as the infrastructure for the CPS database, that the knowledge graph of the smart building then can be queried, discovered, and shared across applications. On the basis of a partial classical domain ontology, combined with the required expressions, we give formal definitions of the main concepts and properties, as well as the hierarchical relations between the cross-subject concepts. The emergency drill scenario is used to finally testify the proposed ontology.

Keywords

Digital twin, Ontology, Knowledge graph, Data integration.

1. Introduction

Recent advances in sensing, networking and intelligence technologies have led to the rapid emergence of smart buildings as a reality. Related research objectives range from low-level data acquisition by sensors to high-level contextual knowledge integration and inference. When data generated by human activities as well as smart building systems are correctly and automatically identified, a wide range of applications and services become possible, such as autonomous mobility, consumption management, security management, etc. [1]. The concept of Cyber-Physical Systems (CPS), proposed as a complex, multidisciplinary, human-computer interacting engineering system, has penetrated all aspects of the daily activities of smart buildings. It integrates the physical world into cyberspace, or a digital twin, for optimization and interpretation using computing technology, communication control, convergence of information and physical processing [2].

A desirable CPS for a smart building is assumed to have the ability to facilitate the integration of data between multiple real/virtual devices and facilities in real time by storing and unifying the data [3]. For example, it may generate and update virtual duplication in real time by using certain game engines and integrates various data that are shared among multiple services for realistic spatial control. Data utilized/generated from such system, not to mention those reproduced in the CPS, often show a lack of semantic information and topologic relationships. Furthermore, data can be incomplete, unreliable, incorrect, also one type of information can be expressed by different physical measures. To process heterogeneous data of various sources, it is important for the data processing platform to realize both the integration of information and the interoperability of applications. Ontological modeling is used to explicitly specify core concepts and their attributes within the problem domain to identify and describe entities and their relationships. These concepts are organized and diagrammed in a hierarchy to form class and subclass relationships [4]. With such a knowledge representation of the graph structure, it becomes possible for the service provider to search and retrieve the necessary information based on the graph and to use it for analysis based on the patterns of the graph [5].

In this study, we designed a CPS-oriented ontology, Spatial-temporal urban digital twin Ontology, describing entities of people, objects, data, etc. under various domains and relationships among them. It can build enough application scenarios in the virtual space to reproduce realistic smart building life, optimize data management, simulate special scenes, etc. according to actual demands. This allows our application developers to easily retrieve and analyze the information they need for service and physical/virtual space control. Moreover, as one of the use cases of a smart building CPS, the scenario of emergency drill is applied with the proposed ontology and constructed for a knowledge graph, in order to testify the practicality and applicability of the designed ontology. Here, for the key spatial information metadata obtained, we indicate the method used to transform the building structure data.

The paper is organized as follows: Section 2 introduced related work for laying the research ground and technology comparison. Section 3 details the design method of the proposed ontology. Section 4 uses an actual example to verify the proposed ontology. Finally, Section 5 summarizes the whole work.

2. Related work

2. 1 Cyber-physical system

A Cyber-Physical System (CPS) represents a higher degree of integration and coordination between physical and computational elements. It deeply interweaves physical and software components at multiple spatial and temporal scales. Sophisticated system designs can execute and interact with multiple behaviors as the environment changes [6]. As shown in Figure 1, a mature CPS typically has an interactive network of physical inputs and outputs, with a design philosophy closely related to a network of robots and sensors [7], combined with a practical, intelligent mechanism that is dominant in smart buildings.

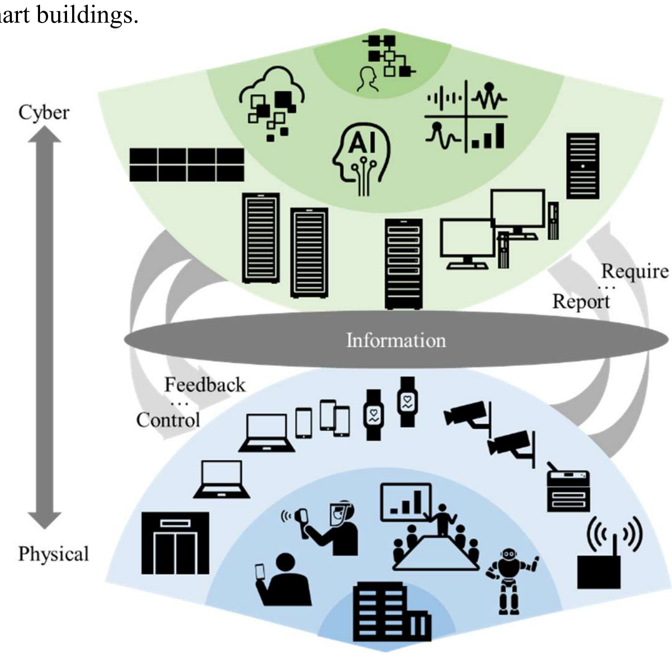

Fig. 1. Architecture of cyber-physical system

An advanced CPS is expected to share and reproduce spatial and temporal data and establish a digital twin of smart buildings, which means it can enable better decision-making and control in real-world environments through virtual rehearsal/deduction. In such context, such CPS platform should own semantic knowledge of the static environment information and various dynamic living scenes, which enables machines to recognize surroundings to collaborate under shared space and contextual awareness with humans and facilities.

2. 2 Ontological modeling

On the one hand, ontologies help to achieve a natural abstraction of the topology of the entity-relationship network that can support interoperability. On the other hand, a logical and clear hierarchical design as well as reasoning techniques can both simplify the modeling process and support the implementation of complex intelligent behaviors within smart buildings.

Regarding semantic databases applied to smart spaces, many studies have proposed various domain ontologies to simulate and model them. Some of them focus on smart systems in small spatial scopes, such as smart homes, smart offices, etc. Most of them pay attention to the interactivity between humans and their surroundings and consider the data updates generated by various activities at certain level, such as COSE (Casas Ontology for Smart Environments) Ontology, SOUPA (Standard Ontology for Ubiquitous and Pervasive Applications), etc. [8, 9]. However, due to the small scope of activity space, they involve limited scenarios, people, and objects, with long data update cycle. Some ontologies extend the spatial scope to the building level, but they focus more on the optimal integration of equipment and facilities without considering the activities and interventions for human beings, while the updates in the time dimension are also limited, such as RealEstateCore Ontology, etc. [10]. Meanwhile some domain ontologies focus aims at the extension of human activities on the time scale, with limited consideration for space, such as COBRA-ONT (COntext BRoker Architecture-ONTology) [11], etc. "Spatial-temporal urban digital twin Ontology" presented in this study takes into account the relationship between smart buildings and the activities of people in them and is accurate in the 3D spatial dimension and updated in real time in the temporal dimension. It fills a gap in the CPS field and can be used both as a base line and as a framework to provide a database model for a wide range of specific services and application scenarios together with other domain ontologies.

3. Methodology

A well-designed ontology helps realize the goal of smart building CPS by integrating heterogeneous data and allowing a common understanding shared in one building or buildings. When designing the Spatial-temporal urban digital twin Ontology, we took into account these points: first, considering the number of projects and packages, the proposed ontology enables the reuse of classic domain knowledge; second, the proposed ontology makes domain assumptions explicit so that specific use cases (e.g., emergency drills) can verify these assumptions and alter them if needed; and finally, the proposed ontology was developed with compatibility for its powerful mechanisms being able to framing other components.

3. 1 Core concept

The proposed ontology describes data in two categories: static data, including metadata of building information, people, devices and facilities, and their objects/data attributes (object attributes refer to substantial, point-to-point, relationships between entities, while data attributes, especially spatial and temporal attributes, can be assigned as variables to entities.) and relationships; dynamic data, which is responsible for carrying external inflow data, event information, etc., updates the attributes and relationships, and specific temporal/spatial data will be written into the knowledge graph as entities linking to static data directly.

For the development of functions and applications around the core concepts of CPS, spatial and temporal data are critical. Every entity present in the building should be wrapped with corresponding object attributes and data properties: for spatial positioning, first, we refer to the metadata that is properly extracted and transformed from the BIM data, waiting for be linked to any device, man or activity entity as the object attribute, then, an entity can be assigned to a point (x, y and z coordinates), a 2D (2 Dimensional) plane or a 3D (3 Dimensional) volume with specific value as the data attribute. Such a labeling method is appropriate for aggregating multi-source data into a plane or volume; for temporal positioning, first, there should be a temporal entity branch as an object attribute that allows us to dynamically describe events and activities unfolding along the timeline, and then, events and activities also have specific temporal data attributes. Both attributes should be designed with "time interval" and "time stamp" to provide different perspectives of time. Note that the convention of using timestamps needs to be specified, which means that it should be clear whether the timestamp indicates the beginning, middle or end of a discrete time interval.

The required ontology supposed to be categorized as follows:

- Agent: It is to organize information of man as well as the machinery with autonomous activities. Its functionality is twofold: first, describing objective information about an individual (e.g., name and age) and identifying his/her role (e.g., employee, customer, etc.). Both can be changed for multiple events with one individual or one event with multiple individuals, therefore this class is designed to capture and adapt this complexity.
- Factor: For smart buildings, a large number of IoT devices is inevitable, and these devices constitute an e-physical network for information interoperability and sharing. In addition to electronic devices with simple functions, such as printers, air conditioning units (whose state is, of course, crucial for energy/resource optimization), we focus more on sensors. Most of the CPS in-flow data should be streams of time-stamped values generated by heterogeneous sensors deployed in the building or attached to the agent.
- Product: It is to record the impact on the building environment caused by the results of activities and events. Even though the impacts are the result of dynamic activities or events (e.g., machine damage, facility recovery, etc.), they are written in static final result-labels or process-logs to reduce the data redundancy in the database.
- Spatial info: As discussed before, for modelling the common location knowledge in smart buildings, all building units in a smart building, such as offices, meeting rooms, activity centers, etc., can be describe as an entity to position agents, factors, events, etc.
- Event: We designed two branches: active events, which are interactions initiated by agents, i.e., activity; passive events caused by some non-human or unintentional human factors, and it also includes experience to record reactions, behaviors, etc. of agents in those events. Moreover, to establish a close association with spatial info, the relationships of event locations are described as a special branch. Each event entity is initially provided by the sensor data and recorded after data processing, which necessarily involves other dynamic/static subjects, such as spatial location, agent, time, etc.
- Data: All the data entities are provided by a variety of heterogeneous real or virtual sensors. Data collected from different sensors are completely different in data format, and the lack of a unified representation of theses data can lead to weak interoperability and reusability. This class is designed to provide a mechanism to manage perceptible data and annotate such heterogeneous data with peer-to-peer semantics, and ultimately improving interoperability and providing contextual information.
- Occurrent: As mentioned before, it consists of time interval and time stamp, in order to concretize the timeline and to establish a sound temporal space for subsequent analysis. They will be associated with events, agents, etc., therefore, the occurrent entities may be added, subtracted and changed at any time.

3. 2 Framework and conceptual modules

Having studied existing domain ontologies [12, 13], though none can completely meet all our requirements, certain relevant ontologies or design patterns can be partially reused. Therefore, the Spatial-temporal urban digital twin Ontology we proposed connects and alters a series of ontologies for describing various sub-domains required for contextual knowledge modeling, and for most of the special smart building applications, we design the corresponding classes from scratch.

The more generic an ontology is, the more likely it is to be usable, but the less likely it is to be reused in heterogeneous applications. Accordingly, we employ an upper ontology, multiple general subjects (generic, domain-independent for different knowledge domains, such as, temporal subjects, spatial subjects and agent subjects), multiple domain subjects (modeling common concepts and aspects of certain application topics), and special scenario-regenerating subjects for a smart building, and together they allow modeling both generic and specialized concepts for the proposed ontology. Protégé [14], providing a graphical user interface to model classes, properties and relationships, is used here for the construction of proposed ontology and specific knowledge graph.

skos (Simple Knowledge Organization System)(https://www.w3.org/TR/2008/WD-skos-reference-20080829/skos.html) was chosen as the upper-level ontology due to its wide reusability and comprehensive base. It provides a set of architectural concepts to facilitate interoperability and align with many mid-level and lower-level subjects.

For general subjects, namely temporal, spatial, and agent ontologies (to describe who, where, when), respectively, we used FOAF (Friend Of A Friend)(http://xmlns.com/foaf/0.1/) ontology to model generic information about an agent, such as the name, age and profile, and to provide the description of agent relationships. Time (https://www.w3.org/TR/owl-time/) ontology is to describe the temporal properties in the real or virtual world. The ontology provides a vocabulary for expressing topological relations among time instants and intervals, together with information about durations and temporal position. BOT (Building Topology Ontology)(https://w3c-lbd-cg.github.io/bot/), as spatial ontology, is introduced as a minimal, classic ontology for describing the core topological concepts of a building. It can be an extensible baseline for keeping the schema no more complex than necessary.

As for domain ontologies, in most cases they generate subordinate or executive relationships with certain topics, hence the chosen ontology theories that, in addition to containing sufficient branches, should also have a large number of object attributes to describe the exhaustive connections. Therefore, to express building elements (e.g., walls, doors, etc.), ifcowl (a Web Ontology Language representation of the Industry Foundation Classes)(https://standards.buildingsmart.org/IFC/DEV/IFC4/ADD2_TC1/OWL/index.html) ontology is adopted for entities being directly obtained from BIM (Building Information Modeling) data conversion, while to describe various devices (e.g., AC, vending machine, etc.), generic SSN (Semantic Sensor Network)(https://www.w3.org/TR/vocab-ssn/) ontology is utilized. The Event Ontology (EO: https://motools.sourceforge.net/event/event.html) is used to identify events in the building. Although activity is a subclass of events, after investigation, dicp (Processes of Digital Construction)(https://w3id.org/digitalconstruction/Processes) ontology complements EO in detail, and human activities are one of our focuses, so we additionally introduce dicp. Naturally, we do not express all sub-subjects with existing ontologies, since some entities are strongly related to the CGPF special applications and none of the existing ontologies is adequate, which pushes us to independently design this part.

For the CPS application subjects of a smart building, we have newly designed various branches/sub-branches, and their related object attributes and data attributes according to the scenario to be described. Since the architecture of required Spatial-temporal urban digital twin Ontology and the core concepts in it have been defined, this means that a structured and formalized knowledge base has been created. On this basis, specific subjects and actual use-cases can be developed and designed to improve efficiency and practicality. Most of them belong to broad branches, while specific design methods include completely new design sub-branches, expanding sub-branches of an ontology, rewriting sub-branches of an ontology, and fusing several ontologies.

Figure 2 gives a picture of the various classes of the Spatial-temporal urban digital twin Ontology and the connections between them.

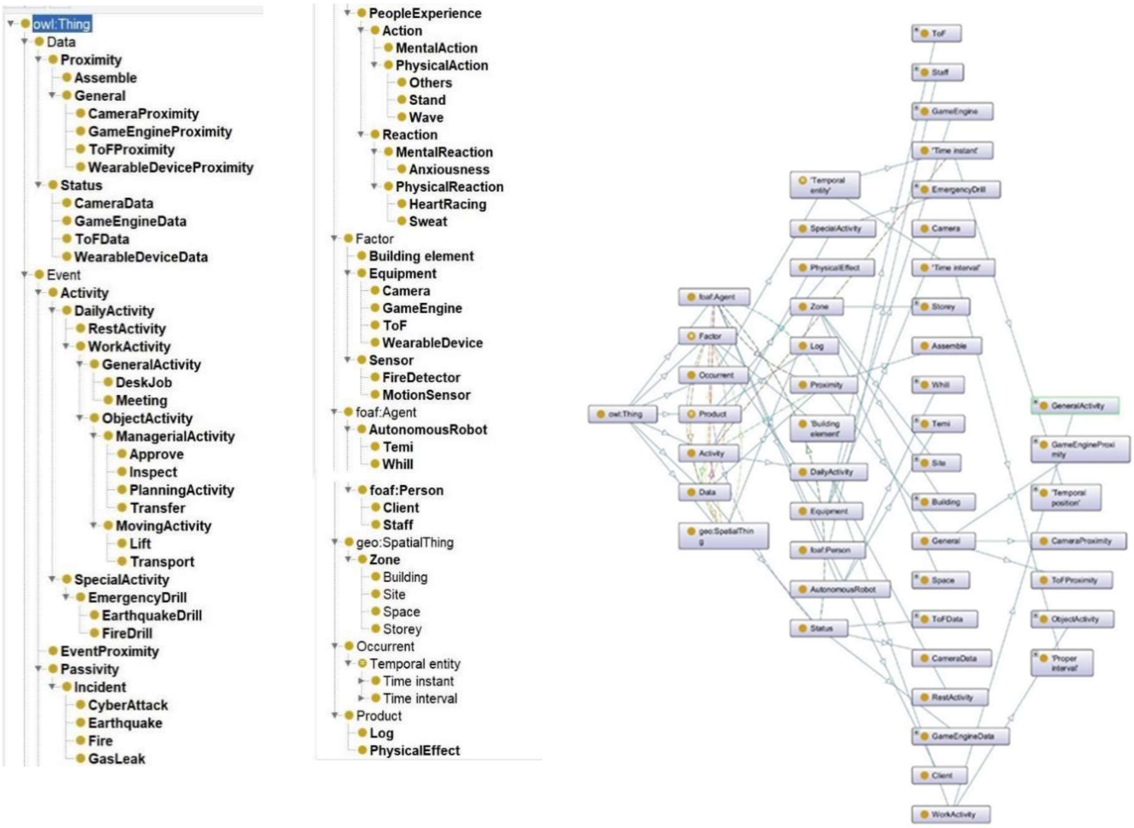

Fig. 2. Snapshot of Spatial-temporal urban digital twin Ontology

4. Verification and discussion

To verify the feasibility and completeness of the proposed ontology, we examine its data management and integration performance under a specific scenario in smart buildings.

4. 1 Metadata conversion of building structure

Firstly, the structural data of the smart building is required for spatial information. BIM is a computer-generated representation of the actual components used in a building. IFC (Industry Foundation Classes) holds information about each of these components and facilitates the exchange of data between software. Modern buildings, including smart buildings, improve operational efficiency by distributing attribute information data in IFCs to exchange three-dimensional data about buildings and civil structures.

In the validation study, we instead assume that building information is stored in the form of IFC files, from which we extract building entities (e.g., doors, walls, rooms, etc.), entity attributes (e.g., door dimensions, wall materials, etc.), and relationships between entities (e.g., doors on a particular wall, rooms on a particular floor, etc.). One way is to use the official RDF parser to convert IFC files to the knowledge graph on the ifcOWL ontology framework [15]. However, for our proposed ontological framework, such detailed metadata would instead create data redundancy. This is because our focus is on the constant inflow of dynamic human activities, real-time state information, etc. Although static spatial data is the basis of the whole knowledge graph, the large amount of material information and supplier information recorded in the IFC file cannot be utilized in the Spatial-temporal urban digital twin Ontology, and we need to eliminate them to save storage space, computing power, and streamline the data framework. Therefore, the BOT ontology, which is also the minimal ontology describing the core building topology concepts, is used in the "SpatialThing" class of the Spatial-temporal urban digital twin Ontology. However, we keep some of the ontologies described by the ifcOWL ontology in the "building element" subclass. Figure 3 shows the data conversion pipeline from IFC file to final BOT ontology-based RDF (Resource Description Framework) database. We used the mentioned official IFCtoLBD converter to obtain ifcOWL based RDF data which is then aligned to BOT ontology RDF data while saving key ifcOWL RDF data.

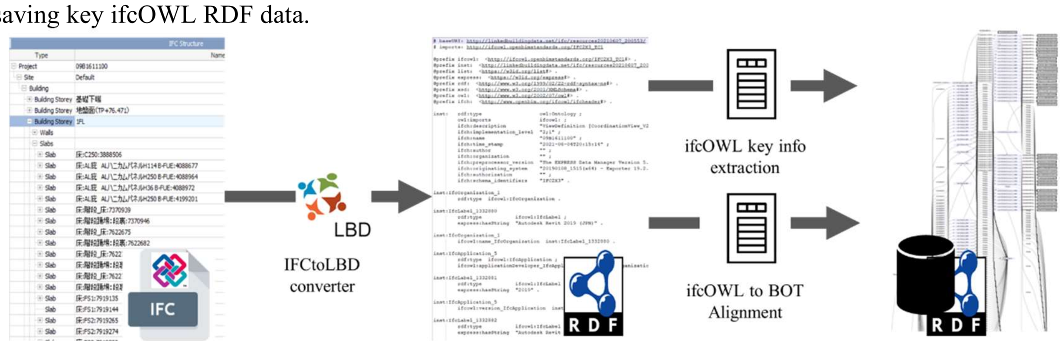

Fig. 3. Conversion pipeline

4. 2 Establish of knowledge graph

The validation study must contain a sufficient variety and number of entities and their relationships, for which we choose "emergency drill" scenario. In the proposed ontology, under “specialactivity” class, “emergencydrill” subbranches have been designed to represent the hierarchy of related events and have been established with the required object attributes to associate with other classes or subclasses.

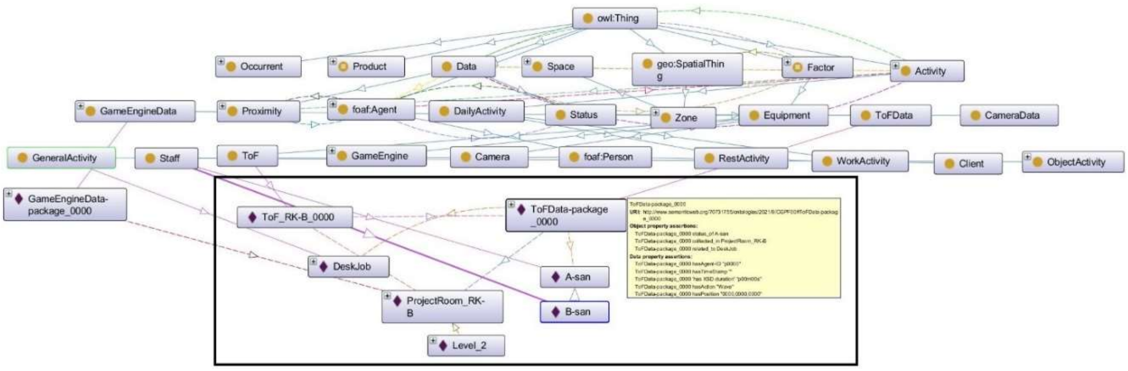

Fig. 4. Representation among entities and attributes in fire drill scenario

Since the activity will involve the collaboration of people and objects within the building, entities of this subbranch will have connections to each participating other subject entities to reflect their roles in this scenario. Specifically, in the case of the fire drill: firstly, we assume that a certain number of employees are proceeding with their daily work activities, and these event entities will be recorded in an "activity" subbranch parallel to "passivity". Naturally, in addition to the broad level recording, details of their actions/reactions behaved in the activities are also recorded in "PeopleExperience". They are captured by various sensors, such as cameras, wearable sensors, etc. The heterogeneous data are processed and fed into the corresponding "data" classes or data attributes, where the most critical procedure is to build and update the association of object attributes with temporal and spatial entities; then the fire occurs, the real and data environment of the entire building produces changes in the state of people and objects, and ontological entities change. The notification of the fire is captured and transmitted from the cameras/fire-alarm sensors and established its own temporal and spatial object/data attributes as general rules of "event". At the same time these entities (fire, time, space, etc.) are going to associate with agents, devices, etc., causing a change in their position, status/activity, psychophysiological changes (such as increased heart rate, sweating, etc.), etc. As the fire progressed, new entities (such as people escaping, firefighters entering, etc.), renewed entities (status data, position, etc.), deleted entities (daily activity, action, etc.), all these recording will be updated repeatedly with the data sampling frequency. The specific representation between entities and attributes is shown in Figure 4.

We assume that all data are in-flowed externally, which will certainly create problems such as inconsistent formatting, data redundancy, etc. Therefore, in our ontological theory, some core data is processed at certain level before written/rewritten into the knowledge graph, whose form of related temporal and spatial data is specified for the purpose of data streamlining.

5. Conclusions

To achieve optimal strategy and control of smart buildings, CPS can help share large amounts of heterogeneous data to connect people, objects, events, and even real space and virtual duplicand. Its integrated database should create semantic static and dynamic digital twins in time and space dimensions.

This study details the design of the Spatial-temporal urban digital twin Ontology, which is the cornerstone of data sharing, management, and integration in-question. A special schema is proposed for representing contextual knowledge and complex-event processing while supporting temporal/spatial reasoning. We construct a suitable overall framework, then find suitable existing ontologies and localize them as upper, general and domain ontologies, finally develop a series of Spatial-temporal urban digital twin Ontology specific application branches/subbranches. The entire design pattern including the core concepts of the main classes, the fusion framework and the conceptual modules are carefully introduced, as well as the showcase of the finalized ontology. The usability and reliability of the proposed ontology are confirmed by implementing data management/integration in an emergency drill scenario of a smart building. By capturing participants' behavioral data and storing it in a knowledge graph, the prototype is superimposed on the real space, and is verified its efficiency.

References

[1] Agarwal, Y., Balaji, B., Gupta, R., Lyles, J., Wei, M., & Weng, T. (2010, November). Occupancy-driven energy management for smart building automation. *In Proceedings of the 2nd ACM workshop on embedded sensing systems for energy-efficiency in building* (pp. 1-6).

[2] Baheti, R., & Gill, H. (2011). Cyber-physical systems. *The impact of control technology*, 12(1), 161-166.

[3] Shih, C. S., Chou, J. J., Reijers, N., & Kuo, T. W. (2016). Designing CPS/IoT applications for smart buildings and cities. *IET Cyber-Physical Systems: Theory & Applications*, *1*(1), 3-12.

[4] Wang, Z., Zhang, J., Feng, J., & Chen, Z. (2014, June). Knowledge graph embedding by translating on hyperplanes. In *Proceedings of the AAAI conference on artificial intelligence* (Vol. 28, No. 1).

[5] Shi, B., & Weninger, T. (2018, April). Open-world knowledge graph completion. In *Proceedings of the AAAI conference on artificial intelligence* (Vol. 32, No. 1).

[6] Baheti, R., & Gill, H. (2011). Cyber-physical systems. *The impact of control technology*, *12*(1), 161-166.

[7] Hu, J., Niu, H., Carrasco, J., Lennox, B., & Arvin, F. (2022). Fault-tolerant cooperative navigation of networked UAV swarms for forest fire monitoring. *Aerospace Science and Technology*, *123*, 107494.

[8] Wemlinger, Z., & Holder, L. (2011, June). The cose ontology: Bringing the semantic web to smart environments. *In International Conference on Smart Homes and Health Telematics* (pp. 205-209). Springer, Berlin, Heidelberg.

[9] Chen, H., Finin, T., & Joshi, A. (2005). The SOUPA ontology for pervasive computing. In *Ontologies for agents: Theory and experiences* (pp. 233-258). Birkhäuser Basel.

[10] Hammar, K., Wallin, E. O., Karlberg, P., & Hälleberg, D. (2019, October). The realestatecore ontology. *In International Semantic Web Conference* (pp. 130-145). Springer, Cham.
[11] Wang, X. H., Zhang, D. Q., Gu, T., & Pung, H. K. (2004, March). Ontology based context modeling and reasoning using OWL. In *IEEE annual conference on pervasive computing and communications workshops, 2004. Proceedings of the second* (pp. 18-22). Ieee.
[12] Ni, Q., Pau de la Cruz, I., & Garcia Hernando, A. B. (2016). A foundational ontology-based model for human activity representation in smart homes. *Journal of Ambient Intelligence and Smart Environments*, *8*(1), 47-61.
[13] Culmone, R., Giuliodori, P., & Quadrini, M. (2015). Human activity recognition using a semantic ontology-based framework. *International Journal on Advances in Intelligent Systems*, *8*(2), 159-168.
[14] Musen, M. A. (2015). The protégé project: a look back and a look forward. *AI matters*, *1*(4), 4-12.
[15] Beetz, J., Van Leeuwen, J., & De Vries, B. (2009). IfcOWL: A case of transforming EXPRESS schemas into ontologies. *Ai Edam*, *23*(1), 89-101.