Towards Integration of IndoorGML and GDF for Robot Navigation in Warehouses

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Abstract

With the development of the navigation technology, the outdoor navigation has made great progress, whereas the indoor navigation has some areas which is underdeveloped, insufficient to meet the rapidly increasing demands of people as well as the robotics. Even though, the advance in indoor navigation technology still has really brought a wide range of applications and a broad market, for instance, the flourishing intelligent warehouse system utilizes multi-robot operation which have the certain requirement for an accurate indoor navigation system. As for the indoor navigation, the OGC standard IndoorGML has been released and undergoing revision constantly. While the document really provides more advantageous support for the applications of Indoor Location-Based Services (LBS), in some aspects, especially the door-to-door navigation and the warehouse environment, it is not sufficiently adaptable, with still some room for improvement. IndoorGML is powerful for the common indoor scenarios like malls and offices, while as for carefully-arranged warehouse environment and other large-scale operation scenarios with multi-robots that is more similar to an ordered system, it is obviously insufficient. In this paper, we discuss about the potential to combination of IndoorGML and ITS standard ISO 20524 (GDF5.1), and extend the OGC standard indoorGML. We analyze the definition as well as function of related concepts, making some comparisons between these two standards. We conclude that these two standards are well-matched with vital potential to merge and unify the indoor and outdoor systems for spatial information.

1. Introduction

The field of Geographic Information Systems (GIS) has traditionally been focused on the data analysis, visualization, and understanding of outdoor spatial environments, which have been instrumental in urban planning, navigation and so on, providing comprehensive data and insights about the outdoor world. However, as the demand for more nuanced and granular spatial information grows, the focus of spatial information community is expanding from these expansive outdoor space into the more intricate and nuanced realm of indoor spaces. Lots of data formats and standards, including Industry Foundation Classes (IFC), City Geographic Markup Language (CityGML), Indoor Mapping Data Format (IMDF), IndoorGML and so on, have emerged to be compatible with indoor Location-Based Services (LBS). For exploring the ability of the description of indoor space, (Kim et al., 2021, Li et al., 2019b) make a comparison among these standards and formats, pointing that IFC stands out for its comprehensive building object and relationship representation, providing rich semantic data and detailed geometry crucial for BIM data exchange. CityGML excels in urban model representation with its thematic and geometric focus, with less emphasis on indoor specifics. They both pay more attention to the 3D modeling instead of the indoor spatial relationship. IMDF, tailored for effective indoor mapping and navigation, simplifies space and object categorization, enhancing building space management. Among these, IndoorGML uniquely excels in indoor navigation by mandating single closed geometries and explicitly defining topology, making it superior for precise route finding in complex indoor settings.

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With the development of robotics, an increasing number of robots are introduced to work in the indoor space, which places stringent demands on the accuracy of the indoor space representation, especially when it comes to indoor navigation. In the field of logistics, it is of vital significance for robots to play an active role in the warehouse (Bogue, 2016). In this context, robots can rapidly get rich information from the topological model in IndoorGML, instead of the 2D layout information in IMDF, which requires additional methods to parse. This explicit topological description provides IndoorGML with a significant advantage in creating detailed and efficient indoor navigation solutions, positioning it as the optimal choice for indoor navigation for robots.

In the common scenarios, like malls and offices, benefiting from the proposal of IndoorGML (Kang and Li, 2017), the demand for complex spatial representation has been satisfied. Suffice it to say, IndoorGML is relatively complete for human and their daily life. Considering the application of IndoorGML, it is perfectly compatible with malls and handheld LBS, such as various applications in smartphone and portable devices. Within malls, IndoorGML enables sophisticated navigation aids, allowing visitors to easily locate stores, amenities, or exits, thereby enhancing the shopping experience and ensuring safety through efficient emergency evacuations. In addition, in the realm of handheld LBS, IndoorGML extends its utility beyond malls to airports, museums, hospitals, and office buildings. This empowers users with real-time information and interaction capabilities within complex indoor environments.

While the IndoorGML achieves the representation of indoor spatial information and provides a fundamental data model for indoor navigation, there are still some aspects remaining uncertain and lacking. In the context of an intelligent warehouse, different from the daily application and scenarios above, where shelves are carefully organized in discernible patterns, such as a grid layout, a substantial number of robots are orchestrated to operate systematically. For example, it is defined to consider a certain space as a *CellSpace* in IndoorGML, while in the warehouse, the selection of *CellSpace* is quite vague and unnatural because there is no room-like feature, making the space dividing difficult. More importantly, in IndoorGML, the dual space focus more on the transition of state, which is instantaneous, and there is no actual process. And this can be seen from IndoorGML1.x, where the node and edge in the topological network is named as *State* and *Transition*. However, for the robot navigation, the process is vitally necessary and significant, without only emphasizing on the transient migration of states, particularly in a space with multi-opening among which intersections are the most representative. When robots navigating, it is indispensable to restrict and control how robots reach one position from another position, and the process is capable of being artificially chosen and prescribed in principle, which is similar to the door-to-door navigation (Liu and Zlatanova, 2011). And this disadvantage is particularly evident in the topological transitions at intersections. Based on the controllable process, it is available to prescribed correlation among three neighboring points. It means although there are several paths among three neighboring points, it is allowed to set the restrictions to force the users to reach a specific location only from another specific location through a particular process or path. It is more similar to the introduction of traffic regulations. However, for IndoorGML, all of these are difficult to accomplish, for the topological structure is relatively vague and not meticulous, which is the most important cause why IndoorGML is not perfectly compatible with the warehouse and not to be applied straightforwardly.

Therefore, since this scenario closely mirrors the dynamics of a traffic system, where there is a profound interplay between the transport infrastructure and the participants, we are inspired by urban traffic system and introduce the traffic items or the concepts that are relatively well-developed to the indoor space. *Belt Feature* is a concept in the international standard ISO 20524 (GDF5.1) (ISO/TC 204, 2020a, ISO/TC 204, 2020b), also used to describe the road element in the ITS (Intelligent Transport System), among which the *BeltRepresentativeLine* and *ConnectionPoint* are vitally potential to connect these two standards and to be introduced in IndoorGML as an extension. In this work, the contribution can be stated as follows:

1. Analyzing the strongly related concepts in IndoorGML and GDF.
2. Elucidating the correspondent relationship between IndoorGML and GDF.
3. Integrating two different topological structures derived from two standards.

The remainder of this work is structured as follows. An overview of the previous publications including the development of the standards and formats that are related to indoor spatial information representation and the international standard referred to ITS is given in Section II. Furthermore, in Section III, we illustrate some related concepts in GDF and IndoorGML, preparing for the analysis of the correspondent relationship. Section IV constructs the connection between two standards, and proposes the combination of the two topological structures. Finally, Section V is the conclusion and the future work.

2. Related work

With the advancement of indoor positioning and mapping technologies, including indoor Location-Based Services (LBS), various indoor positioning and spatial information services has emerged. Given the distinct nature of indoor environments compared to outdoor spaces, some formats and standards for indoor maps have been introduced.

GeoJSON, a widely recognized standard, facilitates the representation and exchange of spatial data through JSON (Frozza and Mello, 2020). This format outlines how different types of JSON objects can be organized to represent geographic information, including the details of their attributes and spatial dimensions. GeoJSON supports seven principal geometric types defined by *OpenGIS Simple Features Access* (OGC, 2011). This compatibility underscores the utility of GeoJSON in a broad spectrum of applications, ranging from simple point locations to complex polygonal shapes, thereby serving as a foundational tool in the realm of web-based geographic information systems (GIS) and beyond.

The Geography Markup Language (GML) (OGC, 2012) and Keyhole Markup Language (KML) (OGC, 2015) are two pivotal XML-based frameworks developed under the auspices of the Open Geospatial Consortium (OGC), each serving distinct but complementary roles in the domain of geographic information representation and visualization. GML, officially recognized as ISO 19136 (ISO/TC 211, 2020), emerges as a sophisticated structure aimed at facilitating the exchange and sharing of geospatial data across varied platforms and systems. On the other hand, KML specializes in the geographic annotation and visualization within user-centric platforms such as Google Maps and Google Earth. Originating from Keyhole, Inc., which was later acquired by Google, KML has been widely adopted for web applications, prized for its simplicity and broad acceptance. However, KML's focus predominantly lies in the visual portrayal of geometries, often at the expense of semantic depth. Both KML and GML are powerful geographic data representation formats suitable for a wide range of geographic information applications. However, since they are not specifically designed for indoor navigation, they have limitations when applied to robotic indoor navigation, such as the lack of the direct support for indoor structures.

The Indoor Mapping Data Format (IMDF) , developed and published by Apple Inc., represents a significant advancement in the domain of indoor spatial data representation. Utilizing the foundational structure of GeoJSON, IMDF is engineered to articulate the nuances of indoor environments, catering to a broad spectrum of venue types including airports, malls, and train stations. The OGC has recognized IMDF as an OGC Community Standard, underscoring its utility and relevance in the broader geospatial community. Its explicit focus on indoor feature and venue types directly addresses the complexities and specific requirements of indoor mapping, offering a structured yet flexible framework for representing diverse indoor spaces.

Industry Foundation Classes (IFC) and CityGML are two standards developed to address the need for standardized semantics, geometry, and topology in the realm of building and urban data modeling. IFC is recognized for its semantic richness and object-oriented structure, offering a 3D representation where all geometries are topologically valid solids. With a comprehensive set of classes dedicated to building components and constantly expanding to accommodate complex construction management needs, IFC stands out as a preferred model for creating precise indoor 3D maps. It encompasses detailed notations for architectural elements and crucially includes information about room spaces and furniture. The detailed connectivity information (derived from doors, windows, and stairs data) supports the straightforward automation of network creation, enhancing localization and navigation applications for users and assets. CityGML, developed by the OGC, serves as a semantic information model and XML-based encoding format for the exchange of 3D city models. CityGML aims to capture the 3D geometry, thematic features, and appearance of city objects across four Levels of Detail (LoD), with 3D indoor modeling dispersed to every levels. Unlike IndoorGML, CityGML does not explicitly model room-to-room topology but allows for its derivation from shared surfaces between adjacent rooms, enabling the positioning of furniture and other indoor elements like stairs.

IndoorGML, conceived by the OGC, marks a significant leap in the realm of geospatial standards, aimed specifically at revolutionizing the way indoor spatial information is represented and exchanged (OGC, 2014, Li, 2016, Li et al., 2019a). By meticulously integrating spatial topology, geometry, and semantics, IndoorGML lays down a robust framework that enhances the precision and efficiency of indoor navigation applications. Over the years, IndoorGML has captivated the interest of the academic and professional communities, thanks to its innovative approach to modeling indoor spaces, notably through the concept of cellular space. Substantial research efforts have been dedicated to refining the standard's capacity to model complex structures accurately. Several researches focus on the space subdivision to address the challenge of representing complex structures and delve into enhancing indoor navigation (Krūminaitė and Zlatanova, 2014, Jung and Lee, 2015, Diakité et al., 2017). In parallel, a considerable volume of scholarly work focuses on the integration of IndoorGML with other standards and models, aiming to augment its adaptability and multi-functionality, making it a versatile tool for a broader spectrum of geospatial applications (Kim et al., 2014, Zlatanova et al., 2016, Alattas et al., 2017, Teo and Yu, 2017, Claridades et al., 2019, Alattas et al., 2020). Currently, IndoorGML is undergoing a pivotal revision with the development of IndoorGML2.0 (Diakité et al., 2020). This new iteration aims to refine and clarify previously ambiguous concepts while introducing the Flexible Space Subdivision (FSS) framework (Diakité and Zlatanova, 2018). The FSS framework will represent a quantum leap in the standard's evolution, offering a more granular approach to space subdivision and thus, significantly enhancing the navigation capabilities of autonomous indoor robots and bestowing the meaning of robot navigation.

The Intelligent Transport System (ITS) has significantly evolved over the past few decades, catalyzing a wealth of research and the development of numerous standards. At the forefront of this evolution is the Navigation Data Standard (NDS), an initiative by the Navigation Data Standard Association designed to revolutionize how geospatial road-related information is stored within ITS databases. A notable component of the NDS framework is the NDS Open Lane Model (Navigation Data Standard, 2016), an open specification that draws parallels with the Geographic Data Files (GDF) standards. Specifically, GDF5.0, developed under the auspices of ISO 14825 Geographic Data Files (GDF) (ISO/TC 204, 2011), has long been recognized as a global benchmark for facilitating information exchange between databases housing geospatial information crucial for road navigation. Building upon the foundation laid by GDF5.0, the subsequent iteration, GDF5.1 (ISO/TC 204, 2020a, ISO/TC 204, 2020b), introduced in 2020, marks a significant leap forward. GDF5.1 expands the scope of its predecessor to encompass additional aspects pertinent to ITS (Jetlund et al., 2019), offering a more granular and versatile framework for capturing and representing road and road-related features. A distinctive feature of GDF5.1 is its ability to conceptualize roads and associated objects (such as lanes and intersections) as specific area features, termed as a "Belt", sharing a striking similarity with IndoorGML. This innovative approach facilitates the transformation of roads and related objects into line shapes that more accurately depict the general direction of vehicular movement, providing a reference line or center line of a lane (Rondinone, 2019).

3. Illustration about the related concepts in GDF5.1 and IndoorGML2.0

In this section, we are intended to analyze and discuss the definitions and concepts in GDF5.1 and IndoorGML2.0. For integrating these two standards, it is necessary to understand these concepts as a precursor.

3.1 Introduction of GDF5.1

To facilitate the illustration, Figure 1 illustrates the data model of *AbstractBeltFeature* and Figure 2 represents an example of *AbstractBeltFeature* (ISO/TC 204, 2020b). It is important to note that although there are 12 subclasses in the data model of *AbstractBeltFeature* in GDF, we only show and introduce some critical terms strongly related to IndoorGML in the following section.

Belt In the ISO 20524(GDF5.1), as is mentioned above, a specific area feature is introduced and referred to as a *Belt*, which can be degenerated into a line shape. According to the semantic of the *Belt*, it can be divided into different types of *Belt* (such as *IntersectionBelt*, *RoadBeltElement* and *LaneBeltElement*, in Figure 2). But all these categories are aimed to represent an intersection or a segment of the road or lane. In this level, we are able to consider any road space as a *Belt*, and a *Belt* is the smallest structural and organizational unit in the road network. Besides, one of the most important attributes of the class *Belt* is defined to *direction*. Aiming to the connection between two standards, it is available to simplify the semantic of *Belt* and only consider the concept of *Belt*.

Side Line and Terminal Line Every *Belt* shall be bounded by Side Lines and Terminal Lines, as illustrated in Figure 3, among which Side Lines are often represented by real partition lines such as lane markings, flow-markings, curbstones and so on, and Terminal Lines often have no representation in real world. In the document, the definition is unclear, while in the functional level, Side Line can be used to calculate the width of *Belt* and Terminal Line is used as "direction control valves" and connection between two *Belts*. A Terminal Line often connects

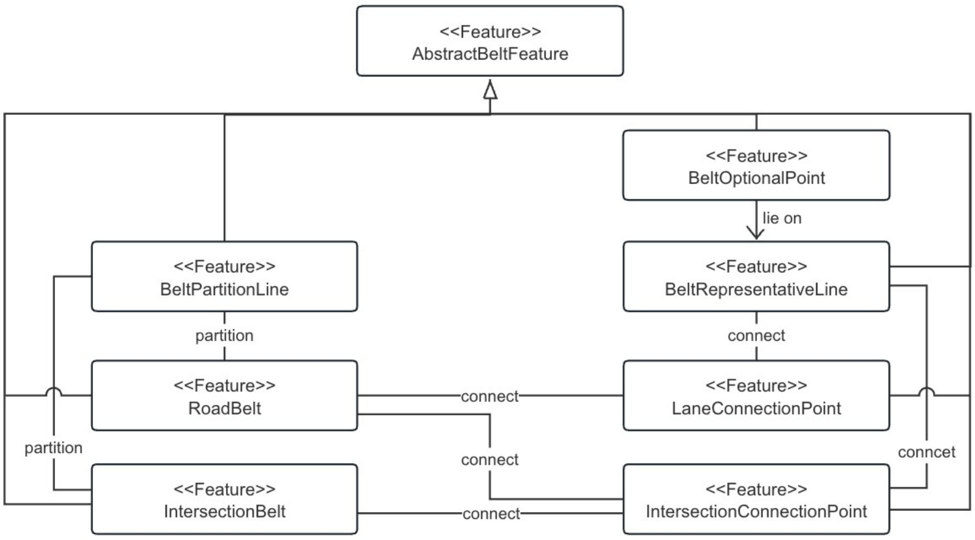


Figure 1. Data model of AbstractBeltFeature adapted from (ISO/TC 204, 2020b)

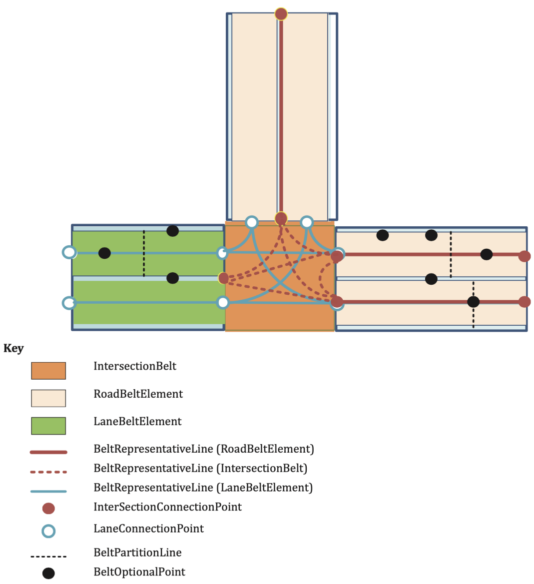
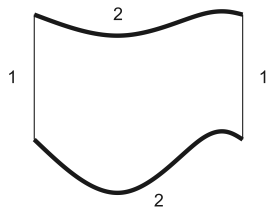


Figure 2. Example of AbstractBeltFeature from (ISO/TC 204, 2020b)

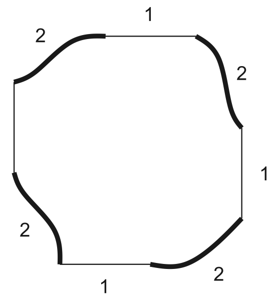
two *Belts*. Both of these lines are essentially boundaries of *Belt*, they are just divided according to different semantics.

BeltRepresentativeLine In the document, *BeltRepresentativeLine* introduces a simplified approach to modeling and representing road networks within geospatial databases. This specific type of line acts as a crucial connector, bridging a pair of Terminal Lines that define the boundaries of a *Belt*. In essence, the *BeltRepresentativeLine* serves as a streamlined representation of a *Belt*, allowing for a more simplified yet effective depiction of road networks. This simplification is particularly beneficial in rendering the road network more intelligible and navigable for users, by distilling the complexity of a *Belt* into a singular, comprehensible line. However, a *BeltRepresentativeLine* does not always lie in a central or lateral position of a *Belt*. It means that *BeltRepresentativeLine* focuses more on geometric properties even though it also has topological properties. Moreover, an important aspect of the *BeltRepresentativeLine* is its ability to inherit attributes from its corresponding *Belt*. This attribute inheritance mechanism ensures that the critical characteristics and data points that define a *Belt* are seamlessly transferred and encapsulated within the *BeltRepresentativeLine*. Consequently, this not only preserves the essential information pertaining to the road network but also ensures that the simplified representation does not compromise on the richness and accuracy of the spatial data.

ConnectionPoint *ConnectionPoint* plays a pivotal role in delineating road networks. Positioned precisely where a *BeltRepresentativeLine* intersects the Terminal Lines of a *Belt*, the *ConnectionPoint* serves as a critical juncture, marking the transition between distinct segments of the transportation infrastructure. This specific location, being the endpoint of a *BeltRepresentativeLine*, is beneficial to define the spatial dynamics of road networks, facilitating an understanding of how different sections of a road are interconnected. In this way, *ConnectionPoint* has also both geometric and topological properties and as same as *BeltRepresentativeLine*, it accentuates geometric properties. The utility of a *ConnectionPoint* extends beyond mere representation; it encapsulates the functionality of the Terminal Line it corresponds to, effectively



(a) Road Belt



(b) Intersection Belt

Figure 3. Example of Belt adapted from (ISO/TC 204, 2020b). (a) Road. (b) Intersection. 1-Terminal Line; 2-Side Line

embodying the transition or intersection point within the road network. GDF further categorizes *ConnectionPoints* based on the nature of the *Belts* they connect, introducing nuanced classifications such as the *InterSectionConnectionPoint* and the *LaneConnectionPoint* (see Figure 2). These specialized types of *ConnectionPoints* offer a granular perspective on the connectivity within the network, distinguishing between different forms of intersections and lane transitions. For instance, an *InterSectionConnectionPoint* specifically denotes the meeting point of *Belts* at an intersection, highlighting the complex interplay between multiple roads. Conversely, a *LaneConnectionPoint* represents the linkage between lanes within the same road or between adjacent roads. To summarize their function, we simplify *InterSectionConnectionPoint* and *LaneConnectionPoint* to *ConnectionPoint*.

As a consequence, as for the road network, if we divide road space into primal space and dual space, as the same as the operation in IndoorGML, it is definite that *Belt*, Terminal Line and Side Line are in primal space, equipped with the geometry feature. Due to the topological properties of *BeltRepresentativeLine* and *ConnectinoPoint*, in dual space, *Belt* can be simply mapped to *BeltRepresentativeLine* meanwhile Terminal Line can be mapped to *ConnectinoPoint*. Consequently, we can get the topological relationship from GDF.

3.2 Review of IndoorGML2.0

Even if IndoorGML2.0 has been still under compilation and not published, there are some articles and documents related to the modification. In this work, we are aimed at IndoorGML2.0 draft v.0.3 under preparation and use the newly modified structure and terms. For establishing the relationship between two standards, it is necessary to focus on the basic concepts. One of the modification is the deletion of the thin wall model and the thick wall model, completing the definition of *CellSpace* and *CellBoundary*, which provides the convenience for the relationship establishment.

CellSpace In IndoorGML, *CellSpace* is defined as the smallest organizational and structural unit of indoor space, which is functioned as the same as *Belt* in GDF. In the core module, doors and walls are both considered as *CellSpace*, and in the Navigation module, the subclass, *TransferSpace*, is simplified to only doors and windows.

CellBoundary In IndoorGML2.0 proposal, *CellSpaceBoundary* has been revised to *CellBoundary*. *CellBoundary* is not clearly defined while it is manifestly apparent that *CellBoundary* represents the connection or the adjacency between two *CellSpaces*. In the Navigation module, there are two children classes, *NavigableBoundary* and *NonNavigableBoundary*. The concept of "thin door" has been removed.

Node and Edge In IndoorGML2.0 proposal, *State* and *Transition* have been removed for the common confusion. *CellSpace* and *CellBoundary* in primal space are mapped to *Node* and *Edge* respectively based on the Poincaré Duality, so that in dual space we are able to get a topological graph.

4. Integration of IndoorGML and GDF

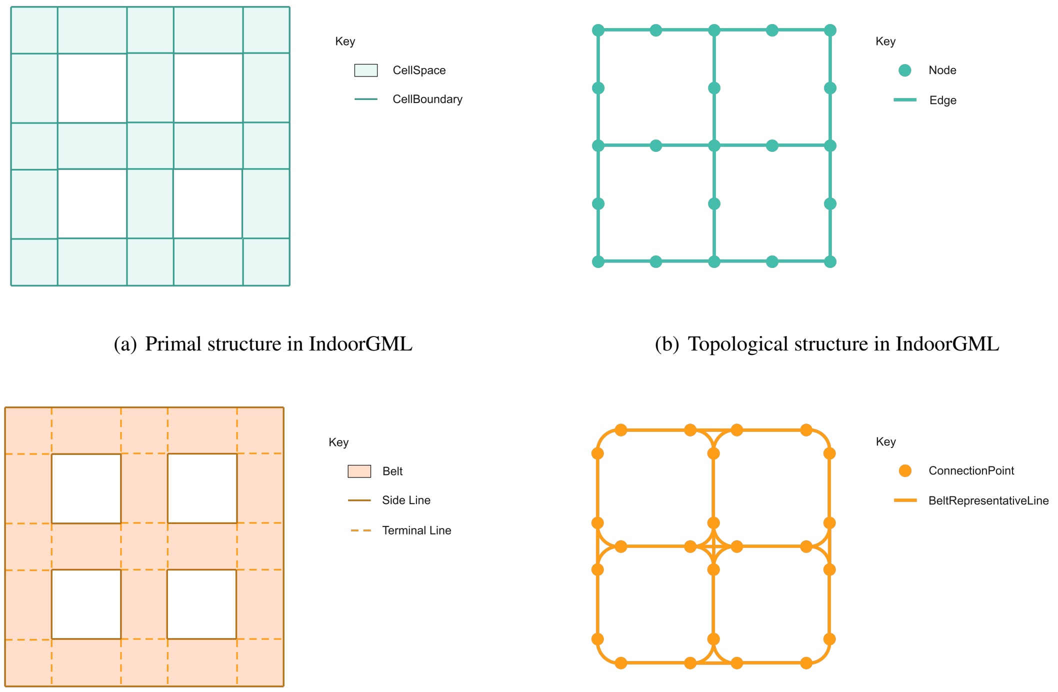
4.1 Connection establishment

By analyzing the related concepts, it is obvious that there are two different topological structures in the two standards, representing indoor and outdoor systems respectively. In this section, we will discuss the connection and difference between them.

Belt and CellSpace As mentioned above, in the road network, *Belt* is the smallest organizational or structural unit, as the same status as the *CellSpace* in indoor space. In this way, it is reasonable to equate *Belt* with *CellSpace*. And they can both be mapped to the *Node* in the topology.

Terminal Line, Side Line and CellBoundary All of these three elements represent the connectivity, among which Side Line may focus more on the real physical segmentation. Considering the Navigation module in the proposal of IndoorGML2.0, *CellBoundary* handles two children classes, *NavigableBoundary* and *NonNavigableBoundary*. So according to the focus of Terminal Line and Side Line, they can respectively correspond to *NavigableBoundary* and *NonNavigableBoundary*. However, doors and walls are categorized into *CellSpace* in the proposal of IndoorGML2.0. To build up the connection between the two standards, we propose to consider the thin wall model, re-considering doors and walls as *CellBoundary*, and redefining it, so that it is more compatible to match the indoor and outdoor systems.

BeltRepresentativeLine and CellSpace From the topological properties of *BeltRepresentativeLine*, *Belt* can be degenerated into a line shape, meaning that *Belt* can be mapped to the *BeltRepresentativeLine*. If only focusing on the *LaneBeltElement* and *RoadBeltElement*, it is correct. In spite of it, Figure 2 illustrates three types of *BeltRepresentativeLines*,



(a) Primal structure in IndoorGML

(b) Topological structure in IndoorGML

(c) Primal structure in GDF

(d) Topological structure in GDF

Figure 4. Differences of topology between IndoorGML and GDF

among which the *BeltRepresentativeLine* in intersection is special and different from other types. In a *IntersectionBelt*, there are more than one *BeltRepresentativeLines*, resulting in the inappropriateness of the above statement. To address the dilemma, we propose a concept of "container", which is a set containing all the *BeltRepresentativeLines* in a *Belt*. It is remarkable that *BeltRepresentativeLine* is an element accentuating the geometric properties, making the container is also a concept focusing on geometry feature. It is discernible that it bears notable similarities to class *CellSpace* across various dimensions. This container, can be considered as a set determining the rules of passage of this *Belt* functionally. Therefore, we are able to analogous the container of *BeltRepresentativeLines* to *CellSpace*.

ConnectionPoint and CellBoundary In the GDF, as delineated previously, the *ConnectionPoint* is situated on the Terminal Line, serving as an indicator of the juncture between two distinct *Belts*. Conversely, the *CellBoundary* is conceptualized as delineating connectivity or adjacency. Consequently, despite the former manifesting as a point feature and the latter as a line feature, the connection between these two elements is discernible. It is noticeable to acknowledge that the GDF predominantly accentuates the spatial depiction of the road and traffic network, without an elaborate exposition of topological intricacies. Predominantly, it is the geometric feature that the *ConnectionPoint* accentuates; thus, geometric attributes are propounded as the foundational benchmark to forge a correspondent relationship between the *ConnectionPoint* and the *CellBoundary*.

Therefore, it is feasible to build up a relationship of the concepts between two stardards (see Table 1). It is clear that in IndoorGML, the topological structure is generated by Poincaré Duality officially (see Figure 4(a) and Figure 4(b)). The Poincaré Duality (Munkres, 2018) offers a theoretical foundation for the transformation of indoor spatial configurations into a Node-Relation Graph (NRG), which delineates the topological relationships among spaces. Meanwhile, in GDF, as mentioned in Section 3.1, we have gotten a topological graph represented by *ConnectionPoint* and *BeltRepresentativeLine*, which is different from the topological structure beasd on the Poincaré Duality. Figure 4(c) and Figure 4(d) illustrate this process. In this topologization process, the following steps are taken:

1. Map the *Belt* to the *BeltRepresentativeLine*.
2. Map the Terminal Line to the *ConnectionPoint*

In the topological structure (see Figure 4(d)) derived from GDF, it is observed that the door-to-door navigation can be better accessible. Because in this process, the Terminal Line is mapped to a node, *ConectionPoint*, and the container of *BeltRepresentativeLines* is mapped to an edge. This topology ingeniously converts edges—traditionally perceived as mere connections between nodes—into pivotal points within the topological framework. Such a transformation facilitates a unique form of navigation, termed edge-to-edge navigation, which diverges from the more commonly encountered node-to-node navigation paradigm. Edge-to-edge navigation is especially valuable in scenarios where precise, context-specific guidance is required, such as directing a user from one specific door to another within a labyrinthine building. By redefining edges as navigable entities, this approach enables a more granular and intuitive navigation experience, allowing for seamless transitions between distinct but directly connected spatial elements. It offers enhanced navigational clarity and efficiency in environments where traditional node-to-node pathways may not suffice.

Space (in IndoorGML)	IndoorGML	GDF
Primal Space	CellSpace	Belt
Primal Space	CellBoundary	ConnectionPoint
Primal Space	NavigableBoundary	Terminal Line, BeltPartitionLine, LaneBeltJoint
Primal Space	NonNavigableBoundary	Side Line
Dual Space	Node	—
Dual Space	Edge	—
—	—	BeltRepresentativeLine
—	—	PotentialEvadingArea
—	—	BeltOptionalPoint

Note: "—" indicates 'Not Applicable'.

Table 1. The correspondent relationship between IndoorGML and GDF

4.2 Combination of topological structures

From a navigational perspective, the topological framework produced by GDF is fundamentally characterized by an edge-to-edge structure, focusing more on the adjacency of entrances and exits in the indoor space, whereas IndoorGML predominantly generates a node-to-node topology, emphasizing more on the adjacency of cellular spaces. By strategically integrating or combining these two distinct topological structures, there is a significant enhancement in the capacity to store and articulate a broader spectrum of map information. This amalgamation or connection essentially acts as an augmentation or refinement of the insights provided by IndoorGML. Additionally, the combination represent the unification of indoor and outdoor systems.

One of the most significant distinctions between the two topological structures, particularly relevant in environments like warehouses or airports where intersections or the space with multi-opening are common, lies in how intersections are structured and utilized for navigation (see Figure 4(b) and Figure 4(d)). In IndoorGML, an intersection is typically mapped to a single node for robots, based on the Poincaré Duality. This approach contrasts with that of GDF, where an intersection can be represented by multiple nodes, according to its exits and entrances. Through integrating this structure, it can details the process of the transition of two states, showing how the robots move between two adjacent points on the occasion where there are multiple path options. The distinction also facilitates the incorporation of traffic regulations into the map's structure. Such regulations can include turning restrictions and right-of-way rules, significantly enhancing navigational efficiency and reducing potential conflicts. Based on it, it is available to build up the correlation among several neighboring route points. By merging these topological frameworks, the map's route points are refined, and the indoor environment becomes more ordered, especially crucial in settings with large-scale robot operations. The integration effectively transforms intersections from singular nodes into complex junctions detailed by their specific access points, thereby distributing congestion more evenly across an intersection's exits and entrances, improving overall capacity, and minimizing congestion risks. This fusion not only sharpens the delineation of the indoor map but also introduces a methodical basis for implementing indoor traffic rules, thereby ensuring a more structured and efficient indoor navigation environment.

This approach to navigation not only enriches the informational depth accessible through the map but also facilitates a more intuitive and efficient navigation experience, especially in complex spatial configurations. This synergy between the two standards exemplifies a progressive step towards achieving a more comprehensive and detailed representation of spatial environments, thereby enhancing the utility and applicability of topological data in practical navigation scenarios.

5. Conclusion

In this paper, we have undertaken a in-depth analysis of IndoorGML and GDF, with the objective of delineating and establishing the interconnections between these two pivotal standards. Our aim is to seamlessly integrate and synthesize the indoor and outdoor navigation systems, thereby fostering a unified approach. Through a detailed examination of each standard's foundational concepts, we have identified two distinct yet complementary topological frameworks: one emphasizing a node-to-node structure and the other an edge-to-edge structure. By exploring these frameworks in depth, we have not only elucidated the unique characteristics and strengths of each but also successfully constructed a coherent relationship between the two standards. And our aim is to pave the way for a comprehensive navigational system that encapsulates a wealth of spatial data, thereby enhancing navigational precision and user experience across diverse settings.

Moving forward, our research will persist in refining the relationship between IndoorGML and GDF, with a concerted focus on establishing a rigorous topological framework. Our objective is to encapsulate the wealth of information inherent in both standards within a unified topological structure. This endeavor will not only enhance the integrity and comprehensiveness of the spatial data but also unify indoor and outdoor environments. Based on the integration of two standards, we intend to add some semantic representation about traffic regulations to the newly-integrated data model tailored for the complex warehouse environment and apply it to robot navigation, enhancing the order of the system.

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