2019 International Conference on Indoor Positioning and Indoor Navigation (IPIN), 30 Sept. - 3 Oct. 2019, Pisa, Italy

Survey on Indoor Map Standards and Formats

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***Abstract*—With the adoption of indoor positioning solutions, which enable for a variety of location-based spatial services, a number of indoor map standards and formats have been proposed in the last decade. As each of these indoor map standard has its own purpose, the strengths and weaknesses are necessary to be understood and analyzed before selecting one of them for a given application. The *Indoor Map Subcommittee* has been established under IPIN/ISC in 2017. Among others, the goal of this working group is to compare available indoor map standards, provide a guideline for their application and advise on changes to their standardization development organizations if necessary. In this paper we present a survey of indoor map standards as an achievement of the subcommittee. The scope of the survey covers official standards such as IFC of BuildingSmart, IndoorGML and CityGML of OGC, and Indoor OpenStreetMap. We present several use-cases to show and discuss how to build indoor maps.**

***Index Terms*—indoor map standards, indoor map formats**

I. INTRODUCTION

A variety of indoor positioning and spatial information services became available with the progress of indoor positioning and mapping technologies such as indoor Location-Based Services (LBS). Several formats and standards for indoor maps were proposed since they significantly differ from outdoor maps. Each indoor map format and standard has its own purpose and features. When we develop an indoor-map application, we have to select a format that fulfills most of the application requirements. Thus, a comprehensive understanding of these indoor-map formats and standards is critical for proper selection, such as the weakness and strength of each format and standard or their interoperability.

In order to respond to these demands, IPIN-ISC Indoor Map Subcommittee[1] was born in 2017 with the following actions:

- survey on indoor map formats and standards,
- comparison of indoor map formats and standards,
- guideline for selection, integration and conversion between formats and standards, and
- submission of change requests if necessary.

This work focuses on the survey and comparison of indoor map formats and standards. The paper covers important indoor map formats and standards, which are either de jure or de facto standards. We briefly explain each format and standard and compare them. In Section 2, a brief survey on previous works and the scope of the paper is given. In Section 3, we investigate the requirements of indoor map formats and standards from two viewpoints - data model and indoor positioning. Important indoor map formats and standards are explained in Section 4 including IndoorGML, CityGML, IFC, and Indoor OpenStreetMap. We discuss how to construct indoor maps based on these standards and formats in Section 5. Use-cases of indoor map formats and standards are to be presented in Section 6. We conclude the paper in Section 7.

II. RELATED WORK

The data models and formats for indoor maps are classified into three main groups:
Indoor map formats for specific domains: Map Data Representation (MDR) [2] provides a map data representation to encode the indoor and outdoor surrounding environments for mobile robots in a inter-operable format. MDR defines 2D representation of an environment in the form of a metric map, a topological map, and/or a combination of both. A similar standard is also under development for seamless navigation of vehicles between outdoor and indoor by ISO/TC204 ITS (Intelligent Transportation System)[3]. Moreover, ISO 17438[4] aims to develop relevant standards for indoor and outdoor seamless navigation of vehicles. It is divided into four parts and part 3 (ISO 17438-3) analyzes the requirements and defines the specification of indoor map formats.
Standard data models and formats for data exchange: Several standard data models and formats are developed for data

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The work of K.-J. Li was supported by a grant (19NSIP-B135746-03) from National Spatial Information Research Program (NSIP) funded by MOLIT of Korean government. The work of C. Laoudias has been supported by the European Union's Horizon 2020 research and innovation programme under grant agreement No. 739551 (KIOS CoE) and from the Republic of Cyprus through the Directorate General for European Programmes, Coordination and Development. Torres-Sospedra and Perez-Navarro want to thank the Spanish network of excellence, REPNIN+,TEC2017-90808-REDT. The work of A. Moreira has been supported by FCT – Fundação para a Ciência e Tecnologia within the Project Scope: UID/CEC/00319/2019.

[1] http://www.ipin-conference.org/isc/

[2] https://standards.ieee.org/standard/1873-2015.html

[3] https://www.iso.org/committee/54706.html

[4] https://www.iso.org/committee/54742.html

exchange. Their goal is to reduce the loss of information during data exchange and format conversion. In order to achieve this goal, they focus on the expressive power of a data model and define the encoding schema. IFC (Industrial Foundation Classes) of buildingSmart specifies the data model and encoding scheme for BIM (Building Information Modeling) covering indoor and outdoor spaces. CityGML of Open Geospatial Consortium (OGC)[5] provides a semantic 3D city model as an application schema of GML (Geographic Markup Language)[6]. CityGML Level of Detail 4 defines the feature model and encoding schema of the interior space of buildings. OGC IndoorGML[7] is a standard data model dedicated to indoor space as an application schema of GML. gbXML is also an application schema of XML for sharing building information between software tools covering indoor space.

Indoor map format for specific services: The ones falling into this category are not standards, but formats to support specific services. For instance, OpenLevelUp defines an extension of tagging schema from OpenStreetMap to describe indoor maps in 2D with multiple levels. Apple published the Indoor Map Data Format (IMDF), which is based on GeoJSON and provides the definitions of important indoor feature types and certain venue types such as airports, malls, and train station.

A few works have been previously reported to compare only two formats, such as in [1] where a comparative study between IndoorGML and CityGML was introduced. Several works have dealt with the integration (e.g., [2]) and conversion [3] of multiple indoor maps. However, none of them addresses the conversion of CityGML LoD 4 for indoor space.

III. REQUIREMENTS OF INDOOR MAPS

In this section we discuss the requirements of indoor map formats and its standards from two different viewpoints; data modeling and indoor positioning.

A. Data Modeling Aspects

One of the most important requirements of standard indoor map formats is the exchange of data between systems and services. In order to support the exchange of indoor maps, we have to consider two different aspects, which are of trade-off relationship: expressive power versus efficiency. On one hand, the standard indoor map formats should provide enough expressive power to minimize the loss of information that may take place during format conversion. On the other hand, the overheads introduced during transmission, encoding, and decoding have to be minimized at the same time. Brown et al. have investigated requirements for 3D indoor modelling for indoor navigation in [4]. In this paper we consider more general requirements. In order to determine a proper compromise between expressive power and efficiency, the following aspects have to be fully taken into account for each application;

- *Coordinates Reference Systems (CRS) in indoor space*: The identification of location in a given space is a fundamental requirement and the location is determined by coordinate (x, y) in 2D or (x, y, z) in 3D space under a CRS. Indoor space however differs from outdoor space in spatial reference systems by using either relative CRS or symbolic identifiers (e.g., room number).
- *Determination of unit space and their topological relationships*: An indoor space consists of a set of unit spaces (e.g., rooms), where each unit space is surrounded by physical architectural components (e.g., walls) or separated by virtual boundaries. Once we identify each unit space, we have to represent its geometry and topological relationships (adjacency and connectivity) between them.
- *Structures of indoor space*: Unlike outdoor space, indoor space is often characterized by its proper structure. An indoor space might be separated by level, wing and zone (parking, commercial, residence), which should be hierarchically represented in the indoor maps.
- *Representation of indoor features*: In addition to indoor spaces and structures, the indoor map standard should support additional features such as construction elements (doors, windows, stairs), furniture, pipes, or events.
- *Constraints of indoor spaces*: The accessibility constraints depends on the type of users, time and location [5]. For example visitors are only allowed in commercial areas during the opening hours. Standard indoor maps should support the flexible representation of constraints.
- *Map visualization*: Indoor maps can be represented either in 2D or in 3D depending on the application. Moreover, the wall representation (thick or thin) will also depend on the application. Standard indoor maps should provide high-quality representation for all supported applications.
- *Seamless integration between indoor and outdoor spaces and between indoor spaces*: Many applications require a seamless integration between indoor and outdoor spaces and, therefore, of multiple global and local CRS.

We summarized the requirements from the data model viewpoint. But it does not mean that all the requirements listed above are mandatory for all indoor map standards. Depending on the application, we may select proper ones from them.

B. Indoor Positioning

Indoor positioning algorithms can also profit from adequate representations of the indoor space. The major requirements for these representations are the following:

- *Compatibility with maps used for visualization*: Positioning algorithms provide the position (2D or 3D; pair of coordinates and altitude) or location (symbolic representation of a space, e.g. room A, second floor of building B), and their output must be compatible with the maps representations used for visualization as many applications require that the current position/location of a user be shown to humans. Combining and converting to/from geometric representations of the space from/to symbolic and hierarchical representations of the same space is a challenge, especially if both indoor and outdoor spaces are simultaneously considered.

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[5] http://www.opengeospatial.org/standards/citygml

[6] http://www.opengeospatial.org/standards/gml

[7] http://www.opengeospatial.org/standards/indoorgml

- *Hierarchical representations of the space*: hierarchical representations of the space, with buildings, floors, rooms, corridors, etc., can be exploited by indoor positioning algorithms to provide more accurate estimates of the location of a user by resorting to a hierarchical estimation process. These hierarchical maps should provide representations for inclusion (one space is inside another), adjacency (one space is next to another), proximity, accessibility (one space is accessible from another), and other properties that can be used to improve the location estimations, namely while tracking a moving object.
- *Navigable areas*: Not all spaces indoors can be visited by a pedestrian or a vehicle. A geometric representation of the navigable areas inside a building can be explored to: 1) reduce positioning errors through map matching; 2) avoid invalid trajectories across non-navigable areas (e.g wall-crossing); 3) improve, significantly, the performance of positioning methods with Kalman or Particle filters.
- *Topology*: A representation of the topology of a building, with information about connectivity between different individual spaces, can be exploited through the use of map matching and tracking techniques to improve the performance of the position estimation algorithms, namely by avoiding outliers and other large errors.
- *Infrastructure mapping*: maps with the position of certain elements of the infrastructure (e.g. location of Wi-Fi APs or BLE beacons) can also be used, or are even mandatory, in the operation of some positioning solutions.

While indoor maps are often seen as fundamental for visualization, their role is actually even more important for the operation of the indoor positioning algorithms. Therefore, further work is still needed to include the above requirements into the existing and future formats and standards.

IV. STANDARD INDOOR MAP FORMATS AND MODELS

A. Indoor OpenStreetMap

OpenStreetMap (OSM)[8] was born to be a free editable map of the whole Earth created from scratch by volunteers. The maps are released under the Open Database License.

When a user creates or modifies a map in OSM, what they are actually doing is tagging a point, a line, an area/polygon or a relation. The tags modify the semantics of the place by adding features like the name, type of building, type of amenity, the opening hours, among many others. The OSM community decides which are the available tags, that depend on the nature of what is being tagged. Nevertheless, new tags can be added. Although it was created for outdoors, its adaptation to indoors seems straightforward. Indoor maps based on OSM use plans from the architects as well as any floor plans, in raster (e.g., jpg) or vector (e.g., dwg) format.

Marcus Goetz proposed the extension to OSM for indoor environments in 2011 [6] and a mechanism for creating 3D indoor routing using crowdsourced data in 2012 [7]. There was a mobile indoor navigation system compatible with OSM in 2013 [8], and we saw a smart city implementation of OSM, including IndoorOSM draft and a mobile indoor navigation tool, in 2014 [9]. Some important projects in OSM are: OpenStationMap[9]; an extension for building 3D representation[10]; a draft to combine existing indoor mapping approaches with outdoor 3D building modeling[11]; or using a semantic mapping extension for OSM applied to indoor robot navigation [10].

The main drawback of OSM for indoor mapping is the lack of a true standard, which might explain a decrease in the interest in this initiative in recent years. On the other hand, the main advantages of OSM are its simplicity and that it benefits from the tools available for OSM outdoors like *OpenLevelUp*, *Vespucci*[12] and *Osiris*[13].

B. OGC IndoorGML

IndoorGML aims to provide an exchange format for indoor maps. OGC published it in 2016 as a standard for exchange format and data model of indoor map data. The main goals of this standard are to enrich the expressive power for reducing the loss of information during a data conversion process and to establish a basis of indoor spatial data model. IndoorGML assumes that an indoor space consists of a set of non-overlapping cells, where each cell represents a unit space such as room, corridor, or toilet. We call it *cellular space model*. Therefore, IndoorGML provides a data model to describe details of cells; cell *geometry* and *semantics*, *topology between cells*, and *multi-layered space model*.

- *Cell Geometry*: To build an indoor map in IndoorGML, we have to specify the geometry of each cell either as a point, as a 2D surface, or a 3D solid. Note that any cell should be a closed geometry such as a surface or a solid.
- *Cell Semantics*: Once a cell is identified with its geometry, semantics are to be added such as classification of cell, name, attributes, and so on.
- *Topology between Cells*: The topology between cells is also useful information for developing indoor map applications. Since no overlapping between cells is allowed, the only topology considered is the adjacency and connectivity between two cells. Two adjacent cells share a common boundary, and if the common boundary is passable, such as doors, we call it *connectivity topology*. Fig. 1 illustrates an example of the topology (Adjacency Graph) derived from a given indoor layout.
- *Multi-Layer Space Model*: An indoor space may be interpreted in several ways depending on viewpoints. As shown in Fig. 2, Room 3 is a cell for walking pedestrians. However, it is no longer a single cell for persons on wheelchair due to a step in the middle of the room, and consequently divided into Room 3a and Room 3b. This leads to two different configurations of an indoor layout, where each configuration is called a *space layer*. With

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[8] https://www.openstreetmap.org

[9] https://openstationmap.org/#2317.16/52.52405/13.370211/8.8/55https://openstationmap

[10] https://wiki.openstreetmap.org/wiki/F3DB

[11] https://wiki.openstreetmap.org/wiki/Simple_3D_buildings

[12] http://vespucci.io/

[13] http://osiris-indoor.github.io/

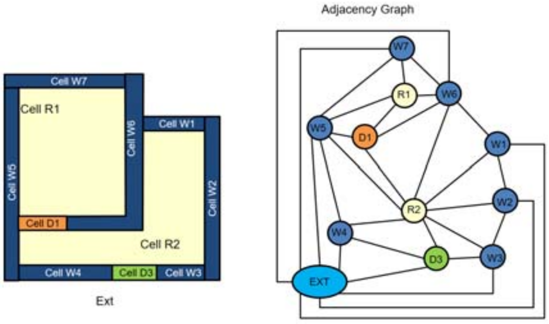

Fig. 1. An Example of Adjacency Graph [11]

multi-layer space model of IndoorGML, we can integrate multiple space layers via inter-layer connection. It is very useful to enrich the expressive power of IndoorGML. For example, the hierarchical structure of an indoor space is easily represented by the multi-layer space model [12].

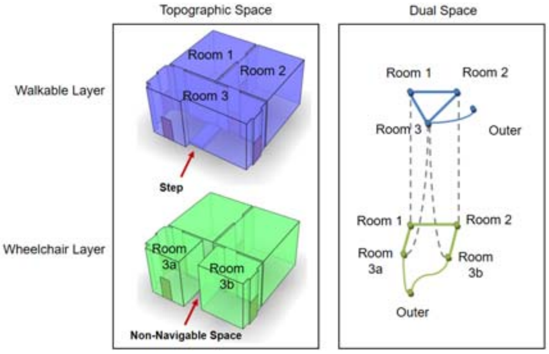

Fig. 2. An Example of Multi-Layered Space Model [12]

C. IFC

BIM(Building Information Modeling) is a general concept for object-oriented modelling and can be realized differently by software vendors. Therefore, standardization of semantics, geometry and topology is needed to share information across organizations, departments, IT systems and databases. Standards have been developed since the mid-1990s but the widely accepted one is IFC (Industry Foundation Classes). IFC is semantically-rich, object-oriented and truly 3D in which all geometries are topologically valid solids. IFC has a large number of classes dedicated to buildings and is being extended with even more classes to be able to comprise the complex construction management of large civil engineering projects. In many countries IFC is accepted as a national standard and legally forced into use.

IFC is a very suitable model to provide a precise indoor 3D map. Besides the notations for walls, slabs, connectors between different floors (stairs, elevators) doors and windows, IFC models can contain information about spaces in rooms and most importantly, furniture. Related to indoor positioning and location-based services, several IFC classes are of particular interest: ifcSpace, ifcVirtualElement, ifcOpeningElement, ifcSpaceBoundary, ifcRelContainedInSpaceStructure, ifcAgregate and the well-known and largely used ifcWindow, ifcDoor and ifcStair. The connectivity information (obtained with the help of information about doors, windows and stairs) makes the automatic creation of a network relatively straight forward. The notion of space opens numerous new directions for enhancing the localization and navigation of users and assets. Authors in [13] presented a framework for delineation of the space free of obstacles considering ifcSpace and ifcFurniture. Alattas et al. [5], suggested that spaces can be further semantically enriched to give indications about space accessibility for different types of users. Due to its high geometric resolution, IFC can be also a valuable source for map-based localization of assets or people (e.g., [14]) when kept up to date.

TABLE I
COMPARISON - INDOOR OSM, INDOORGML, IFC, AND CITYGML

	Indoor OSM	IndoorGML	IFC	CityGML
2D vs. 3D	2D, 3D	2D, 3D	3D	3D
Modelling Scope	Feature Model	Space Model	Feature Mode	Feature Model
Geometry	Boundary	Closed Geometry	Boundary	Boundary
Expressive Power	Low	High	High	High
Efficiency	High	Low	Low	Low
Encoding	Tag and XML	XML (GML)	Express and XML	XML (GML)

D. OGC CityGML

OGC CityGML is a common semantic information model and XML-based encoding format for exchange of 3D city models, defined as an application XML schema of GML 3.1.1. It aims to provide a basic entity model with 3D geometry of city objects and thematic feature models as well as appearance model. CityGML differentiates five Levels of Detail (LoD), where LoD 4 represents a 3D indoor model.

The feature types defined in CityGML LoD 4 for indoor space are room, surface, opening, installation, and furniture. Surface is classified into ceiling, floor, and interior wall surface and opening includes door and window.

The geometry of indoor features in CityGML are mostly represented as multi-surfaces except room, which can be represented as either multi-surfaces or as a solid. Unlike IndoorGML, CityGML does not contain any explicit topology between rooms but it can be derived from common surface shared by two adjacent rooms. CityGMS allows locating furniture and other elements, such as stairs, indoors.

E. Comparison

We present a comparison between the different formats with respect to seven criteria as shown in Table I. It includes Indoor OSM, OGC IndoorGML, IFC, and OGC CityGML LoD 4.

While the geometry in IndoorGML should be a single closed one such as a solid in 3D and a polygon in 2D, the geometry of the other standards in the table does not need to be closed. As IFC, CityGML LoD 4, and IndoorGML are based on well-defined data models and schema, they have strong expressive power. However, Indoor OSM uses simple tag-based representation and its expressive power is relatively limited. On the contrary, the data size of indoor OSM is small and easy to encode and decode, whereas the sizes of the other standards are big and relatively complicated, which result in low efficiency. Only IndoorGML explicitly describes the topology and therefore the navigation network.

V. BUILDING INDOOR MAPS

The unavailability of indoor maps and the lack of indoor map standards hinder the proliferation of indoor navigation and tracking solutions. While no global solutions exist for indoor maps, outdoor maps are widely and freely available.

Some companies are working on their proprietary indoor mapping solutions, e.g., *Google Maps Indoor*, and *HERE Indoor Maps*. Several other companies are active in this field including *mapspeople*, *IndoorAtlas*, *Cartogram*, *MazeMap*, and *Micello* among others.

In this section, we overview various approaches for building indoor maps. These can be used as baseline for producing high quality indoor maps and models according to the standards discussed previously.

A. From LiDAR

LIDAR-based systems include the *Google Cartographer* that creates indoor floor plans with 5 cm resolution [15]. The system consists of a backpack, featuring multi-echo laser scanners and an inertial measurement unit, while the Cartographer is a standalone C++ library. As the backpack-wearer walks through a building, SLAM technology generates the floor plan in real time and displays it on an Android tablet connected to the backpack's computer. The *STeAM* sensor tracking and mapping system developed by European Commission, Joint Research Centre (JRC) demonstrated 20 cm accuracy in the 2015 Microsoft Indoor Localization Competition (MILC) [16]. Commercial systems include the *Leica Geosystems Pegasus Backpack*, which is equipped with 5 high-end camera modules, 2 LIDARs and a commercial-grade GPS receiver. *Pegasus* localizes using a combination of GNSS, inertial and LIDAR technologies; however, it does not provide real-time positioning and navigation that can begin immediately after the survey as a post-processing step. *Pegasus* demonstrated 5 cm in the 2016 MILC [17]. Other commercial solutions are the *RealEarth Contour* and *Stencil* systems. *RealEarth*'s real-time localization and mapping software combines range data, visually tracked features, and inertial sensing, to estimate motion with 6 degrees of freedom. Their solution achieved 16 cm accuracy in the 2016 MILC [18].

B. From vision-based systems

Indoor SLAM solutions based on *Microsoft Kinect* vision sensor have attracted the interest of the research community due to the lower development cost [19]–[21]. From a technical viewpoint, the Microsoft Kinect is based on RGB-D cameras that are able to capture RGB images together with depth information for each pixel. Authors in [19] investigate how this technology can be used for building dense 3D maps and present a full 3D mapping system named RGB-D Mapping. A mapping and navigation system that uses the Microsoft Kinect sensor as the sole source of range data is presented in [20] that achieves performance comparable to state-of-the-art LIDAR-based systems and is capable of generating usable 2D maps of relatively large spaces. An autonomous indoor mobile robot localization and navigation solution is presented in [21], where all algorithms process only the depth information without additional RGB data. The localization algorithm is based on an observation model that down-projects the plane filtered points on to 2D, and assigns correspondences for each point to lines in the 2D map, while the full sampled point cloud is processed for obstacle avoidance for autonomous navigation.

C. From smartphone SLAM

Smartphone-based SLAM solutions are becoming increasingly popular because they are capable to generate indoor radio signal maps (i.e., cellular, Wi-Fi, magnetic) together with the floor plan map using the on-board wireless communication and inertial sensor modules.

Smartphone-based SLAM solutions can be categorized as follows. Solutions in the first category produce both a floor plan map and an associated signal map, while the second category includes solutions that output only the floor plan map. The second category is relevant to this paper; see [22] for a survey and comparison of smartphone-based SLAM solutions.

Authors in [23] use IMU and a foot-mounted piezoelectric sensor to estimate the lengths and orientations of the hallways for relative floor mapping. The *CIMLoc* system uses crowdsourced data from smartphone IMU sensors to derive users' trajectories with pedestrian dead reckoning and particle filter [24]. On the other hand, *MapGENIE* uses foot-mounted IMU data to generate the hallways and processes them to estimate the remaining structure (e.g., geometry of rooms and their areas) [25]. *Walkie-Markie* exploits the Wi-Fi infrastructure to define Wi-Fi marks for fusing crowdsourced user trajectories obtained from smartphone IMU [26]. *CrowdInside* uses Wi-Fi RSS and IMU sensors and corrects inertial motion traces with indoor points of interest, such as elevators and stairs, for error resetting [27]. *SenseWit* uses only IMU data to identify motion state, extract features, label featured locations, and bundles sequences of locations to generate a complete floor plan [28].

Jigsaw extracts the position, size, and orientation of landmark objects from images and obtains the spatial relation between adjacent landmarks from IMU data [29]. *JustWalk* employs a participatory sensing approach using smartphones where user-collected motion traces are processed by means of different mathematical and image processing techniques to detect the overall floor plan shape and higher level semantics such as detecting rooms and corridors shapes along with a variety of points of interest in the environment, without requiring any obtrusive user actions [30]. A solution for automatic generation of 2.5D indoor maps by processing images collected with off-the-shelf tablets or smartphones and

IMU data is presented in [31]. *Google Tango* technology uses better IMU and multiple cameras, such as RGB, depth, and motion tracking, to enable 3D indoor localization and mapping[14]. Tango was reported experimentally to provide low-detail scanning; however, the point cloud produced can be processed with standard shape detection methods or simple heuristics to identify floors, walls, doors or openings, which makes it a good option for building 2D floor plan maps [32]. Currently, this project is discontinued due to the requirement for additional hardware sensors that increase the cost and battery consumption of smartphones.

VI. USE-CASES

A. *Indoor navigation (2D/2.5D)*

Anyplace[15] is an open, modular, scalable, and extensible indoor information service that collects indoor data (e.g., location-dependent Wi-Fi readings) through crowdsourcing to attain high location accuracy (i.e., less than 2 meters) and deliver indoor navigation directions for reaching the desired Point-of-Interest (POI) in a user-friendly way. The Anyplace MIT-licenced open-source software stack has to this date been used by thousands of researchers and practitioners, while the number of real user interactions with the public Anyplace service is over 100,000. In this paper, we outline the mapping and indoor space modeling aspects of Anyplace that enable POI-based user navigation within the same floor (i.e., 2D navigation) as well as multi-floor (i.e., 2.5D navigation) through the use of floor transition POIs, such as stairs and elevators.

1) Overview of Anyplace: The Anyplace software stack consists of five main modules, including the *Server*, the *Data Store*, the *Architect*, the *Viewer* and two client applications running on Android smartphones, namely the *Logger* and the *Navigator* [33]. In our paper, we focus on the Anyplace *Architect* that is a *Web App* implemented in *HTML5, CSS3, JS* for enabling users to design and upload structural building information, i.e., floor plan maps, to the Anyplace *Server*. On the other hand, the Anyplace *Viewer* is a respective Web App that allows off-the-shelf POI search and navigation, without installing any application on the smartphone.

2) Buildings Management with Anyplace Architect: The Anyplace *Architect* offers a feature-rich, user-friendly and account-based (i.e., log-in with a Google account) interface for managing indoor space models. Through the built-in floor editor the user can upload, scale, and rotate the desired floor plan maps to fit them properly with multi-floor support on top of tile layer providers such as Google Maps and OpenStreetMap, as shown in Figure 3a. The floor layer comprises of a floor plan map (e.g., a raster image in JPG format), a set of annotated POIs (e.g., door, entrance, office), edges connecting the POIs to indicate walking paths through the floor, and signal maps (e.g., location-tagged Wi-Fi data crowdsourced by users). A building represents several floors logically linked together by POI edges (i.e., by connecting stairs or elevators of two floors).

Figure 3b illustrates additional features of the Architect including i) *monitoring crowdsourcing progress* to orchestrate the construction of Wi-Fi signal maps using color heat-maps; ii) *making a building public or private*, i.e., choosing between sharing a building on the Anyplace *Viewer* interface or keeping it for private use; and iii) *export and import of indoor models and signal maps* that allows users to quickly backup/restore a building, expedite user input of POIs (e.g., drag-n-drop and batch modes), and create a new model for a different purpose.

B. *Indoor navigation (3D) - Voxelization*

Recently, many approaches have been presented for a true 3D localization and navigation. This means that the computed path considers any type of movement (in any direction) without being restricted to a specific surface (e.g. floor). Naturally, researchers have been attempting to extend and adapt 2D approaches to three dimensions. However, the 3D space poses challenges to computational performance and geometric and topological validity.

In this respect, a very promising approach for 3D navigation, applicable for all kinds of locomotion modes (walking, driving, flying) is the voxel representation. Voxels are the volumetric equivalent of pixels, forming discrete volume elements that define a 3D space. Representing 3D indoor scenes using voxels brings two benefits: 1) it facilitates spatial analysis: path computation and distance estimation and well-known algorithms, 3D intersections become simple selection operations and 2) modelling and traversing volumetric spaces such as air becomes readily achievable. An important merit of the voxel data structure is the unification of the data type; every object is represented by only one primitive (a voxel) instead of a set of multiple geometries as in the vector domain.

Any 3D vector-based model such as the indoor map standards IFC, CityGML, or IndoorGML can be taken as an original indoor map and voxelized. Several algorithms for voxelization are available for robotics and computer graphics, and have been further adapted for GIS/BIM domain. A set of algorithms for points, lines and surfaces is provided by [34]. Note that during the voxelization the semantics of the original 3D indoor maps (BIM or GIS) is preserved, i.e. each voxel obtains the properties of the corresponding indoor feature of interest (wall, floor, ceiling, door, window, stairs). All ‘empty’ spaces are tagged as ‘air’ or navigable. When the voxel model is available, any path can be computed from a given point to a target point though the voxels space using raster algorithms such as distance transform [35]. The advantage of voxels for navigation is that it forms a continuous space. Thus, a path above or below certain obstacles can be easily computed to consider the size of the agent (Fig. 4b).

To be able to represent all needed components in a building, the size of a cell might need to be as small as 10 cm. This indeed will create large volumes of data and will require special management of the voxelized models. Several approaches can be followed: 1) the voxels can be organized in an octree data structure, in which the size of the cell is decreased only to represent change in the properties of the voxelized space

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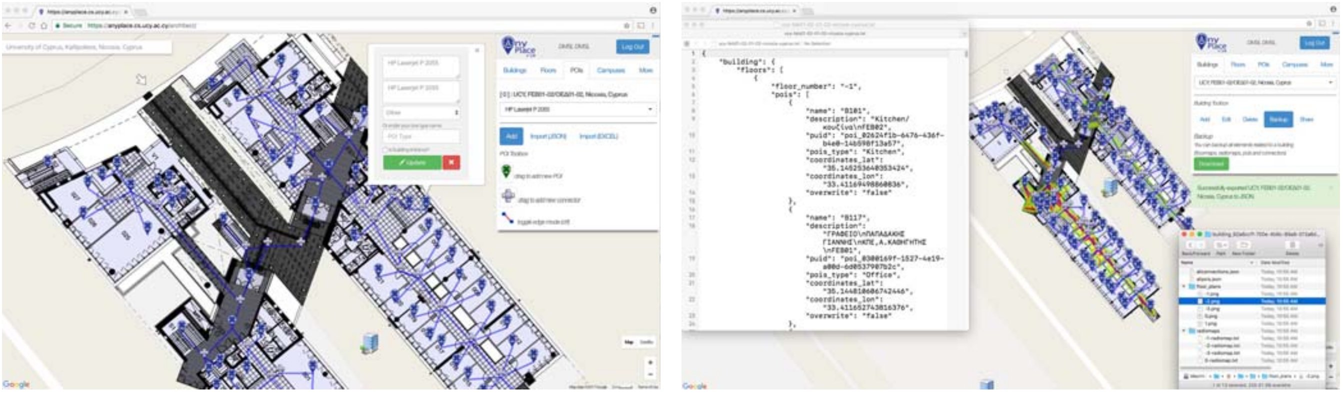
[14] Google Tango. http://get.google.com/tango/

[15] Anyplace. https://anyplace.cs.ucy.ac.cy/



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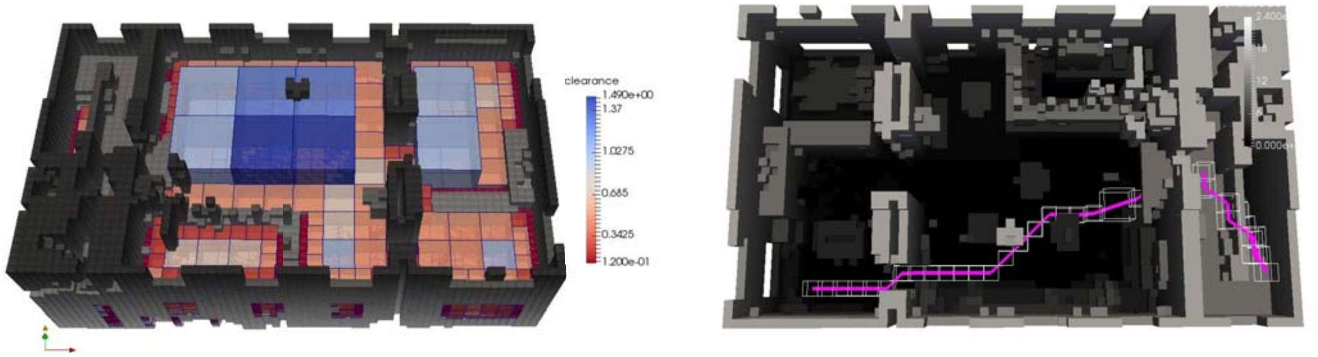
(a) Built-in floor editor (b) Anyplace Architect

Fig. 3. Anyplace Architect Web app (courtesy [33]).



(a) Voxelization to octree (b) Path finding

Fig. 4. Voxel representation courtesy [36]

(Fig. 4a), which can further be linked to Discrete Global Grid Systems (DGGS)[16], 2) the voxels can be organized in a database management system to be able to extract only those sets of voxels needed for the analysis [34] or 3) the voxels can be created on the fly only when needed for a path computation. Each of the approaches has certain benefits and further research is needed to estimate which one would be most appropriate for localization services.

Voxel approach is very promising for working directly with point clouds as they can be quickly converted to voxels, which effectively converts unstructured data to structured, and hence a path can be computed. Once the path is available, it can be visualized back into the original point clouds (Fig. 5).

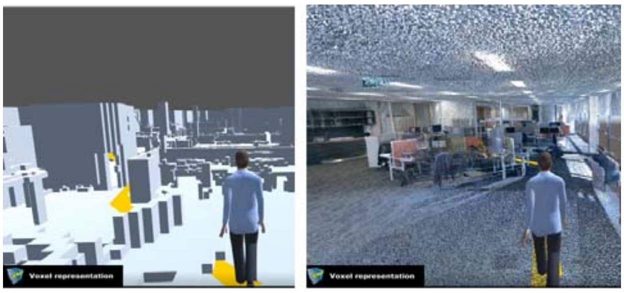


Fig. 5. Path computation on voxel data structure create directly from point clouds: a) voxel representation and b) visualization in the original point cloud (video: https://vimeo.com/299332236)

VII. CONCLUSION

The demand for indoor maps grows and several formats and standards have been developed so far, each one with a purpose and inevitably its weaknesses and strengths. To develop an application of indoor maps, we have to select one of them according to the application requirements.

We reported a survey on indoor map formats and standards to understand their concepts and objectives as the result of IPIN/ISC Indoor Map Subcommittee. We also presented a brief overview on commercial systems and approaches to create indoor maps. To illustrate the use of indoor standards, we have elaborated on two use cases.

As this work is the first achievement of the Indoor Map Subcommittee, our future plan includes a guideline of indoor map production and application for above mentioned map format and standard. The conversion between different formats and standards will be also studied, as well as the integration of

[16] http://www.opengeospatial.org/projects/groups/dggsswg

multiple standards, if necessary. We also aim to provide indoor map data in one of the indoor map standards and formats with its handling tools in next IPIN competitions. The Committee is an open community and any researchers or developers are welcome to join by contacting one of the co-authors.

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