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Algorithms for automated generation of navigation models from building information models to support indoor map-matching

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ABSTRACT

Navigation models are explicit representations of geometrical and topological information of physical environments that can be utilized for map-matching of indoor positioning data. This research paper presents algorithms for automated generation of three different types of navigation models, namely, centerline-based network, metric-based and grid-based navigation models, for map-matching of indoor positioning data. The abovementioned navigation models have been generated in an automated fashion from Industry Foundation Classes (IFC)-based building information models (BIM). Specifically, we have 1) built on and targeted addressing limitations of existing algorithms that generate centerline-based network navigation models for polygonal shapes, 2) developed an approach to extract 2D geometry and topology from IFC-based BIM for creating metric-based navigation models, and 3) modified an existing algorithm to generate grid-based navigation models using geometry and topology extracted from BIM. The abovementioned three types of navigation models have been generated for six different testbeds with varying shape, size and density of spaces. We have validated the *generality* of the developed algorithms by evaluating the accuracy of geometrical and topological information contained within the three types of navigation models generated from testbeds with varying spatial characteristics.

1. Introduction

Map-matching is the process of matching raw positioning data output from a positioning system to a map or a two dimensional (2D) navigation model depicting the surrounding physical environment [1,2]. Map-matching was first introduced to improve the overall position estimate from a Global Positioning System (GPS) by correcting erroneous raw data output by a GPS onto two dimensional (2D) road network navigation model stored in Geographic Information System (GIS) databases [2–4]. The existence of the road network navigation models in standard GIS vector format with nodes and edges assists greatly in map-matching of the GPS data [5–7]. Map-matching of indoor positioning data, on the other hand, is still not formalized as there is no standard representation of indoor environments for map-matching (akin to GIS-based representation for map-matching GPS data).

This paper addresses the issue of lack of approaches for automated generation of the navigation models identified in [8] for map-matching of indoor positioning data. Manual generation of navigation models for the purpose of indoor map-matching can be very expensive for large buildings, such as malls and hospitals. Moreover, buildings keep on changing and get renovated periodically over their lifecycle. Cotts [26] pointed out that on an average 30% of all building area is changed annually due to repairs and renovations. There is a lack of existing approaches that automate the generation of different types of navigation models required for map-matching of indoor positioning data even though there are several methods for automated generation of GIS-based road network navigation models [21–25], which are utilized for map-matching of GPS data.

Approaches for automated generation of indoor navigation models should utilize widely used building spatial information formats, such as DWG [27] and IFC [28]. For the research described in this paper, we have selected Industry Foundation Classes (IFC)-based building information models (BIM), for automated generation of different types of navigation models required for indoor map-matching. The main reasoning behind such a selection is the fact that IFC provide standard for product modeling schema in the Architecture/Engineering/Construction domain [28].

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Taneja [8] identified the requirements for map-matching of different types of indoor positioning data with varied navigation model representations and developed a domain-model to formalize the process of map-matching indoor positioning data. Requirements for map-matching identified in [8] include utilizing a) *network elements*, such as nodes and edges, that conform to the geometry and topology of the environment they represent; b) *boundary-representations* that contain connectivity information regarding the spaces they separate; and c) *grids* that contain connectivity and adjacency information regarding neighboring grids. Altogether, Taneja [8] identified three broad categories of navigation models that are applicable for map-matching indoor-positioning data, namely i) network-based model, ii) metric-based model and iii) grid-based model. In this research work, we have developed algorithms for automated generation of the above-stated three broad categories of navigation models. The following paragraphs describe briefly the contribution of this research work towards developing automated generation approaches for the three categories of navigation models.

In this paper, we compare the strengths and weaknesses of existing computational geometry algorithms, such as the Medial Axis Transform [31], the Voronoi Graph [31,32], and the Straight Medial Axis Transform [30] (described in detail in Section 3.1), developed within the robotics and computational graphics domains for generating a centerline-based network navigation model similar to the GIS-based road navigation network. Due to the shortcomings of current algorithms to generate a centerline-based network navigation model with linear elements, we developed a Modified Medial Axis Transform algorithm by modifying existing algorithms. The shortcomings of the Straight Medial Axis Transform algorithm [30] as well as the conceptual idea of the Modified Medial Axis Transform were presented in an earlier conference publication [50] and the current research work contains the results of the generated centerline-based network navigation model and validation of the Modified Medial Axis Transform.

To develop an approach for automated generation of metric-based navigation models, we have extracted *boundary-representations* of obstructions and portals existing in indoor environments from IFC-based BIM and added semantic information to each extracted boundary to determine whether the boundary is navigable (like a portal) or non-navigable (like an obstruction). Finally, for grid-based navigation models, we have modified existing algorithms, originally developed by Yuan and Schneider [29] and Li et al., [49], for extracting topologies from IFC-based BIM and automated the process of generating the *grid* occupancy map and movement probabilities required for map-matching indoor grid positioning data.

The algorithms developed for automated generation of navigation models have been verified and validated in a Java-based prototype developed with the goal of supporting the spatial queries contained within different types of map-matching algorithms. The algorithms developed in this research have been validated by generating the aforementioned three types of navigation models for six testbeds that differ in terms of i) total area of the testbed, ii) average area of the spaces in the testbed, iii) 75th percentile area of the spaces in the testbed (75th percentile area is the area of the space in the testbed that is larger than 75% of the spaces present in the testbed), iv) average room/space perimeter, v) average form factor (form factor is the ratio of the area of a space polygon to the area of the smallest circumscribing circle of that space polygon), vi) node density (node density is the number of nodes per unit area in a network navigation model), and vii) average edge length in network navigation model.

The next section overviews the requirements for composition of navigation models to support the spatial queries required for map-matching of indoor positioning data. The subsequent sections describe the representations of geometrical and topological information contained in the IFC2 $\times$ 3 schema [28], background research on algorithms for transforming geometrical and topological information into navigation models, and the algorithms and approaches developed in this research paper for automated generation of a) centerline-based network, b) metric-based and c) grid-based navigation models from IFC-based BIM models. This paper concludes with the presentation of results, validation and discussions.

2. Requirements for composition of navigation models to support spatial queries required for indoor map-matching

Taneja [8] identified four major categories of spatial concepts; 1) free areas/spaces, 2) portals, 3) obstructions, and 4) paths; all of which are required to execute geometrical and topological queries contained within various map-matching algorithms. For example, a map-matching algorithm could query the free area/space within which the current raw indoor positioning data resides or a map-matching algorithm could query if the indoor positioning data crossed a physical obstruction. These spatial queries, which are incorporated within map-matching algorithms, are generated from physical laws of human navigation. An example of such a physical law is that humans are always contained within a certain room/space or that humans cannot pass through physical walls inside a building. To support the queries arising out of these physical laws of human navigation, existing navigation models abstract *spatial objects* contained in indoor environments, such as rooms/spaces, doors and walls, into corresponding *spatial concepts*, such as free areas, portals and obstructions respectively. Thus one of the main requirements of map-matching is representing the above-stated spatial concepts within navigation models. For example, for GPS map-matching, roads can be represented as edges in a GIS-based network spatial model. Section 2.2 describes the different compositions of navigation models that have been utilized by different researchers to represent the above-stated spatial concepts and in turn support the execution of indoor map-matching queries. The next section presents the details of another important requirement for map-matching of indoor positioning data: the format of indoor positioning data.

2.1. Characteristics of algorithms for map-matching different types of indoor positioning data

Taneja [8] identified that different types of indoor positioning data formats, such as i) absolute point-positioning data, ii) relative-point positioning data, and iii) grid-positioning data, require different geometrical and topological queries for map-matching. Hightower and Borriello [14] classified indoor positioning data into two broad categories: 1) point positioning data, and 2) symbolic positioning data. Point positioning data is the positioning data described as a coordinate point in some frame of reference. Point positioning data can be further classified into i) absolute point positioning data, which has a global frame of reference, and ii) relative point positioning data, which has a local frame of reference [14]. Examples of absolute point positioning data include WLAN-based Ekahau system [15] that outputs data in the global coordinate system of a building and examples of relative point positioning data includes inertial sensor data, which reports only the displacement relative to the previous reported location. The second broad category of positioning data is called symbolic positioning data and it represents a position as a symbol, such as a room number or a zone number [14]. Symbolic data can also be classified into regular shaped grid data or irregular shaped room/zone data [14]. Proximity-based positioning systems, such as ultrasonic-sensor-based systems [16] and bluetooth-based systems provide positioning data as a room number or a zone number when a user is in proximity to a positioning sensor. A number of positioning systems also output position data as grids of variable sizes [14]. Such data represents position as a grid number rather than a point (for example, grid number 64).

Map-matching of point positioning data can be performed by confirming data on to a network navigation model represented by nodes and edges [11,12,17–19]. Various researchers such as [1,2], have shown that a 2D GIS-based representation of the road network can