2D Arrangement-based Hierarchical Spatial Partitioning: An Application to Pedestrian Network Generation

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ABSTRACT

This paper addresses the creation and maintenance of partitions of city surfaces for mapping and transportation applications. It proposes a hierarchical spatial surface partitioning, encoding the spatial partition with a 2D arrangement and structuring a generic hierarchy of semantic objects with a directed acyclic graph (DAG), in which the leaves point to the partition elements (polygonal regions, line strings, points). Semantic objects such as buildings, sidewalks and roads are described by grouping other objects and partition elements with their semantic relationships. In the proposed generic data model, geometry and spatial relationships of the semantic objects are respectively described by the geometry and topology of the planar partition. The proposed geometric data structure for creating and maintaining this partition is a 2D arrangement. In addition, the hierarchical object model encodes the thematic and semantic relationships between the objects. Besides the data model, methods and algorithms are discussed for leveraging existing vector datasets to create and maintain such partitions. These partitions are then fit to further processing and analysis using computational geometry and graph theory algorithms. For this purpose, three application-wise generic algorithms were integrated into our system called Streetmaker: two skeleton operators for centerline generation (straight skeleton and medial axis) and connectivity graphs for itinerary calculations. Moreover, specific algorithms can be integrated into Streetmaker for specific applications. We demonstrated an example usage of this framework for generating static obstacle avoiding pedestrian network graphs. The representation of the network graph and the process used to generate it, can be considered as the second contribution of our work besides the proposed data model.

Keywords

Spatial partitioning, 2D arrangement, hierarchical object model, vector data processing, GIS, centerline generation, computational geometry, pedestrian network generation.

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1. INTRODUCTION

Footprints of urban objects such as buildings, sidewalks, roads, road signs, lampposts, etc., constitute space partitions of the city surfaces which are required by many GIS applications. For example, 2D ground maps are commonly used in 3D city modeling pipelines for addressing the land / space cover of urban objects [7, 15]. Moreover, many applications demand detailed partitions of the city environments for navigation purposes such as path planning for the mobility impaired pedestrians, autonomous vehicle navigation and pedestrian simulation [4, 12].

Although creating surface partitions from scratch in a fully manual process is possible, most of the time it is not feasible, especially when the required level of detail is high and the area of interest is relatively large. One possible solution to this problem is the use of existing vector data. However, vector data coming from multiple sources may not be sufficient to generate the partitioning without further processing. Indeed, many vector data may contain geometric and topological errors together with redundant and incomplete data. Our approach is constrained with the cases in which the geometry of the input vector data is accurate but it may be incomplete and the topology may be both erroneous and incomplete. Alignment and correction of geometric inaccuracies are not handled within the scope of this paper.

Another problem is the selection of the data model for creating and maintaining the surface partitions throughout the geometric and topological modifications. Classical vector data models based on simple features (ISO 19125-1, ISO 19125-2) are not sufficient for these purposes since they lack topological relations (adjacency, connectivity, and containment) between the points, lines, and polygons. ISO 19107 "Geographic information - spatial schema" defines such vector data models but its topological aspects are seldom implemented and used.

Planar partitions can be defined as the tessellation of planes into non-overlapping polygons. When partitions are being created, surfaces are continuously subdivided by successively inserting geometric primitives coming from different vector data. Thus, it is highly expected that the footprints of the urban objects may be composed of more than one region in the generated partitions. For instance, the surfaces occupied by lampposts and city furnitures are also parts of sidewalks. Similarly, road surfaces may contain the pedestrian crossings. Therefore, the data model must be able to group the geometric primitives in the generated partitions under some abstractions and a hierarchical model is

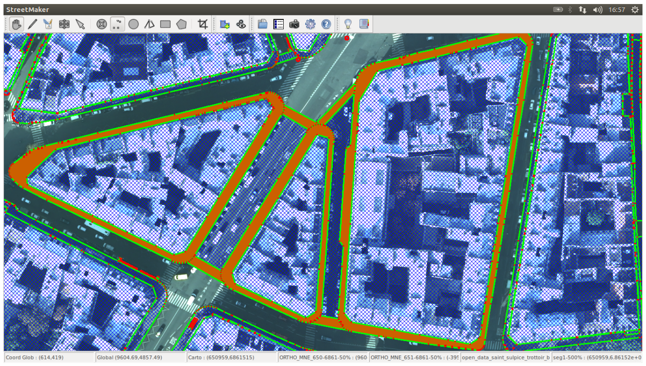

Figure 1: Streetmaker and semantic objects

required to represent the relations between these abstractions.

In this work, our contribution is two-fold. Firstly, we propose a data model based on a 2D arrangement [5] and a DAG-structured object hierarchy to create, process and maintain surface partitions. Each object of the hierarchy represents a semantic entity and contains geometric, topological and semantic information about the modeled spatial urban objects. The geometric and topological aspects of these objects are represented by a surface partition which is realized by a 2D arrangement. A 2D arrangement is a well-known concept in computational geometry which is used to compute and maintain the topology induced by the intersections of a set of input planar curves. On the other hand, a DAG is used to construct the thematic and mutual relationships between the semantic objects. As a second contribution, a process for generating detailed pedestrian networks is proposed which relies on our data model. The resulting network graphs avoid static obstacles and the nodes and edges of the graphs contain information about the surrounding semantic objects.

The data model and the implemented algorithms are encapsulated within a tool, called Streetmaker (Fig. 1). As a GIS, Streetmaker operates on data by means of layers and each source of data is opened as a vector or raster layer depending on the type of the data. The raster layer is used for loading images like orthophotos which are used to guide the human operators in order to create or edit (selecting, deleting, snapping, drawing) vector layers. Moreover, some automatic tools are also designed for correcting topological anomalies that may exist in the input vector data. As the partitions of the surfaces are being generated, semantization may be performed by manually creating semantic objects on top of the partition elements and existing semantic objects. For many applications, surface partitioning and semantization is only the starting point and further geometric computations are required. Three generic algorithms are integrated into Streetmaker: connectivity graph generator between the semantic objects for itinerary calculations, straight skeleton [2] and medial axis [6] for centerline generation. Specific applications can utilize Streetmaker as a framework by defining object types, constraining the object hierarchy and integrating application specific algorithms.

The rest of this article is organized as follows. Section 2 discusses the related work. Section 3 describes the proposed data model and its generation and maintenance, and generic geometric algorithms that are applicable to any semantic partition. Section 4 addresses the pedestrian network generation process as a demonstration of the proposed approach and Section 5 is used for conclusions and future works.

2. RELATED WORK

There are a lot of desktop GIS and spatial databases in the market that rely on different data models. In many of these GIS, explicit representation of topological relations are not supported except a few of them such as PostGIS topology package and GRASS GIS. PostGIS topology package (available since version 2.0) depends on the ISO/IEC 13249-3 SQL/MM specification and GRASS GIS has a very similar topology representation for vector data. These GIS are multi purpose complex systems designed with a database point of view. Although spatial databases are crucial for storing, querying and displaying data, for efficient and effective computation, fast accessing to geometry and topology is required which is the main focus of our data model. Recently, Laakso et al. [10] proposed an object based information model for pedestrian routing and navigation databases. However, their main focus is on the representation of the pedestrian network object hierarchy. Ours is on the creation and maintenance of such a constrained data model. Furthermore starting from a common spatial partitioning allows to build multiple application-specific object hierarchies that are interoperable.

Theoretical background of planar partitions were described by Plümer and Gröger [13]. In their work, the consistency of the planar partitions for surfacic objects was validated by using a set of graph theory axioms. By using 2D arrangements to represent planar partitions, 5 of the 7 axioms are automatically satisfied. In fact, the two remaining axioms exclude the isolated (degree 0) and dead-end (degree 1) points from the partitions which are not needed for surfacic objects. On the contrary, in our work surfacic (e.g. buildings, sidewalks), linear (e.g. road marks) and punctual objects (e.g. building entrances/exists) are supported. Moreover, the same set of axioms were used by Matijević et al. [11] for maintaining the integrity of a cadastral database upon updates. However, they represented polygons by simple features which imply many Euclidean distance calculations to check the axioms.

Pedestrian networks have been generated with different levels of detail for different purposes. In urban planning and unaided pedestrian navigation systems, relatively rough networks are acceptable [3, 14]. On the contrary, more detailed networks are necessary for mobility impaired pedestrian and autonomous vehicle navigations [9, 4, 12]. In all of these works, sidewalk centerlines are manually digitized with a commercial GIS to avoid static obstacles. Moreover, Kasemsuppakorn and Karimi [9] and Beale et al. [4] performed field surveys to refine the manually generated centerlines and to detect the surface properties such as material type, slope and width. Finally, Mayerhofer et al. [12] expressed the need for a semi-automatic / automatic tool for generating detailed and accurate digital maps for mobility impaired pedestrian routing and navigation. Our work may be considered as an answer to this demand in which the centerlines for walkable surfaces and the related lengths and widths are automatically computed by using two different skeleton operators (straight skeleton and medial axis) after a relatively fast and semi-automatic surface partitioning process which utilizes previously created vector datasets.

3. PROPOSITION

3.1 Data Model

A planar partition can be defined as the tessellation of a plane into non-overlapping polygons. The 2D arrangement data structure is a very good candidate for representing a planar partition which is indeed a subdivision of a surface by a set of planar curves into zero-dimensional vertices, one-dimensional edges and two-dimensional faces. In fact, in a 2D arrangement all intersection points between the curves are calculated which avoids overlapping polygons. The geometry and topological relations between the vertices, edges and faces are stored into an half-edge data structure [5] also known as doubly connected edge lists (Fig. 2). In this data structure an edge is represented by two oppositely oriented half-edges which are called twin half-edges. Half-edges circulate around the borders of the faces and holes in counter clockwise and clockwise orientations respectively. Holes can be faces or edges located inside other faces. Vertices of an edge can be accessible by both twin half-edges. Note that source vertex for an half-edge is the target vertex for its twin. Moreover, each half-edge is incident to a face on its left and each face stores references to one of the surrounding half-edges of its border and its holes. A non-isolated vertex is incident to half-edges that are targeting the vertex itself whereas an isolated vertex (no incident edge) is incident to its containing face. Faces also keep references for the interior isolated vertices. Keeping track of all these topological relationships provides very efficient traversal of the geometric primitives such as fast accessing the neighboring polygons, the edges connected to the same point, the holes of a polygon, etc.

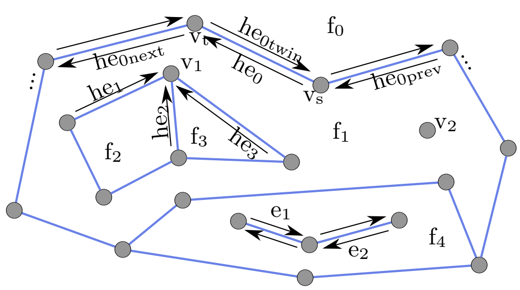

Figure 2: A 2D arrangement and its representation with the half-edge data structure: f_0 is the unbounded face containing f_1 and f_4. f_2 and f_3 are holes for f_1 whereas e_1 and e_2 are holes for f_4. v_2 is an isolated vertex in f_1. he_1, he_2 and he_3 are incident to v_1. he_{0next} and he_{0prev} are respectively the successor and the predecessor of he_0. v_s and v_t are the source and target vertices for he_0, he_0 is incident to f_1, while its twin he_{0twin} is incident to f_0.

A DAG is a directed graph that contains no cycles, i.e., no path starts and ends at the same vertex. A DAG is constructed between the objects based on the thematic and semantic relationships (Fig. 3). In this hierarchy, level-0 objects which have only incoming edges correspond directly to the groups of partition elements (vertices, edges and faces of the arrangement). On the other hand, higher level semantic objects group the other objects and may not directly contain partition elements.

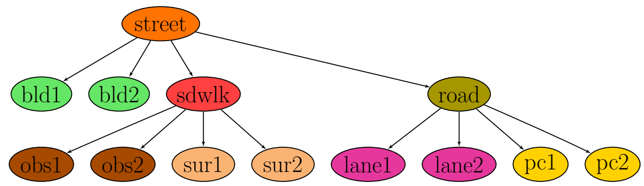

Figure 3: An example DAG-structured object hierarchy: sdwlk(sidewalk), bld(building), sur(surface), pc(pedestrian crossings, obs(obstacle)

3.2 Creation and Maintenance of Spatial Semantic Partitions

3.2.1 Creation

Vector data coming from multiple sources can be used to create partitions of the city surfaces. The first step is the construction of the 2D arrangement by using the geometric primitives from the input vector data. Many vector data can be combined into a single 2D arrangement or equally, separate 2D arrangements can also be generated for each vector data. These initially created 2D arrangements are rarely sufficient for partitioning the city surfaces due to the possible topological errors or incomplete data that may exist in the input vector data. These errors / missing data must be corrected / completed in order to be able to generate geometrically and topologically valid partitions. Our system has basic GIS capabilities to fix errors or complete missing data.

Semantization can be done interactively as the partitions are being created. Semantic objects are created on the underlying partition by grouping the partition elements and/or previously created objects (Fig. 1). Attributes can be inserted into the semantic objects at this stage. A leaf semantic object (level-0) in the object hierarchy can be composed of any combination of vertices, edges and faces. Even a single vertex or an edge can be defined as a semantic object.

3.2.2 Maintenance

Maintaining a planar partition means keeping the topological relationships between the partition elements (vertices, edges and faces) consistent with the addition and deletion of geometry. Editing the spatial partition is performed by inserting or erasing points and line segments. Since topological relationships are encoded by the 2D arrangement data structure, the topological modifications are then performed implicitly (e.g. splitting and merging of faces and edges, updating incidence relationships, etc.). As soon as a semantic object contains a modified partition element, it has to be updated accordingly. If the user tries to delete a partition element that is defining the boundary of a semantic object, the deletion is canceled and the user is reported with the list of objects that prevented it.

3.3 Generic Algorithms

Generic algorithms are needed for creating a basis for further processing the partition of city surfaces.

3.3.1 Connectivity Graph

The aim of this algorithm is to create a connectivity graph (Fig. 4) between the semantic objects which can be used for itinerary calculations. This algorithm recursively checks the boundaries of semantic objects and if a boundary is crossable a graph node is created on the corresponding boundary. The crossable property of a boundary is a boolean function defined by specific applications.

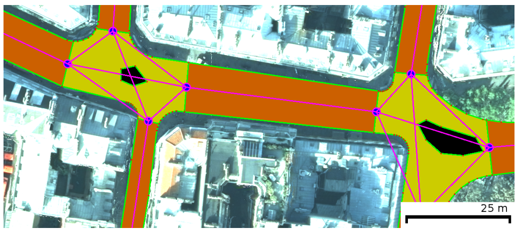

Figure 4: Connectivity graph for a road network

3.3.2 Straight Skeleton and Medial Axis

Skeleton operators (Fig. 5) are commonly used for centerline generation in cartography and navigation applications [8]: the straight skeleton is defined by an edge-parallel shrinking process and the medial axis is based on segment Voronoï diagrams. A typical application of straight skeletons is to generate a plausible roof structure from a building footprint for quick 3D visualization. On the other hand, the medial axis is interesting for navigation purposes as it directly encodes the maximal allowable width, at the cost of parabolic segments rather than straight line segments.

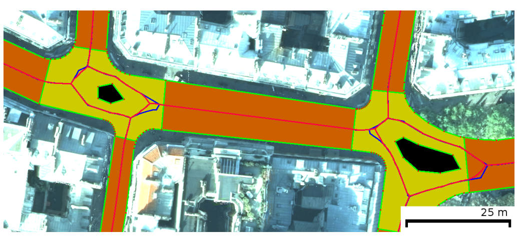

Figure 5: Skeleton operators: Medial axis (red) is superimposed on Straight skeleton (blue)

4. PEDESTRIAN NETWORK GENERATION

A partition of Saint Sulpice region (Fig. 6) in the city of Paris was created for pedestrian network generation. The region is about 56 hectares and composed of 57 building blocks. A building block is surrounded by sidewalks which is connected to other building blocks via pedestrian crossings or other types of walkable surfaces.

4.1 Creation of the Semantic Partition

City of Paris has made a set of vector data public, called OpenData [1]. Sidewalks, buildings, signalization (pedestrian crossings, lampposts, etc.) and poles vector data from OpenData and an internal address point location database are used to create the partition. The resultant partition is composed of 27877 vertices, 27561 edges and 4274 faces. Creating the partition and semantization of it took about 9 hours for a human operator which includes converting input vector data to 2D arrangements, running automatic error correction and simplification algorithms, manual error fixing, manually completing the missing data and manually creating the semantic objects.

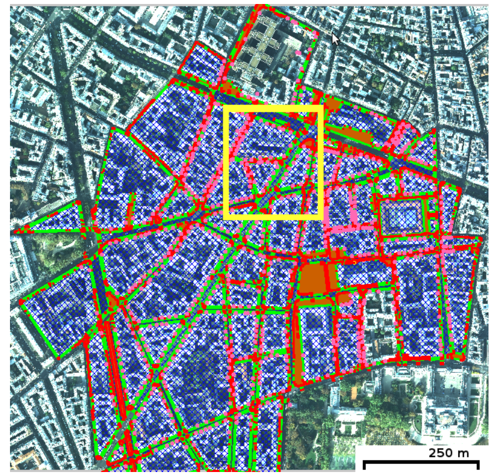

Figure 6: Saint Sulpice region and its semantic partition (see Fig. 9 for the highlighted region)

OpenData Paris vector dataset is not free of topological errors and missing data. For example, when signalization and sidewalks vector data are merged, the end points of the pedestrian crossings do not lie exactly on the borders of the sidewalks in most of the cases. Moreover, borders of some buildings and sidewalks are not complete and/or contain some topological errors. These errors were first corrected via automatic methods. Then manual corrections were applied for completing the missing data and when automatic methods were not sufficient for fixing the errors. Besides error fixing, simplifications were also done to reduce the complexity of the generated partition and to increase the performance of the geometric algorithms that run on the partition.

Three threshold based basic simplification and error correcting methods (Fig. 7) were utilized. `Redundant geometry removal`: If the angle between two consecutive edges is smaller than a predefined threshold (0.1 deg.), the corresponding edges are merged by deleting the shared vertex. `Merging vertices within a neighborhood`: Vertices within the same neighborhood defined by a relatively small disk (radius 5 cm) are merged into their mean-vertex. `Auto connecting lines`: Very close lines are common in vector data because of undershoot errors or coordinate mismatches. Depending on a distance threshold (10 cm) one of the two lines are extended to meet the other one.

We defined the following semantic objects for the semantization of the partition. `Physical Road`: These objects represent physical surfaces that pedestrians can walk on. They lie in the lowest level of the object hierarchy. `Logical Road`: These objects are parent objects for the physical road objects, representing the logical formations on the city surfaces such as streets, avenues, etc. `Street Number`: Street numbers correspond to address point locations (entrance of the

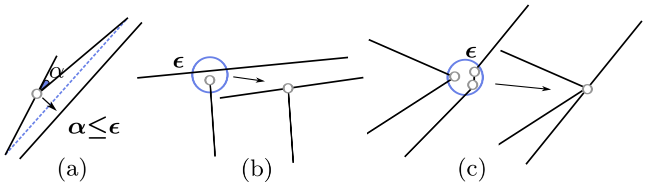

Figure 7: Threshold based simplification and error correction methods: (a) redundant geometry removal, (b) auto connecting lines, (c) merging vertices within a neighborhood

buildings). *Obstacle*: Any static object on walkable surfaces such as benches, lampposts, and poles are considered as obstacles.

4.2 Description of the Network Graph

The output of the pedestrian network generation process is a planar graph. An example graph is shown in Fig. 8. The edges of the graph represent the centerlines for the walkable surfaces. Some of these edges are grouped into logical formations called trajectory arcs which characterize the homogeneous parts of the centerlines. The graph nodes that determine the start and end points of the trajectory arcs are called trajectory nodes and the remaining nodes can be named as ordinary nodes. The degree of a node is defined by the number of incident edges and ordinary graph nodes joining two consecutive edges are degree-two. Degree-one nodes correspond to the start/end points of the graphs and the nodes with degree greater than two are the divergence points for multi-paths on the graph. Another type of trajectory node is the border trajectory node which identifies the points of intersection between the centerlines and the borderlines. Borderlines indicate the boundaries between the semantic objects.

Address point locations and their projections on the closest graph edge define the entrance and exit points of the pedestrians to the graph which will be queried for the itinerary computations. Moreover, total length of each trajectory arc and the minimum width along the path of a trajectory arc is calculated. The minimum width is the maximum radius of a disc translating along the trajectory arc that is fully enclosed in the walkable region. The types of the trajectory arc curves vary depending on the used algorithm for generating the centerlines. Straight skeleton algorithm generates only line segments with an lower-bound of the minimum width whereas medial axis algorithm generates both line and parabola segments with an exact minimum width.

4.3 Methodology and Implementation Details

The object geometries are combined into a larger polygon with holes in order to generate the centerlines via straight skeleton or medial axis. Then, borderlines between the spatial objects are found using the topological relations. These borderlines are intersected with the centerline curves in order to detect the border trajectory nodes. A recursive algorithm is applied to compute the trajectory arcs by checking the degrees of the graph nodes. Finally address point locations are projected to the closest centerline edge. In the resultant network graph, trajectory arcs and trajectory nodes are linked to physical road objects via unique ids. These relations are constructed by querying the trajectory node

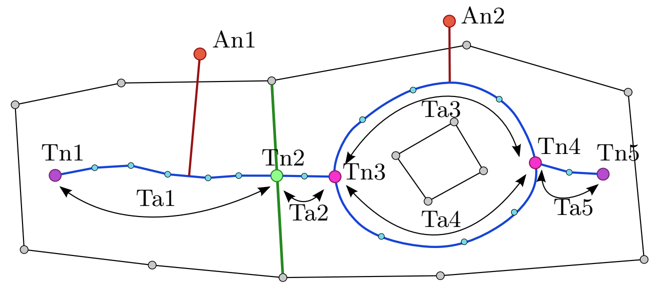

Figure 8: An example pedestrian network graph for two semantic objects separated by a borderline. Trajectory nodes: Degree-one (Tn1, Tn5), Degree greater than two (Tn3, Tn4) and Border(Tn2). Trajectory arcs: Ta1-Ta5. Address points: An1, An2.

locations in the arrangement of the semantic objects. By using these relations, from a trajectory node or a trajectory arc the information about the surrounding surface (semantics about the physical roads and the logical roads) can be reached.

4.4 Results

A part of the obtained pedestrian network graph is given in Fig. 9. The run-time for the pedestrian network graph generation for the whole region took approximately 3 hours for medial axis, and 10 hours for straight skeleton on a standard computer. The generated graph is used within a 3D pedestrian simulation application (Fig. 10) which will be the subject of another paper.

5. CONCLUSIONS AND FUTURE WORKS

In this article we present methods and algorithms for leveraging the existing vector data in order to create semantic partitions of the city surfaces. A distinctive data model is offered for fast and efficient processing of geometry by using 2D arrangements to represent partitions of the city surfaces. Furthermore, we used the offered data model together with a set of algorithms to generate detailed pedestrian networks. As a future work, the proposed pedestrian network graph can be lifted to 2.5D by integrating height and slope information of the surfaces from street level databases. Such information is very important for autonomous vehicle navigation. In the current status of Streetmaker the semantization process is done manually but there will be a work on the automatic creation of the semantic objects by directly using the semantic information that already exists in the vector data. Furthermore, other applications can be developed using Streetmaker such as road network generation and itinerary calculations on the generated network graphs. In order to further help the human operators in editing the vector data, 2D smart plotting tools can be developed. For example, line detection in the images with sub-pixel precision and snapping to detected lines may a good candidate. Finally, 3D GIS is getting more and more importance and one of the future goals is to partition the city environments in 3D using multi-view street level panoramic images. 3D partitions can be generated by partitioning the 2D surfaces embedded in 3D using 2D arrangements on the corresponding views.

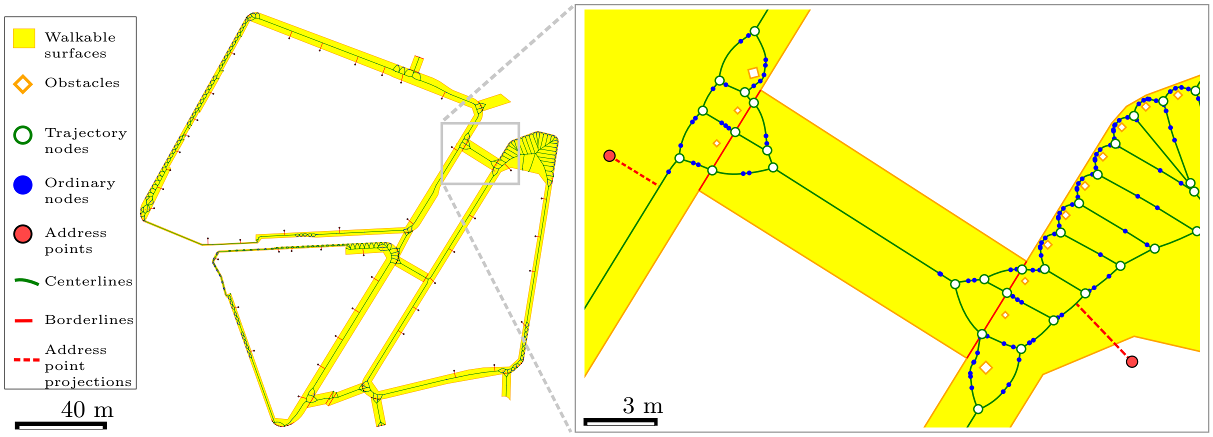

Figure 9: A part of the pedestrian network graph generated for Saint Sulpice/Paris (higlighted in Fig. 6)

Figure 10: Pedestrian simulation application: based on the generated pedestrian network overlaid on a geo-referenced image

6. ACKNOWLEDGMENTS

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