Geometric, Topological & Semantic Analysis of Multi-Building Floor Plan Data

by

Emily J. Whiting

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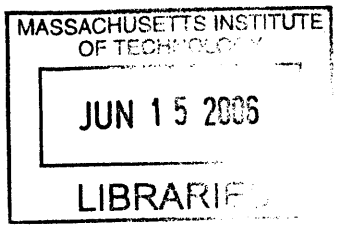

ROTCH

Signature of Author: _____
Department of Architecture
May 25, 2006

Certified by: _____
Seth Teller
Associate Professor of Computer Science & Engineering
Thesis Supervisor

Certified by: _____
Takehiko Nagakura
Associate Professor of Architecture
Thesis Co-Supervisor

Accepted by: _____
Julian Beinart
Professor of Architecture
Chairman, Department Committee on Graduate Students

Axel Kilian
Post-Doctoral Associate in Computation, Department of Architecture
Thesis Reader

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for the Degree of Master of Science in Architecture Studies.

ABSTRACT

Generating a comprehensive model of a university campus or other large urban space is a challenging undertaking due to the size, geometric complexity, and levels of rich semantic information contained in inhabited environments. This thesis presents a practical approach to constructing **topological** models of large environments from labeled floor plan **geometry**. An exhaustive classification of adjacency types is provided for a university infrastructure including roads, walkways, green-space, and the detailed interior spaces of campus buildings. The system models geospatial features for over 160 buildings within the MIT campus, consisting of more than 800 individual floors, and approximately 36,000 spaces spanning indoor and outdoor terrain. The main motivation is to develop an intuitive, human-centered approach to navigation systems. An application is presented for generating efficient routes between locations on MIT's campus with coverage of both interior and exterior environments. A second application, the MIT WikiMap, aims to generate a more expressive record of the environment by drawing from the knowledge of its inhabitants. The WikiMap provides an interface for collaborative tagging of geographical locations on the MIT campus, designed for interfacing with users to collect **semantic** data.

Thesis Supervisor: Seth Teller
Title: Associate Professor of Computer Science & Engineering

Thesis Co-supervisor: Takehiko Nagakura
Title: Associate Professor of Architecture

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Table of Contents

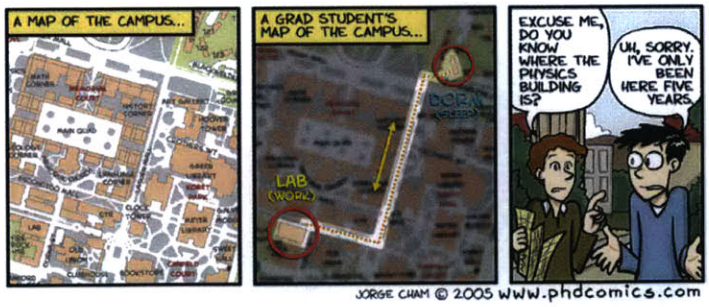
1 Introduction

1.1 Motivation

Navigation tasks are essential to any environment involving movement through complex spaces. The recent developments of online mapping tools such as Google Maps® and Mapquest® have made available interactive geographic visualization tools with comprehensive route searching functions. However, these applications are targeted primarily at travel on the resolution of street networks at the speed of automobiles. Their comprehensive survey of highways, traffic intersections and neighborhood streets overlook local details, which may be important navigational cues to travelers on foot.

Using MIT campus as a test-bed, this thesis presents a system for modeling geospatial features of built environments at the scale of the walking traveler. Methods for analyzing the environment aim to extract an exhaustive set of geometric, topological and semantic properties of space.

Geometric features encapsulate the physical characteristics of space such as coordinates and containment properties. For example rooms have a set of dimensions describing their boundaries and a floor in which they are contained. **Topological** features represent adjacency relationships between spaces, such as doors that connect a hallway to a classroom, or elevators that afford vertical movement through a building. Lastly, **semantic** features capture the various meanings of space (e.g. functional, historic or cultural), which are not expressed through geometric and topological relationships. For example, a specific building may function as a concert hall, student services center, or research laboratories. A certain area of a building may be a classroom, office, or cafe.



The main motivation of this work is to develop an intuitive, human-centered approach to navigation systems. This thesis presents an application for generating efficient routes between locations on MIT's campus with coverage of both interior and exterior environments. A second application, the MIT WikiMap, aims to generate a more expressive record of campus spaces by drawing from the knowledge of its inhabitants.

We offer a searchable and user-populated database, allowing visitors to find "points of interest" on campus, and how to locate them.

Specifically, the work in this thesis aims to make possible the following scenarios:

a) A new student at MIT needs to get to class but is bewildered by the numbering system of buildings on campus. In a web form, he enters his residence Westgate as the start location, and the lecture hall 1-190 as the destination. As he types, Westgate is automatically interpreted as W85. He submits his query and is presented with a route displayed on the campus map directing him along Amherst Alley and through Building 1, as seen in Figure 1-1.

b) A visitor to MIT has an appointment at the Media Lab. When submitting her route query she also chooses to display locations of sculptures and paintings on the map. Discovering that her route through Lobby 10 passes by Killian Court, she takes note to stop and see the Henry Moore sculpture.

c) It's 12:15 PM, and an undergrad student is about to bike to campus for her 1 PM class in 10-250. In the time before class, she would also like to grab lunch. Using MIT WikiMap, she clicks to display all bike rack and quick food locations. Zooming into the area around Building 10, she quickly finds a place nearby to lock her bike, and notes the Building 4 café as the closest place to eat.

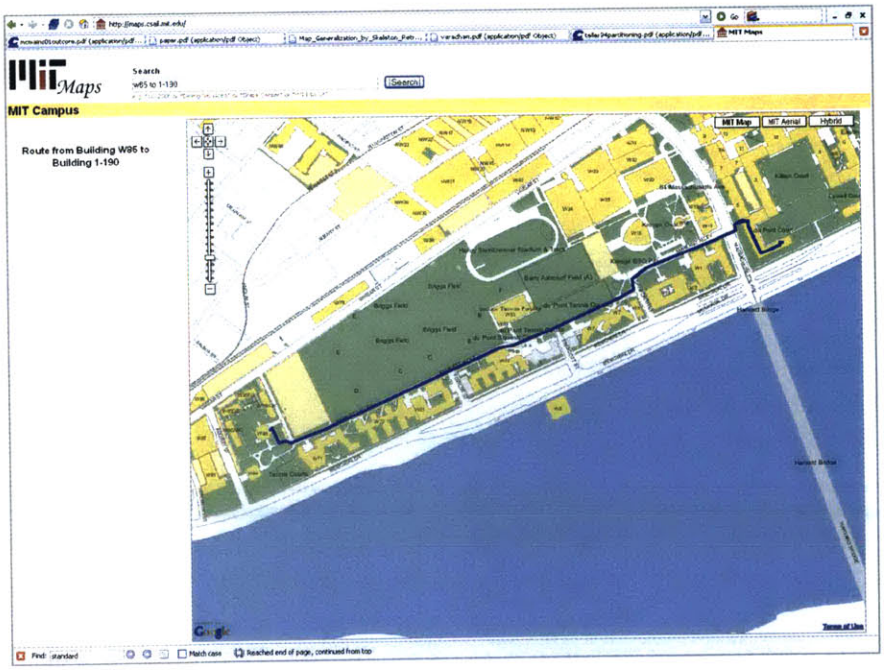


Fig. 1-1: A sample route from Westgate to lecture room 1-190.

1.2 Contributions

This thesis makes the following contributions:

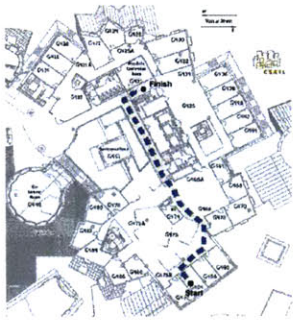
- Framework for constructing graphs of large environments from floor plan data, including an exhaustive classification of portal types for both building interiors and building interfaces.
- User interface for interactive map application: database for storing, editing, and visualizing campus landmarks.
- Substantial improvements to the Location-Aware API developed by [Nichols 2004], including performance optimizations in route generation, and improvements to path rendering methods for route visualization.
- Re-implementation of space triangulation – more robust formatting of output data, and structured as isolated process in pipeline rather than embedded in "stew" of geometry processing.
- Approximated medial axis derived from space triangulation, with applications to intra-space path finding.
- Proposals for identifying landmarks based on properties of the campus topology and geometry.

1.3 Related Work

Substantial work has been done on digitizing road maps such as [Haunert and Sester 2004] and [Gold 1997]. However, extraction of a link-node graph representation for street networks is a clearly defined problem considering the common geometric properties of roads: streets have standard width, a single direction of motion, and intersections can be modeled as a point. Further, centerline maps are often available which obviate the need for simplifying road contours into a 1-D representation. In contrast, walkers in urban environments are not limited to movement along one-dimensional paths. Instead of point intersections, pathways may meet at a courtyard or lobby. Pedestrians can move freely from interior to exterior space, and take short cuts across fields. Online mapping services such as Google Maps® and Mapquest® fail to model these more diverse environments, as seen by the empty space covering MIT campus in Figure 1-2.

Fig. 1-2: Example of route through the city of Cambridge generated by Google Maps. Coverage of paths through the MIT campus is sparse.

A sophisticated example of route generation for indoor environments is the MIT Stata Walking Guide [Look et al. 2005]. The Stata Walking Guide provides both graphical route maps and written walking directions between different locations in MIT's Stata Center. The data model incorporates not just metric distances but higher-level concepts such as the functional purpose of a place, which are then incorporated as landmarks in the written directions (see Fig. 1-3).



"Head out of G494 and
Turn right.
You will see a set of double doors on your left; walk towards it.
Walk through the doorway into a new area (4th Floor Gates).
Walk forward.
You will pass the Elevator Lobby on your right along the way.
Turn right.
Walk through the doorway into a new area (4G Kitchenette).

Turn right, then left, and go straight down the hall through the doors and past the elevators. Go through the first door on your right. [2]"

Fig. 1-3: Stata Walking Guide: output consisting of graphical route map and written instructions [Look et al 2005].

What's missing in the Stata system is an automated process for constructing the underlying data model. Manual methods are used to build the graph for the route-finding component, as well as for landmark identification and collection of other high-level information (e.g. waypoints belonging to the same corridor). These methods are clearly labor-intensive and intractable for extension to all buildings on the MIT campus. The methods proposed in this thesis could fill an important niche, offering a streamlined process from floor plan data to high-level route descriptions.

Other projects have addressed the problem of automatic graph construction from floor plans. However, in examples such as [Lee 2004], the topological model is derived from hallway elements which share the convenient property of street networks: movement is straight and linear, with constant width between opposing boundaries (e.g. walls). Still lacking is a system that robustly generates topology from arbitrarily shaped spaces and varied connectivity types present in raw floor plan data. Further, existing systems apply only to networks within an enclosed building, and do not consider graphs between buildings, spanning outdoor terrain.

1.4 Background

This section provides background material relevant to this thesis, including work by members of the MIT Building Model Generation (BMG) group. The Location Aware API developed by Nichols [2004] and Bell [2003] is reviewed, and subsequent modifications made to the API are discussed. A review of algorithms used in route-finding and geometric computations is also presented, including a brief discussion of Dijkstra's graph search algorithm, constrained Delaunay triangulation, and the medial axis transform.

1.4.1 Building Model Generation Project

1.4.1.1 Overview

Fig.1-4: Three-dimensional model of MIT generated by BMG.

The Building Model Generation (BMG) group at MIT has been tackling the problem of automatic interpretation of floor plan data for a number of years. This project originated at the University of Berkeley [Teller et al 1996] and has expanded through support at MIT [Nichols 2004, Kulikov 2004]. Floor plans in their native DXF format are processed into a more human-readable geometric format, which is then further analyzed to derive three-dimensional models (Fig. 1-4) and a topological layout of the environment. BMG has seen significant progress but still requires improvement of accuracy and completeness in its output.

Previous work in the BMG project had shortcomings at two distinct stages in the pipeline: the initial geometric processing of the floor plan data, and the topological interpretation of the data. The topology-generating engine recognized only a fraction of the connectivity types present on campus. Vertical connections (stairs and elevators) were less than 50% complete, and implicit connections (e.g. continuous corridors) were excluded from the model entirely. The research in this thesis aims to generate a more exhaustive topological representation of campus, building upon the foundations developed by the BMG project.

1.4.1.2 Floor Plan Data

In order to build the applications described in this thesis, a comprehensive dataset describing the campus geometry is required. Given the size of the MIT campus – over 160 buildings and nearly 1,000 individual floors – the proposition of manual data collection is unfeasible.

Our computations are based instead on floor plans. The advantages of adhering to this format are three-fold:

- They are an immediately available data source: floor plans are maintained and regularly updated by MIT's Department of Facilities for every building on campus.

- The drawings are structured to follow strict conventions, such as unique space names, consistent room use codes, and implied adjacency information.
- Construction details are segmented into functional layers including room contours, floor extents and exterior walls, which lends to more streamlined parsing routines.

MIT floor plans are available on the web at https://floorplans.mit.edu. Methods are discussed in Section 2.2 for extracting geometric and topological information from the native DXF format.

1.4.1.3 Basemap

The campus basemap in its raw form is a contour map describing the physical layout of MIT. Position and orientation is specified for building footprints, along with other physical infrastructure such as locations of sidewalks, streets and grass.

The methods developed in [Kulikov 2004] process the original CAD DXF file to generate a properly labeled model of the campus terrain (Fig. 1-5). The basemap is further divided into patches with known adjacency relationships so that inter-building routes can be generated.

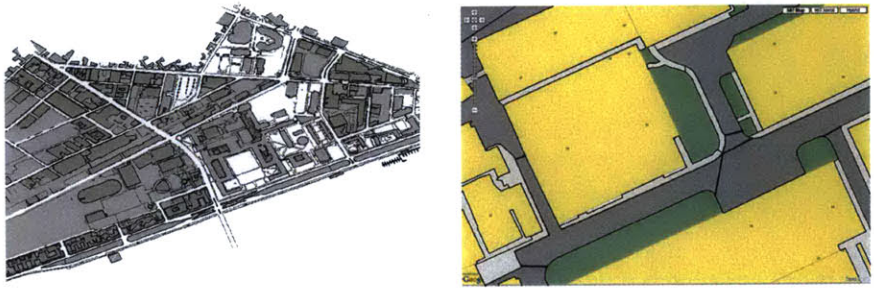


Fig. 1-5: The campus basemap. The close-up image is colored according to space type. Black outlines indicate partitioning of street (dark grey) and sidewalk (light grey) regions into smaller patches.

Each patch is labeled with a terrain type including sidewalk, street, grass, construction, and building. See appendix B for a full listing. These type classifications are later incorporated into constraints for inter-building routes, discussed in chapter 3.

1.4.1.4 Location Server

The Location Server is a network-accessible Java RMI program introduced by Bell [2003] and developed by Nichols [2004] which provides campus geometry and route-finding capabilities to client applications through a general API. The location server currently provides these services to MIT Maps [http://maps.csail.mit.edu] which will be discussed in chapter 3.

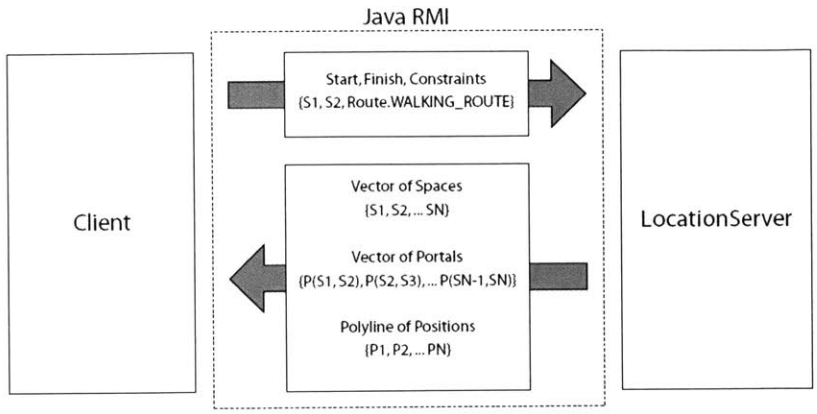


Fig.1-6: Route passing between server and client over Java RMI [Nichols 2004].

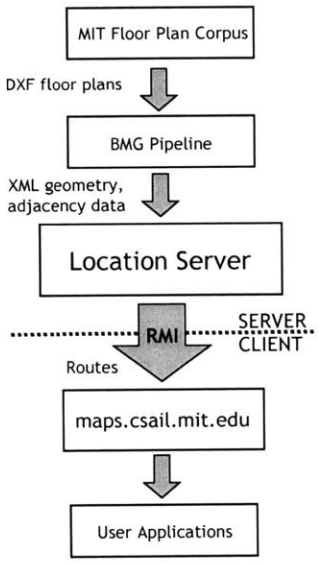


Fig. 1-7: Location Server overview.

As illustrated in Fig.1-6, route requests are made by the client and embedded in a Java route object containing a source space, a destination space and route constraints. The route object is then passed to the Location Server over Java RMI. The returned route contains a path described at three levels of abstraction: as a sequence of spaces traversed, as a sequence of portals traversed while moving between spaces, and as a collection of ordered connected points in the polyline path.

The procedures used by the Location Server for generating routes have been substantially modified since the initial developments of [Bell 2003] and [Nichols 2004]. Performance optimizations and improved rendering routines have been incorporated and will be explained in detail in the implementation section of chapter 3.

Geometry and adjacency data is provided to the Location Server by the BMG pipeline in the form of XML documents. This is a further modification made in this thesis, meant to replace the custom file format for input data specified in [Nichols 2004]. For details on the structure of the XML data model refer to section 2.1.

1.4.2 Core Data Structures & Algorithms

1.4.2.1 Out-of-Core Graphs

Large datasets composed of millions of geometric primitives are commonly used to represent complex geometric models such as architectural buildings and urban environments. The massive size of these models poses challenges for both storage and interactive display. Consequently, "out-of-core" algorithms have been proposed which are designed to process data too large to fit into a computer's main memory at one time. Such algorithms must be optimized to efficiently fetch and access data stored in slow bulk memory [Funkhouser et al. 1992].

As will be discussed in section 2.1.6., our data model stores adjacency relationships between campus spaces using a graph (G) data structure. Each node in G is one XML element. Each edge in G is also an XML element – stored as a child element of its source node, and containing an attribute naming its destination node. By parsing the XML tree structure it is possible to quickly reconstruct portions of the graph in main memory as needed.

1.4.2.2 Dijkstra's Graph Search Algorithm

Dijkstra's algorithm obtains the shortest path from a source node *s* to every other node in a weighted graph G [Cormen et al. 2001].

> *Given a graph G = (V, E), where V is the set of vertices and E is the set of weighted edges, find the shortest path from a given source vertex s* $\in V$ *to each vertex* $v \in V$.

In our application, vertices represent locations on campus, and edge weights represent positive distances between pairs of locations connected by a portal. Dijkstra's algorithm is used to find the shortest route between two locations.

The input to the algorithm is a weighted graph G, a source vertex *s*, and a weighting function *w* which gives the weights of edges in the graph. The cost of a path between two vertices is the sum of weights of edges in that path.

An initial distance of infinity is assigned to each node except for the source, which has an initial distance of zero from itself. The algorithm updates the distance estimates for each node with **edge relaxation:** consider an edge connecting two vertices *u* and *v*. If the distance estimate to *v* from the source is reduced by first traveling through *u*, then the shorter distance value for *v* is saved. The algorithm is structured so that each edge (*u*, *v*) is relaxed only once, when the shortest distance to *u* is known.

The algorithm maintains a set S of vertices for which the minimum weight path is known, and priority queue Q containing all other vertices in the graph. The following pseudocode has been modified to terminate when the destination node is found.

```
Dijkstra(G, s, dest, w)
1   for each vertex v ∈ V(G)                    // initialization
2       Distance(v) ← ∞
3   Distance(s) ← 0
4   S ← ∅
5   Q ← V(G)
```

```
6   while Q ≠ ∅
7       curr ← Extract-Min(Q)
8       if curr = dest
9           return Path(s, curr)
10      else S ← S ∪ {curr}
11          for each vertex v adjacent to curr              // edge relax
12              if Distance(v) > Distance(curr) + w(curr, v)
13                  Distance(v) ← Distance(curr) + w(curr, v)
```

In order to extract the actual path to the destination node, one possible approach is to store the path in the queue, updating it along with the distance estimate every time an edge is relaxed:

line 14: Path(source, v) ← {Path(s, curr), v}

Alternatively, an attribute Previous(v) could be stored for every node that represents the previous node in the shortest path towards source *s*.

line 14: Previous(v) ← curr

Then the path can be read from the source to v by iteration, assuming all vertices are initialized with Previous(v) ← ∅:

```
Path(s, v)
1   P ← ∅
2   while Previous(v) ≠ ∅
3       P ← {Previous(v), P}
4       v ← Previous(v)
5   P ← {s, P}
5   return P
```

1.4.2.3 Medial Axis

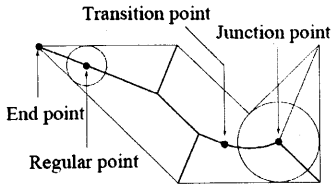


Fig.1-8: Taxonomy of medial axis points [Joan-Arinyo 1996].

The medial axis is a set of curves which roughly follows the centerline of a space. It is a representation often used in navigation applications, as it can generate valid and natural appearing paths with maximal clearance from all obstacles.

Formally, the medial axis is the locus of the centers of all maximal discs inscribed in the polygon boundary [Lee 1982]. **End points** occur at convex vertices where the medial axis runs into the polygon boundary and the disc radius is zero. Every other point in the medial axis can be classified as a **regular point**, where the maximal disc touches two boundary elements, or a **junction point** where several branches in the medial axis meet, and the maximal disc is tangent to at least three boundary elements [Joan-Arinyo 1996]. The type of curve the medial axis path follows is defined by its two closest boundaries:

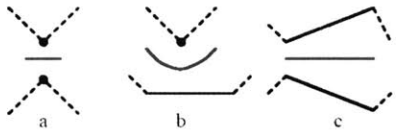


Fig.1-9: Shape of medial axis segments (red). (a) straight line between a concave-vertex pair; (b) parabolic arc between concave vertex and boundary edge; (c) straight line between two boundary edges [Joan-Arinyo 1996].

Straight line segments are equidistant from two concave vertices (Fig. 1-9a) or two boundary edges (Fig. 1-9c). Parabolic arc segments are equidistant from a concave vertex and a boundary edge (Fig. 1-9b).

1.4.2.4 Constrained Delaunay Triangulation

In order to triangulate general polygonal regions, the incremental Constrained Delaunay Triangulation (CDT) algorithm is used. This is a generalization of the standard Delaunay triangulation that forces certain edges (the boundaries) into the triangulation. We use the public domain implementation of [Bern and Eppstein 1992] by Dani Lischinski [1994]. The implementation is based on the quad-edge data structure, designed for representing general subdivisions of orientable manifolds [Guibas and Stolfi 1985].

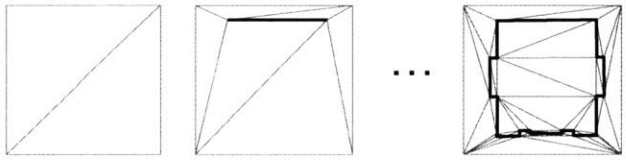


Fig.1-10: CDT construction. Constrained contour edges (black) inserted into an initial bounding mesh. All other edges in the mesh (grey) are unconstrained.

The incremental CDT is initialized with vertices of a bounding convex polygon. This forms a starting triangle mesh large enough to contain all of the edges in the input. Constrained edges are then added into the triangulation one by one. A completed mesh can be seen in Fig.1-10.

Next, in order to find the triangulation for the polygonal region (i.e. triangles inside the polygon), we perform a depth first search. The implementation relies on the following edge functions (see Fig.1-11):

- `Lnext()` returns the counter-clockwise edge around the left face following the current edge.
- `Sym()` returns the edge from the destination to the origin of the current edge.

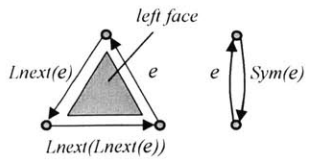


Fig.1-11: Basic edge functions.

Additionally, each edge stores two Boolean values, `c` and `triangleMark`, that indicate a constrained edge and a visited left face (respectively).

The depth first search is illustrated in Fig. 1-12: the root triangle is chosen as the left face of a polygon edge E. This will return an interior triangle assuming E is oriented counter-clockwise, which we guarantee. The orientation of the ordered list of contour points is determined, and if clockwise, then Sym(E) is used as the starting edge.

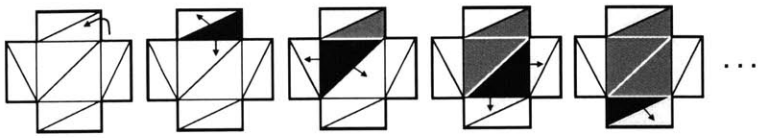


Fig.1-12: Depth-first search for polygon triangulation. The black triangle is at the top of the stack. Light grey/ dark grey triangles are discovered/visited. The search expands only over unconstrained edges interior to the polygon.

From the root triangle, the search proceeds by finding neighboring triangles that share an unconstrained edge. Recall that only the boundary edges of the polygon are constrained. Since the search never crosses a constrained edge, the search is guaranteed to remain inside the polygon.

The algorithm maintains a list T of triangles forming the polygon's interior mesh. Freshly discovered edges are added to a 'last in first out' stack S for expansion.

```
Polygon-CDT(rootEdge)
1   T ← ∅
2   S ← ∅
3   Push(S, rootEdge)
4   while S ≠ ∅
5       currEdge ← Pop(S)
6       T ← T ∪ {leftFace(currEdge)}
7       for e in [currEdge, Lnext(currEdge), Lnext(Lenxt(currEdge))]
8           if e not constrained and leftFace(Sym(e)) not visited
9               Push(S, Sym(e))
10      set leftFace(currEdge) visited
11  return T
```

These methods are applied when determining intra-space paths, discussed in Section 3.3.2.

1.5 System Design

The goals of the Building Model Generation project as a whole are to develop a system that is comprehensive, automated, intuitive to the user, and scalable. To achieve these goals, our system is composed of a central database for storing geospatial elements, and a set of agents designed for a specific set of read/write operations. Section 2.1 reviews the design of the data model itself, and the conventions of our XML representation for geometric, topological and semantic features of locations on campus.

The data model is populated through **input agents** that extract information from our common data sources. The work of [Battat] involved the development of an AutoCAD DXF parser that reads geometry data from raw DXF files, and populates the data model with pertinent information such as building footprints, space contours, and portal locations. Section 2.2 provides an overview of floor plan conventions used by the DXF Parser to recognize portal locations.

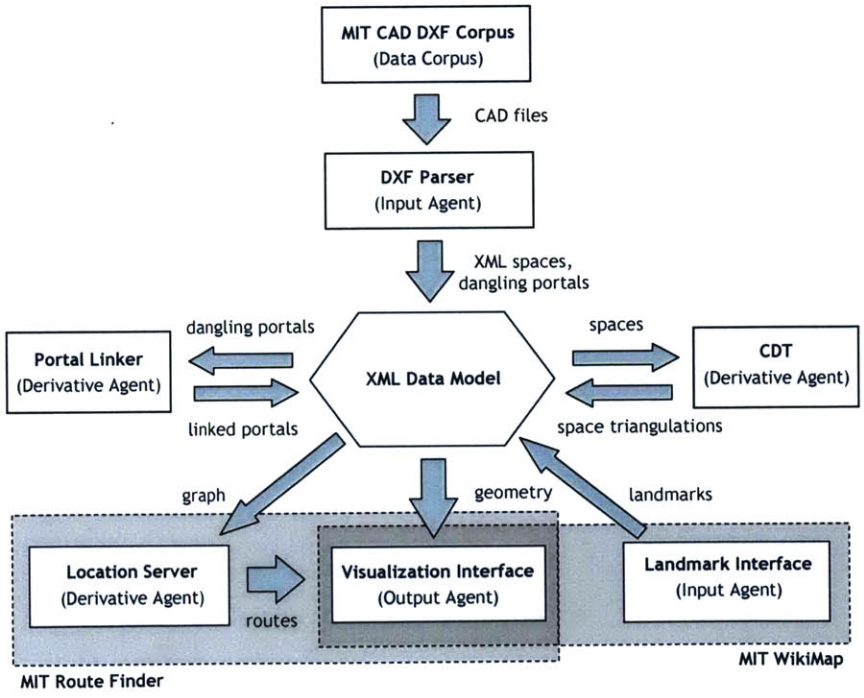


Fig. 1-13: Project overview.

Once the data is inserted in the data model, **derivative agents** operate on the data to derive richer geometric information including space triangulations and topological information such as stairway connections that require further computation on the raw geometry data. These agents can both read and write to the data model. Section 2.2 provides a review of connectivity types and methods for deriving adjacency data.

Output agents act as intermediaries between the geospatial database and external applications, and have only read capabilities. A visualization output agent is designed specifically for display of the campus map in a web interface.

Chapters 3 and 4 present two web-based applications that combine the visualization interface with additional agents. The MIT Route Finder uses the location server to derive campus routes based on adjacency data stored in the data model, and the MIT WikiMap incorporates an additional input agent designed to collect landmark data directly from users.

2 Campus Data Corpus

2.1 Data Representation

2.1.1 Introduction

This section introduces a robust and scalable data representation designed to exhaustively characterize geospatial features. In particular, this chapter discusses the spatial hierarchy used to represent containment relationships in our geometric model of campus. Elements of the data model are described including floors, spaces, portals, and landmarks, as well as the specific XML format designed for each. A review of the space-graph structure is also given, which models the adjacency relationships between geospatial features.

2.1.2 Spatial Hierarchy

The data framework is organized into a tree hierarchy, where each feature node can have attributes and children nodes. For example, the root element of MIT is the basemap of the campus; the basemap has individual buildings as children nodes; buildings have floors as children nodes; and so on. Concurrently, each of those nodes carries with it a series of properties that define it such as its name and its defining contour.

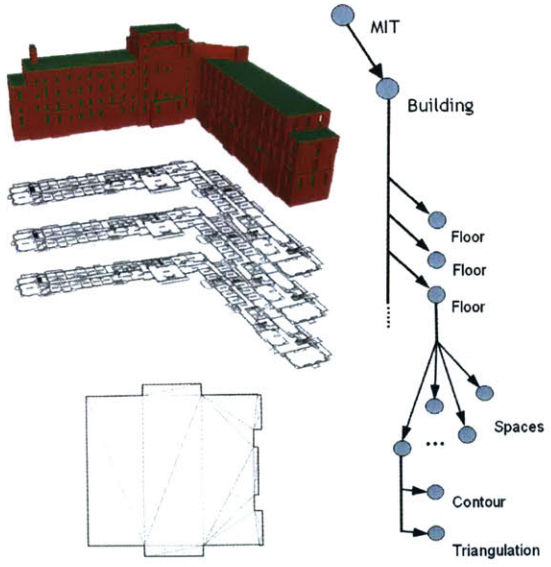


Fig.2-1: Spatial hierarchy of MIT campus.

The hierarchical approach lends itself naturally to a number of geometric operations. For example given a 2D point, its enclosing space may be efficiently computed by progressively refining the search space from regions (e.g. North campus), to buildings (e.g. N51), to rooms (e.g. N51-105).

The XML file format (Extensible Markup Language) was chosen to represent this hierarchy for its ability to store information in a tree-based structure [Bray et al 2004]. Additionally, XML is designed for transferring such richly structured data over the internet, making it well-suited for the web applications described later in this thesis.

2.1.3 Floors

Floors embody the containing region for a set of spaces. They are represented in our XML data model with a top level node called `MITquest` which is the parent element of all spaces on that floor. Floors are physically represented with a contour consisting of an ordered set of 2D points. Each contour has additional elements specifying a bounding box and centroid. For example, floor 1 of Building 1 appears as:

```
<MITquest>
    <floor name="FLOORCONTOUR">
        <contour>
            <centroid x="710039.91" y="495107.19"/>
            <extent maxx="710223.83" maxy="495264.34"
                    minx="709923.96" miny="494964.77"/>
            <point x="709923.96" y="495181.27"/>
            <point x="709935.56" y="495186.55"/>
            <point x="709927.75" y="495203.69"/>
            ...
        </contour>
    </floor>
    <space name="1-142" type="CMPUTR"> ... </space>
    <space name="1-171" type="OFF">  ... </space>
    ...
</MITquest>
```

2.1.4 Spaces

Spaces are physical locations on campus, including both the outdoor environment (such as streets, sidewalks, and grass) and places within indoor environments (such as corridors, classrooms, and lobbies). Spaces may be physically surrounded by walls, or have only implied boundaries such as the transitions between buildings along MIT's infinite corridor.

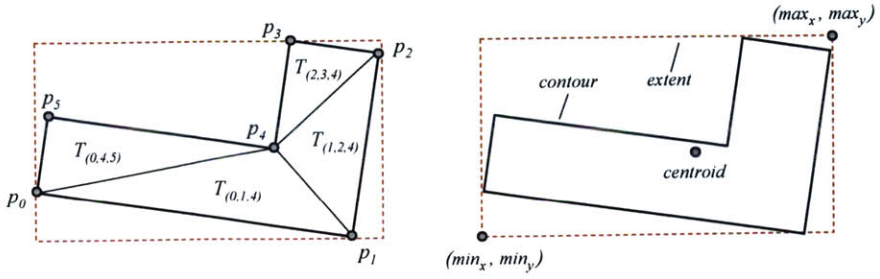


Fig.2-2: Example space. Spaces are physically represented with a set of contour points and a triangulation.

Spaces are represented geometrically as closed simple polygons bounded by an ordered polyline of 2D points that define the contour of the space. Each contour has child properties including its centroid and bounding box extents. A set of triangles corresponds to the space's constrained Delaunay triangulation. And each space has a globally unique name, following the convention `[BUILDING]-[FLOOR][ROOM]` set by MIT's Department of Facilities. In our XML data model, spaces are represented in the following format:

```
<space name=SPACE_NAME type=SPACE_TYPE>
     CONTOUR
          CENTROID
          EXTENT
          POINT1 POINT2 POINT3 ...
     TRIANGLE1 TRIANGLE2 TRIANGLE3 ...
</space>
```

Triangle vertices contain an index which refers to the ordered list of contour points. Contour points are specified in global campus coordinates, corresponding to the Massachusetts State Plane Coordinate System (SPC) in the Mainland Zone. Contour points are measured in feet, where x increases eastward and y increases northward in reference to the SPC origin located in south-eastern Massachusetts [MassGIS]. Our campus coordinates range from (693 000 feet, 489 000 feet) to (723 000 feet, 504 000 feet). The following example specifies a classroom in building 1:

```
<space name="1-150" type="CLASS">
     <contour>
          <centroid x="710044.28" y="495033.19"/>
          <extent maxx="710062.06" maxy="495054.31"
                  minx="710024.92" miny="495011.80"/>
          <point x="710030.10" y="495036.59"/>
          <point x="710039.67" y="495015.58"/>
          <point x="710038.15" y="495014.89"/>
          ...
     </contour>
     <triangle v0="0" v1="1" v2="12"/>
     <triangle v0="0" v1="12" v2="19"/>
     <triangle v0="0" v1="19" v2="20"/>
     ..
</space>
```

Basemap spaces have the same geometric representation as interior spaces, and follow the naming convention: `BMAP-[ID]` where `ID` is a unique integer ranging from 0 to 7,070. A complete listing of codes used for specifying space types can be found in appendix B.

2.1.5 Portals

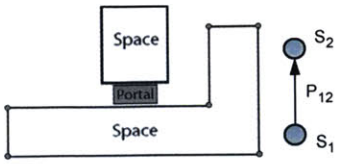


Fig.2-3: Node-edge representation of spaces and portals. Portals have a distinct source and destination, representing one direction of the physical connection between two spaces.

Portals are physical connections (such as doors, elevators, and stairs) representing an adjacency relationship between two spaces. Each portal has a source and a destination space, representing one direction of the physical connection between two spaces. Portals also have an associated type (e.g. `DOOR`, `ELEV`) and a physical representation in the x-y plane.

```
<space name=SOURCE_NAME type=SOURCE_TYPE>
    <portal class=CLASS target=TARGET_NAME type=TYPE [OTHER]/>
</space>
```

In our XML data model, every portal is represented as a child element of its source space. Each portal has class, target and type attributes. The class attribute captures a distinction between vertical and horizontal portals, defined below.

2.1.5.1 Vertical Portals

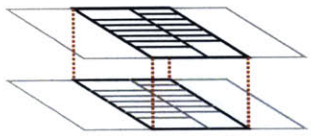


Fig.2-4: A sample vertical portal. Two overlapping staircases.

Vertical portals involve connections between adjacent floors including elevators and stairs. An additional direction attribute is included in the portal definition to indicate an upward or downward traversal. The convention is:

```
<portal class="vertical" target=NAME type=["STAIR"|"ELEV"]
direction=["UP"|"DOWN"]/>
```

For example, a staircase connecting the first floor to the second floor of building 1 is written:

```
<space name="1-100SB" type="STAIR">
   <portal class="vertical" target="1-200SB" type="STAIR" direction="UP"/>
</space>
```

The data model representation of a vertical portal is a closed polyline identical to its source space (e.g. an elevator portal has the same shape as the elevator itself). Rather than repeat the 2D points, each vertical portal is defined by the contour of its source.

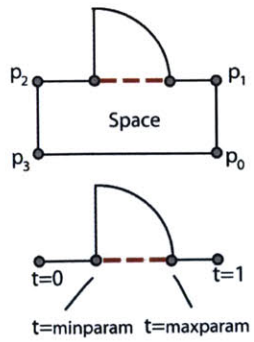


Fig.2-5: A sample horizontal portal. Portal position is defined by an edge index - referencing the ordered list of points for the source space - and the parameterized position along the edge.

2.1.5.2 Horizontal Portals

Non-vertical portals are classified as ***horizontal***. These include connections between spaces on the same floor, connections between buildings, or adjacent basemap spaces. Possible portal types are door, outdoor and implicit. Horizontal portals are represented geometrically as a line segment (Fig.2-5). In our XML representation, horizontal portals have an "edge" child element that provides the line segment parameters: Maxparam and minparam values specify the parameterized position of the

portal along edge (p_{index}, $p_{index+1}$), where p_i is a point on the source contour and minparam is strictly less than maxparam. The format is as follows:

```
<portal class="horizontal" target=NAME type=["DOOR"|"OUTDOOR"|"IMPLICIT"]>
    <edge index=INT maxparam=FLOAT minparam=FLOAT/>
</portal>
```

For example:

```
<portal class="horizontal" target="1-150" type="DOOR">
    <edge index="1" maxparam="0.7" minparam="0.25"/>
</portal>
```

Methods for inferring portal connections from the floor plan geometry are discussed in section 2.2.

2.1.6 Space-Portal Graph

Connectivity relationships between locations are represented with a graph data structure. A graph G = (V, E) is a set of elements V, called **nodes** or **vertices**, linked by a set of **edges** E [Cormen et al 2001]. In our representation, spaces are modeled as graph nodes and portals as graph edges.

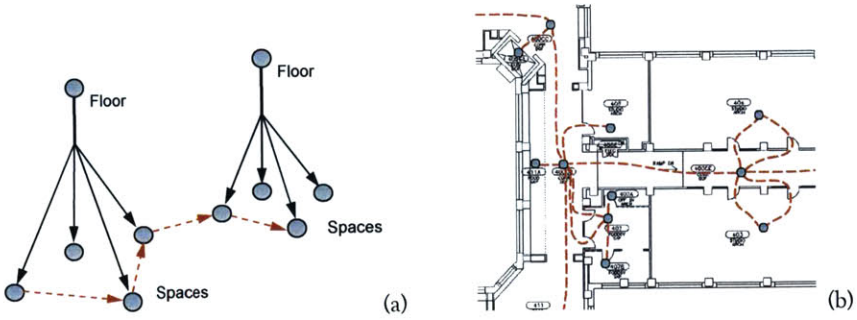


Fig. 2-6: Topological model of campus representing adjacent spaces as nodes (solid circles) connected by graph edges (dashed arrows).

A directed graph has the additional property that each edge has an ordered pair of vertices. Specifically, an edge = (v_1, v_2) is considered to be directed from v_1 to v_2, where v_1 is the source and v_2 is the destination. We model the MIT campus under this convention, capturing the physical fact that portals such as security doors allow exit but not unconditional reentry.

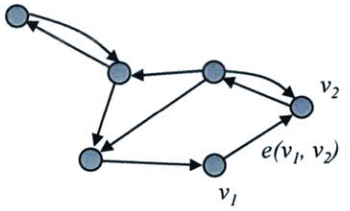


Fig.2-7: Directed graph.

The graph structure is extended by assigning weights to edges. Since we are modeling connections between physical locations, weights are used to represent the distance between spaces centroids.

Finally, a graph is **connected** if for every pair of vertices $(v_1, v_2) \in V$, there exists a path from v_1 to v_2. For a directed graph, if the same property holds when all directed edges are replaced by undirected edges, it is called **weakly connected**. One of the goals of the BMG pipeline is to generate a (weakly) connected graph with coverage of all rooms, hallways, streets, sidewalks and other spaces within MIT.

In the XML data model, a portal edge is contained as a child element of its source space. Each portal has a "target" attribute which points to the portal's uniquely named destination space.

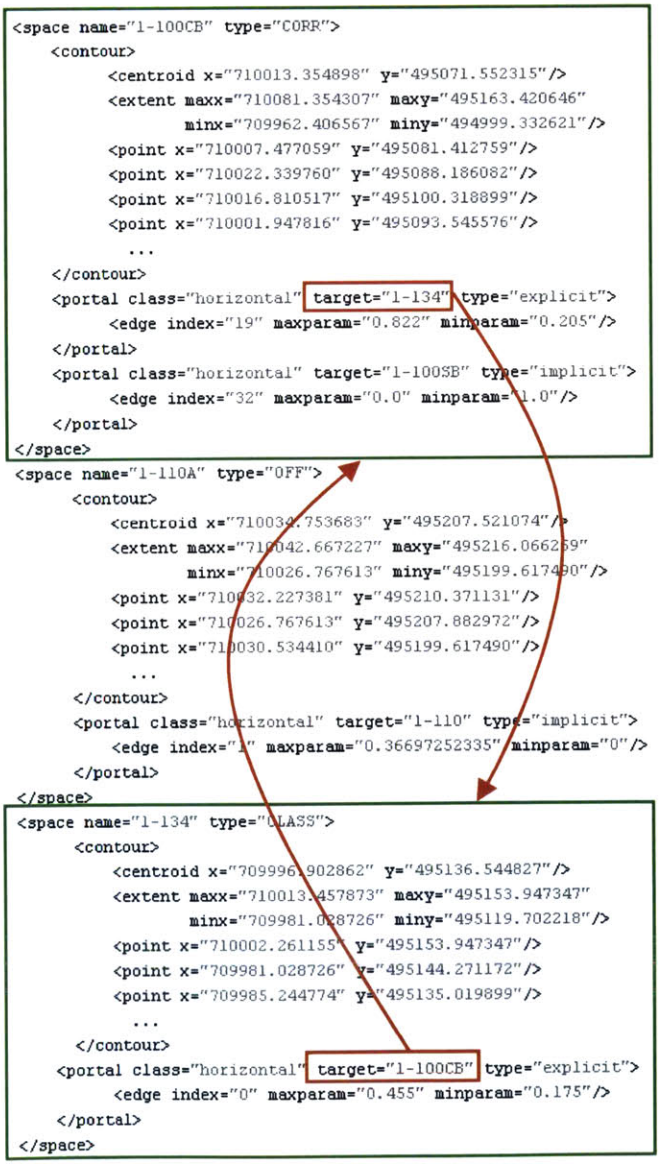


Fig. 2-8: XML representation of the space-graph. Boxes denote nodes in the graph. The target attribute of a portal stores a pointer to the portal's destination space.

2.1.7 Landmarks

Landmarks are physical objects representing points of interest within the MIT campus environment. They may vary broadly in scale – some landmarks are large and seen at great distances, such as the Green Building, others may only be visible at close range, such as a painting in a faculty lounge. Further, landmarks may be characterized by a number of different qualities such as visual contrast (e.g. a brightly-colored wall), structural prominence (e.g. the intersection of Mass. Ave. and Vassar St.), or functional significance (e.g. the Building 4 café) [Sorrows and Hirtle 1999].

To capture variability in scale and salient features, we represent landmarks with the following attributes:

Name – descriptive title.

Location – name of containing region. This allows for varying granularity. A landmark may apply to a single space (e.g. lobby 7-100), an entire building (e.g. Kresge Auditorium), or an outdoor courtyard (e.g. Killian Court).

Position – 2D coordinate. For small objects such as a sculpture in Killian Court, an exact point accurately describes its position within the containing space. When the landmark pertains to a larger area, the coordinate is used for visualization purposes only.

Category – landmark classifications such as painting, sculpture, or public computer cluster.

Description – supplementary unstructured information not accounted for in the above attributes.

We store landmarks in a geo-referenced database using the fields listed above. Although this implementation uses a separate database, landmarks could naturally be incorporated into the xml data model as child elements of a space. For example:

```
<space name="7-407" type="FOODSV">
    <landmark name="steam cafe" category="quick food"
              description="a student-designed cafe">
          <point x="710030.10" y="495036.59"/>
    </landmark>
</space>
```

A landmark could be similarly represented as a child element of a floor or building region to reflect the varying scale of salient features on campus.

2.2 Generating Campus Topology Data

2.2.1 Introduction

This chapter describes the methods used in populating the data model with adjacency information. The chapter begins with an overview of BMG pipeline components dedicated to portal construction. Subsequent sections present a portal taxonomy, which classifies all portal types found in the MIT floor plans. Geometric properties for portal identification are summarized, along with methods for matching portals to their source and destination spaces.

2.2.2 Portal Populating Agents

Methods for populating the data model with portal information are handled by both the DXF Parser, developed by [Battat], and a set of *derivative agents* designed specifically for portal linking.

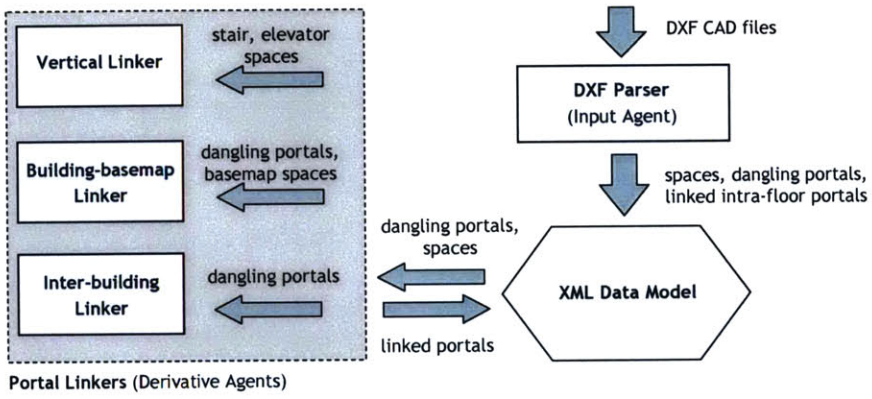


Fig.2-9: Components of BMG pipeline involved in generating portal data.

Portal construction can be divided into two stages: a "creation" stage that associates a portal with a source space, followed by a "linking" stage that determines the portal's destination space. We term portals that are created but not linked as "dangling" portals.

The DXF Parser is responsible for all portal information that can be extracted from a single floor plan: intra-floor portals are fully constructed, and inter-building portals are created but left dangling. See section 2.2.3 for intra-floor portal identification and linking methods; and section 2.2.6 for inter-building portal creation.

A set of Portal Linkers then derives additional topological information. Dangling portals created by the DXF Parser are linked - accounting for both inter-building connections and connections from interior spaces to the basemap (cf. section 2.2.7). An additional agent constructs portal edges between stair and elevator spaces on adjacent floors, providing the vertical connections within multi-story buildings.

2.2.3 Intra-Floor Portals

Portals between spaces on the same floor of a building can be classified as either explicit or implicit connections:

- Explicit

Explicit portals represent connections between spaces that are physically separated by a barrier. The most common example is a doorway embedded in a wall between two rooms. In the floor plan data, doorways also have an explicit geometric representation (Fig. 2-10a): A circular arc is positioned along the dividing wall between its source and destination spaces. The two spaces have non-overlapping contours indicating the thickness of the dividing wall.

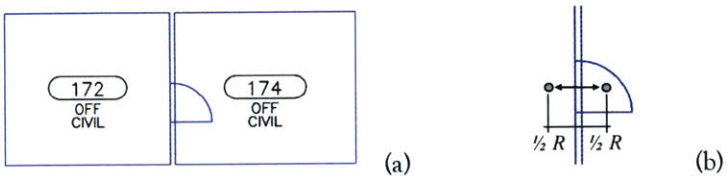


Fig.2-10: Explicit portal. (a) Floor plan representation. (b) Two points offset in opposite directions along the normal vector to the wall. Source and destination spaces are found as the containing region for each point.

A difficulty is that in the floor plan data, a door arc has no association other than geometric proximity with the polylines defining its two adjacent rooms. Further analysis is required to determine the source and destination of the portal: First a vector is positioned through the door frame, normal to the incident wall. Two points, p_1 and p_2, are then placed at the head and tail of the vector, at a distance of half the arc radius from the wall (Fig. 2-10b). To guarantee each point lies inside the correct space, the vector length is chosen to be smaller than shallow spaces such as closets, but large enough to protrude through the wall thickness.

An additional script then searches all spaces in the current floor to find the containing region for each point. A portal is then constructed with the returned spaces, s_1 and s_2, as the source and destination. Note two directed portal edges will be constructed assuming the door allows both exit and re-entry.

ConstructExplicitPortals(doorArc, normalVec, doorCenterPt, Floor)

1 Position(p_1) ← doorCenterPt + normalVec × Radius(doorArc)/2
2 Position(p_2) ← doorCenterPt − normalVec × Radius(doorArc)/2
3 s_1 ← ContainingSpace(p_1, Floor)
4 s_2 ← ContainingSpace(p_2, Floor)
5 Portals(s_1) ← Portals(s_1) ∪ ExplicitPortal(s_1, s_2)
6 Portals(s_2) ← Portals(s_2) ∪ ExplicitPortal(s_2, s_1)

- Implicit

Implicit portals represent connections between spaces where no physical barrier exists. It is normally for organizational reasons that implicit divisions are placed in the floor plans. For example, the photo in Fig. 2-11 shows a large open space outside the "Steam Café" in Building 7. Although there is no wall between the corridor and the café tables, these two regions are defined as separate spaces in the floor plans to differentiate between circulation zones and food services.

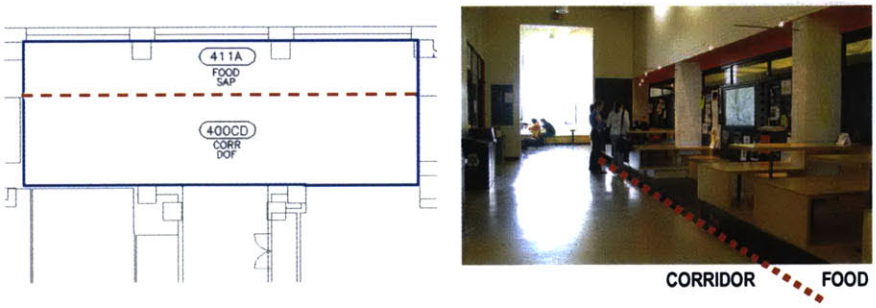


Fig.2-11: A sample implicit portal. The dotted line denotes an incident edge between the space contours. Although no physical barrier exists, the portal places an implicit divide between the corridor and café tables.

Implicit portals are recognized in the floor plans by a coincident edge between two space contours. This is denoted by the dotted line in Figure 2-11. The portal adopts the entire length of the coincident edge as its physical representation in the data model.

2.2.4 Inter-Floor Portals

Inter-floor portals provide the vertical links in a building. Stair and elevator spaces - made for vertical movement between floors - are represented as source and destination nodes in our topological data model. We determine links by finding pairs of vertically adjacent spaces. Specifically, two staircases are said to be vertically adjacent if they belong to neighboring floors and their axis-aligned bounding boxes intersect in the x-y plane.

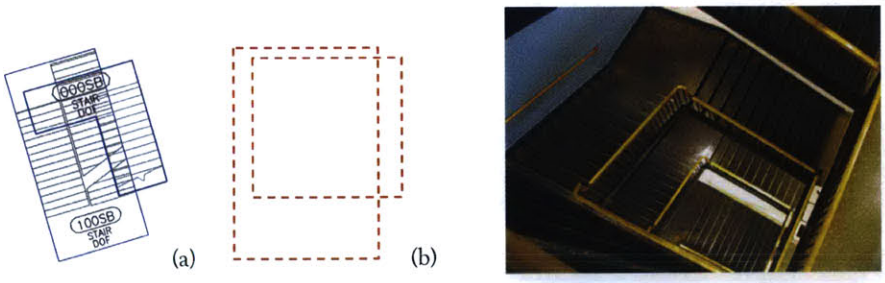


Fig.2-12: Vertical portal. (a) Plan view of stairs on adjacent floors; (b) axis-aligned bounding box for each stair space. Matches are made by testing for overlapping bounding boxes.

Our implementation has two stages. First we construct an ordered list of floors for each building. One complication is that MIT Inventory orders

floors alphabetically rather than numerically (e.g. {1, 10, 11, 2, 3 ... 9} vs. {1, 2, 3, ... 9, 10, 11}), so an additional sorting algorithm was required.

Second, for each ordered pair of floors, we find stair and elevator spaces that overlap in plan view. This is done by simply computing the axis-aligned bounding box for each space (without the height dimension) and testing for intersections in terms of the unit axes:

```
BoundingBoxOverlap(s1, s2)
1   if (minX(s1) > maxX(s2) or minX(s2) > maxX(s1) or
2      minY(s1) > maxY(s2) or minY(s2) > maxY(s1))
3        return false
4   else return true
```

Each stair and elevator space is assumed to have two neighbors – one on the floor above, and one on the floor below – with the exception of the lowest and highest floors of a building. Consequently, each portal is given an explicit direction to indicate an upward or downward direction of movement. The input to the linking procedure is a space s_{curr} of type stair or elevator, and a pointer to the next floor above, $Floor_{next}$. We determine a match for s_{curr} by iterating through every space s_{next} of similar type and testing for overlap.

```
LinkVertPortal(scurr, Floornext)
1   for each space snext ∈ Floornext where Type(scurr) = Type(snext)
2       if BoundingBoxOverlap(scurr, snext)
3           if Type(scurr) is stair
4               Portals(scurr) ← Portals(scurr) ∪ StairUp(scurr, snext)
5               Portals(snext) ← Portals(snext) ∪ StairDown(snext, scurr)
6           else if Type(scurr) is elevator
7               Portals(scurr) ← Portals(scurr) ∪ ElevUp(scurr, snext)
8               Portals(snext) ← Portals(snext) ∪ ElevDown(snext, scurr)
```

Given an ordered list of floors, the algorithm starts at the lowest floor and works its way upward, assuming consecutive floors in the sequence are vertically adjacent.

```
LinkFloors (Floors)                          // naïve: without mezzanines
1   for each floor F ∈ Floors
2       for each stair or elevator space s ∈ F
3           LinkVertPortal(s, Next(F))
```

2.2.5 *Mezzanines in Inter-Floor Connections*

In the general case, vertical portals are matched by analyzing pairs of adjacent floors, and creating links between vertically aligned stair and elevator spaces. However in the instance of a mezzanine, it can become ambiguous which floors are adjacent to each other. We account for the possible scenarios using a technique analogous to ray-casting: Cast a ray upward from the bottom-most staircase s_1. If the ray originating from s_1 intersects the mezzanine floor, then only portals on the mezzanine may provide a valid connection. If the ray does not intersect the mezzanine, then the portal may connect to the full floor above.

The two cases are illustrated in Fig. 2-13. In (a), s_1 is clear of the mezzanine and connects directly to the full floor above. In (b), s_1 connects to a mezzanine staircase.

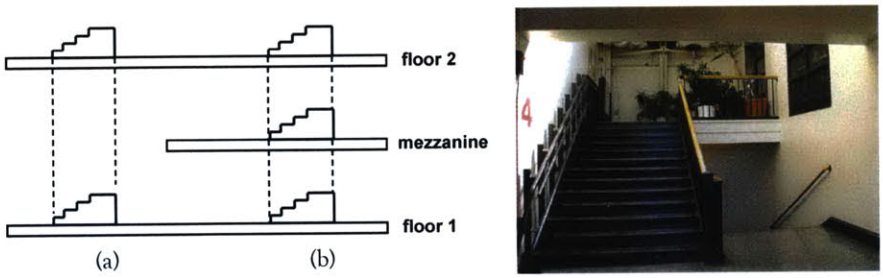


Fig.2-13: Mezzanine floors in vertical portal matching.

We determine if s_1 is adjacent to the mezzanine by testing for bounding box overlap with each space s_M on the mezzanine level, $Floor_M$. The adjacency method returns true if any overlap test succeeds.

```
AdjacentToMezz (s1, FloorM)
1   for each space sM ∈ FloorM
2       if BoundingBoxOverlap(sM, s1)
3           return true
4   return false
```

The following LinkFloors procedure is modified from 2.2.4 to account for the presence of mezzanine floors:

```
LinkFloors (Floors)                          \\ corrected for mezzanines
1   for each floor F ∈ Floors
2       for each stair or elevator space s ∈ F
3           if Next(F) is a mezzanine
4               if AdjacentToMezz(s, Next(F))
5                       LinkVertPortal(s, Next(F))
6               else    LinkVertPortal(s, Next(Next(F)))
7           else LinkVertPortal(s, Next(F))
```

2.2.6 *Inter-Building Portals*

Inter-building portals represent connections between spaces in abutting buildings. Like intra-floor portals, these can be classified as either explicit or implicit.

- Explicit

An explicit portal represents a physical doorway connection between adjacent buildings, or a connection from a building to the basemap. Explicit inter-building portals are recognized using a method similar to explicit intra-floor portals.

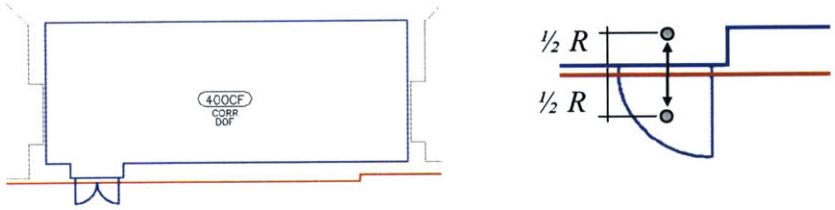


Fig.2-14: Explicit inter-building portal. A point is placed on either side of the door frame. One point is contained by a space contour (blue), the other point lies outside the floor contour (red).

For every door arc found in the floor plans, a vector normal to the incident wall is constructed. Two points, p_1 and p_2, are positioned along the normal vector at distances of half the arc radius from the wall (cf. Figure 2-14). If one of the points p_1 lies outside the floor contour (i.e. it is not contained by any space in the floor), then the portal is tagged as "dangling". The other point p_2 must be inside the floor contour, and its containing space is the portal's source space.

- Implicit

Implicit portals represent connections between adjacent buildings where no physical barrier is crossed. For example, in the photo below the corridor spans buildings 3 and 7 without any visual indicator. Implicit portals are represented in the floor plans by a coincident edge between the space contour and the floor contour.

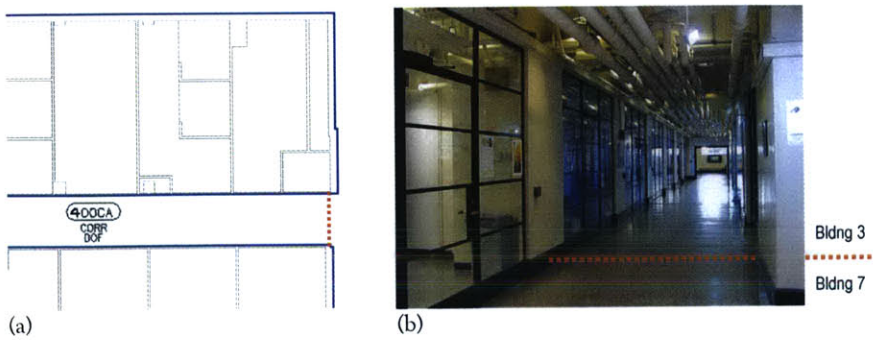


Fig.2-15: Implicit connection between buildings. (a) The floor contour overlaps the space contour, indicated by the dotted line; (b) A corridor in Building 7 connects to a corridor in Building 3, but no physical door or other barrier is present between the two spaces.

An implementation challenge for inter-building connections is that the source and destination spaces reside in separate floor plans. In the

example above, an outgoing portal is created from Building 7 with corridor 7-400 as its source. However the target could be any of over 160 buildings on campus. Consequently, inter-building portals are initialized with only a source space and left unlinked. These "dangling portals" are then resolved using the methods described in section 2.2.7.

2.2.7 Dangling Portals

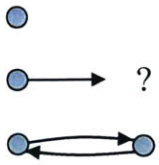


Fig.2-16: Stages of portal linking. Middle is dangling portal with a source but no destination.

Dangling portals are graph edges with a known source space, but an undetermined destination. Dangling portals provide a mechanism to defer analysis of (a) connections between buildings; and (b) connections from buildings to the basemap terrain. In both cases, the challenge faced is a highly unconstrained search for the portal destination space. A portal leading onto the basemap could link to any one of 7,000 basemap spaces. A portal leading to another building must search over 160 distinct buildings at MIT. Rather than process these large sets of geometric data every time we encounter an inter-building portal, we instead identify inter-building linkages with a multi-stage process:

First, all building geometry is processed by the DXF Parser and any portal that leads out of a building is simply tagged, and attached to its source space. Dangling portals are represented in XML with a target pointing to the floor contour, communicating that the portal is incident on the edge of the building.

```
<space name=SOURCE_NAME type=SOURCE_TYPE>
    <portal class="horizontal" target="FLOORCONTOUR"/>
</space>
```

Once dangling portals have been created for every building on campus, the second stage is to match proximal pairs: For each dangling portal p_i, a set of candidate destinations is collected (i.e. all spaces within a preset radius). A successful match occurs when one of the candidate spaces contains a corresponding dangling portal coincident with p_i.

```
LinkDanglingPortals(Buildings)
1   for each building B ∈ Buildings
2       for each dangling portal p_i ∈ B
3           proximalSpaces ← Proximal(Buildings, p_i, Radius)
4           for each space s ∈ proximalSpaces
5               for each dangling portal p_j ∈ Portals(s)
6                   if Distance(p_i, p_j) < Tolerance
7                       Target(p_i) ← Source(p_j)
8                       Target(p_j) ← Source(p_i)
9                       break
```

Connections from buildings to the basemap use similar operations, with the additional constraint that only explicit portals are assumed to link an interior space to the campus terrain. Recall that on the basemap, each edge of a space contour can be a portal. So for each dangling portal p_i leading out of a building, we simply search for the closest basemap edge. When a match is found, p_i is linked, and a new oppositely directed portal is constructed from the basemap to the building interior.

```
LinkDanglingPortals(Buildings, Basemap)
1   for each building B ∈ Buildings
2       for each explicit dangling portal p_i ∈ B
3           proximalSpaces ← Proximal(Basemap, p_i, Radius)
4           for each basemap space s ∈ proximalSpaces
5               for each edge e ∈ Contour(s)
6                   if Distance(p_i, e) < Tolerance
7                       Target(p_i) ← s
8                       Portals(s) ← Portals(s) ∪ Portal(s, Source(p_i))
```

2.2.8 Intra-Basemap Portals

Basemap portals are a simple case of implicit portals. Any two basemap spaces whose boundaries have a coincident edge are considered adjacent. Geometrically, a basemap portal is a straight line segment spanning the incident edge between the two neighboring spaces.

2.2.9 Summary

A summary of portal types is presented in Table 2-1 below:

Table 2-1: Summary of portal types and detection methods.

	Type	Test
Implicit	Intra-Floor	Incident edge between two space contours
	Inter-Building	Incident edge between space contour and floor contour
	Intra-Basemap	Incident edge between two basemap space contours
Explicit	Intra-Floor	Door arc proximal to two space contours
	Inter-Building	Door arc proximal to space contour and floor contour
Stair/Elevator	Inter-Floor	Axis-aligned bounding box overlap

2.2.10 Remaining Challenges

- Misaligned Floors

A remaining challenge for future work is to account for height differentials between adjacent buildings. For example, the third floor of the Stata Center is slightly lower than the third floor of Building 36, necessitating the short staircase in Fig. 2-17. Height differentials may be ignored if we assume that inter-building connections always occur at the same floor. However with the varied building styles at MIT and variations in height of terrain, this assumption does not always hold. An example is at the east end of the Infinite Corridor where floor numbers increase by one from Building 8 to Building 16.

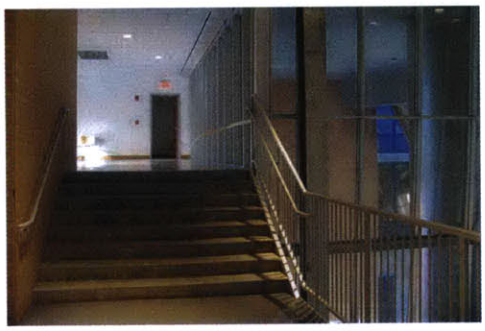


Fig.2-17: The stairs account for a height differential between the Stata Center and Building 36.

- Visual Stairway Identifiers

The DXF Parser recognizes stairways as any space with the "STAIR" room use code. However, this relies on a thorough labeling scheme specific to MIT, rather than more generic visual identifiers. For example, in the figure below there is no "STAIR" label. Nevertheless a staircase is clearly recognizable to the human eye by a sequence of closely spaced line segments and a directional arrow. Incorporating such visual markers into the DXF Parser may result in more complete semantic data, while reducing a reliance on conventions specific to MIT.

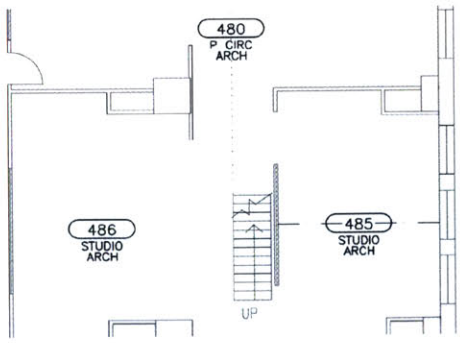


Fig.2-18: Unlabeled staircase. The staircase is part of a larger circulation area and does not carry the "STAIR" type label. However, the closely spaced line segments and arrow make it clear to a human eye that the staircase exists.

- Ramp Vertical Portals

Our current implementation does not incorporate ramp connections. Ramps can be identified by directional arrows labeled "RAMP UP" or "RAMP DOWN". In contrast to stairs and elevators, ramps are typically

contained within larger spaces such as the corridor in Figure 2-19. One complication is that the majority of indoor ramps connect spaces within the same floor (to account for a height differential). A systematic method is still needed to determine the source and destination for a ramp portal, differentiating between intra-floor and inter-floor connections.

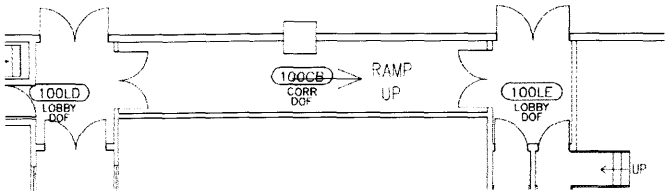


Fig.2-19: A ramp within a corridor space, indicated by a labeled arrow.

3 MIT Route Finder

3.1 Introduction

'MIT Maps' is a prototype application that provides custom routes on the MIT campus using the data framework proposed by BMG. The application is designed to assist campus visitors in the common task of finding their way from one location to another, with the additional ability of specifying route constraints. For example, on a cold or rainy day a visitor might only be interested in routes that remain indoors; or travelers in wheelchairs or carrying excessive luggage may want to avoid taking the stairs. A web interface is provided for specifying source and destination locations, along with visualization capabilities for displaying routes on the campus map.

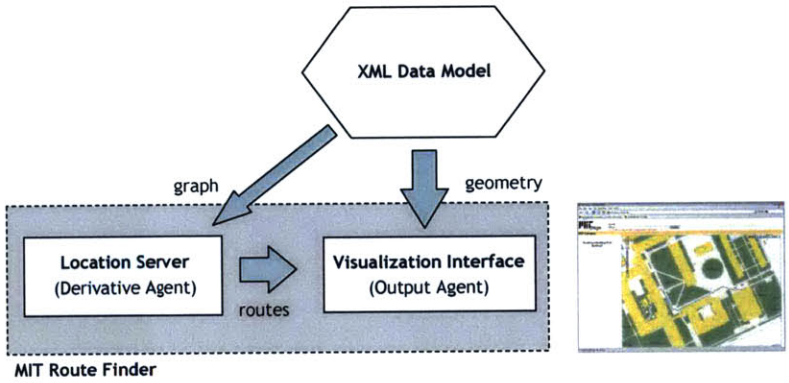


Fig.3-1: Components of the "MIT Maps" route finder application.

Routes between locations are supplied by a central Location Server, introduced by Bell [2003], and substantially expanded in this work. The Location Server provides this information through a Java RMI interface (see 1.4.1.3).

3.2 User Interface

3.2.1 Map Display

A framework for route visualization has been developed combining information from the campus model geometry and path-drawing abstractions. The interface is implemented as an interactive web-based application modeled after the Google Maps API (see [Battat] for implementation details). The interface is designed for use in a regular browser, without plugins or other installation requirements for the user.

Navigating the map is central to the user experience. Direct manipulation controls are provided that allow the user to drag the map to pan and double-click a point to re-center the map. A zoom bar is provided to

change the zoom level. Users may also submit a location in the search field at the top of the page, and the map will zoom and pan appropriately to display the result.

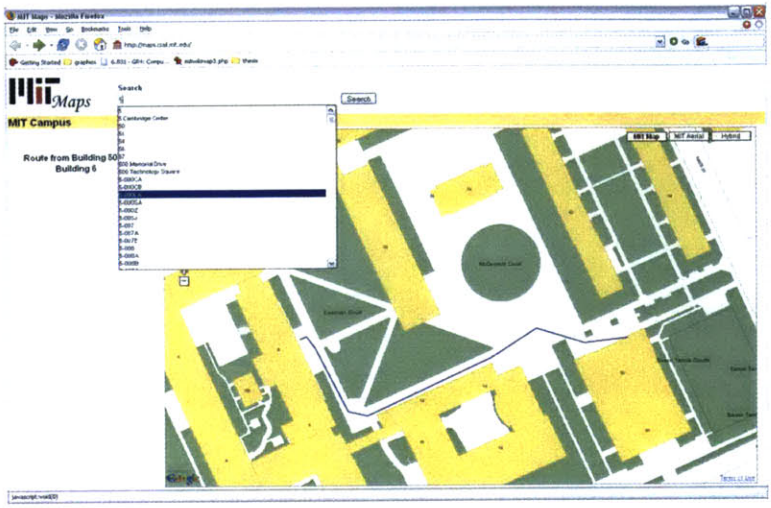


Fig.3-2: MIT Maps user interface.

3.2.2 Route Queries

Route queries are run from the search field with the simple command:

```
[source] to [destination]
```

Source and destination points may be specified at varying levels of granularity, either by building (e.g. "50 to W11"), room (e.g. "1-205 to 1-100LA") or a combination (e.g. "W11 to 1-100LA"). Auto-complete functionality has also been incorporated in the form of a drop-down menu to help prevent errors in location requests.

To visualize space contours and triangulations along with the route, queries can also be run in debug mode using the command:

```
[source] to [destination] to debug
```

Figure 3-3 shows an example route in debug mode from a staircase on the first floor of building 10 to office 10-183A. Each space also has a tack positioned at its centroid, which will display the space's name on mouse-over.

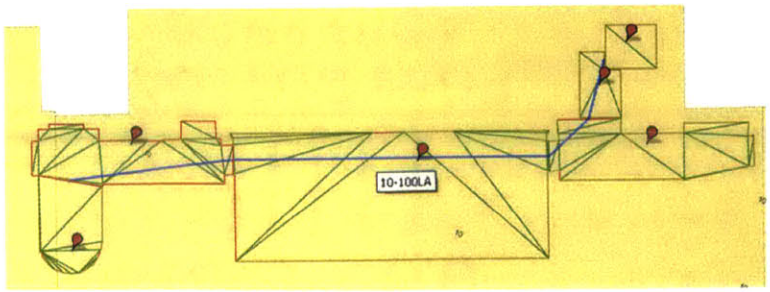


Fig.3-3: Route display in debug mode. Red lines denote space contours, green lines denote space triangulations, and red tacks are positioned at space centroids.

3.2.3 Space and Portal Visualization

The search field also supports visualization queries. Space contours for an entire floor are displayed with the command:

```
draw: [Building]-[Floor]
```

For example, "draw: 50-1" will render all rooms on the first floor of Building 50, as shown in Figure 3-4. Space contours are drawn in red with space labels positioned at space centroids. Every explicit portal (e.g. door) is drawn as an arrow perpendicular to its incident wall. Every implicit portal is drawn as a line segment along its incident contour edge.

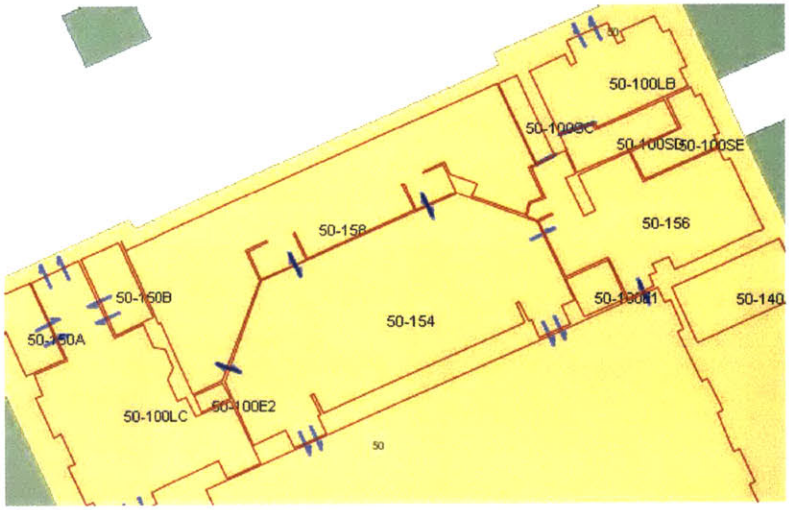


Fig.3-4: Visualization of spaces and portals on floor 1 of Building 50. Blue arrows represent explicit portals. Blue line segments incident on contour edges represent implicit portals.

Basemap spaces are drawn with the command:

```
draw: BMAP-[index]
```

The `index` parameter is an integer between 0 and 14, specifying a chunk of 500 basemap spaces (among a total of 7,070) to be displayed on the map. For example, "draw: BMAP-4" will display all named basemap spaces in the range [BMAP-2000, BMAP-2499].

3.3 Implementation

A requirement of the route finder is the ability to quickly generate routes between any two locations on campus. On the basemap alone there are over 7,000 spaces and 88,000 portals. Considering building interiors expands the search to a 36,000 node graph. Increasing the resolution to space triangulations expands the graph further by an order of magnitude.

The problem of generating routes can be subdivided into two distinct sub-problems: finding the collection of spaces that optimally connect the source and destination spaces, and finding the actual path through each space. These two sub-processes are explained in sections 3.3.1 and 3.3.2. The algorithm combining both steps is then demonstrated in section 3.3.3.

3.3.1 Inter-Space Path Finding

The first search is performed by considering spaces to be "nodes", and portals to be "edges" for the purpose of graph construction and traversal. Edge weights are estimated by the distance between space centroids as depicted in Fig. 3-5. Although the distance between adjacent spaces could be estimated by the length of a valid path (e.g. the shortest path between pairs of portals), this is potentially expensive to compute and ambiguous when multiple portal exit/entry pairs exist.

Dijkstra's algorithm was implemented for graph searching, which is a fundamental algorithm for shortest-path route-finding problems. See section 1.4.2.2 for a review. An optimal sequence of spaces is then determined by applying this standard graph searching technique to the network of spaces as depicted in Figure 3-5.

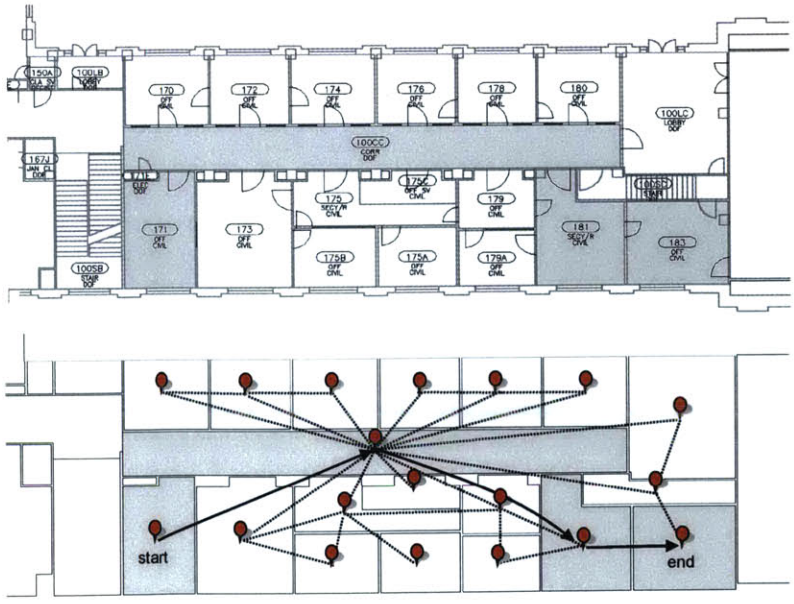


Fig.3-5: Example space-portal graph. Edges (dashed lines) are placed between adjacent spaces, weighted according to the distance between space centroids. In the example path, solid arrows represent traversed edges.

3.3.2 Intra-Space Path Finding

Additional work is required to determine the physical path through a collection of spaces. For convex spaces, a simple straight line from an entry point to an exit portal represents the shortest possible path through the space. However for concave spaces, a straight line can result in an illegal path as shown in Fig. 3-6a.

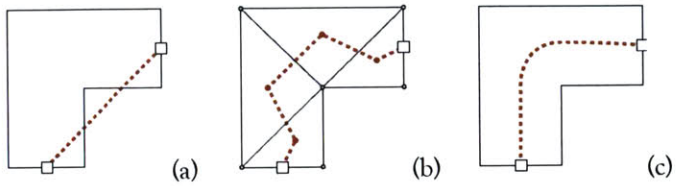


Fig.3-6: Finding a path through a concave polygon: (a) a straight line results in an illegal path; (b) a path traversing triangle centroids yields a valid but jagged path; (c) a smoothed path [Nichols 2004].

The solution proposed by Nichols [2004] is to construct a valid path by connecting centroids of adjacent triangles as illustrated in Fig. 3-6b. While the triangulated path doesn't intersect any of the space's boundaries, it also looks unnatural compared to the kind of path a person might draw by hand (Fig. 3-6c).

Instead we propose the use of the medial axis for intra-space path drawing, which is commonly used in motion planning applications [Latombe 1991]. The medial axis provides a central skeleton for the space, where every point on the skeleton is equidistant from its two closest boundary edges. The medial axis can be thought of as composed of paths with maximal clearance through a room, furthest from obstacle boundaries.

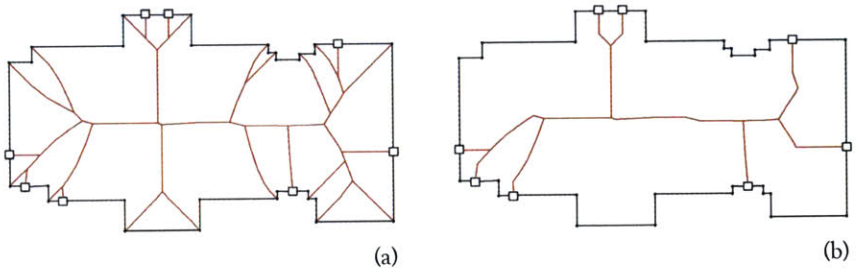
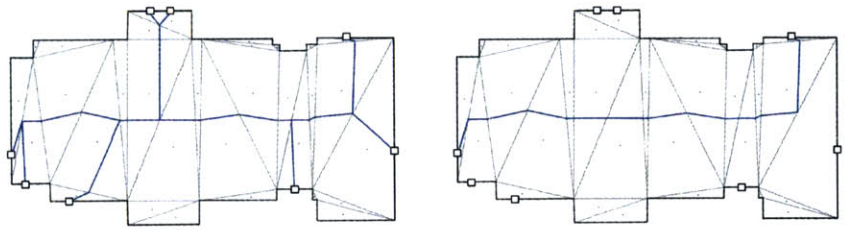


Fig.3-7: (a) Exact medial axis of a typical room contour. Squares are portal positions. (b) Trimmed to remove branches that do not lead to portals.

When computed precisely, the medial axis consists of straight line segments and parabolic arcs. Fig. 3-7a shows the exact medial axis of a typical room contour. On the right, the medial axis has been simplified by trimming off all branches that lead to a convex corner. In the resultant graph, a valid path can be found between any pair of portals.

However, the practical complexity of computing the medial axis is high, and provides more precision than required for path rendering routines. As an alternative, one can approximate the medial axis (MA) with straight line segments using the constrained Delaunay triangulation [Joan-Arinyo et al 1996] as illustrated in Fig. 3-8. Medial axis points are placed at the midpoint of all interior triangle edges, and line segments are constructed between MA points incident on the same triangle. Fig. 3-8a is the

trimmed version, approximating Fig. 3-7b. To find the shortest path between any pair of portals, we simply run Dijkstra's algorithm on the resultant MA graph. A sample path is shown in Fig. 3-8b.



(a) (b)

Fig.3-8: (a) Approximate medial axis of a room contour, connecting midpoints of shared triangles edges; (b) Example of one intra-space path.

In addition to being a simpler representation, the benefit of this method is it leverages triangulation data already present in the data model.

3.3.3 Route Generation

This section illustrates the application of inter-space and intra-space path finding to efficient route generation. The outdoor route in Figure 3-9 is used as an example.

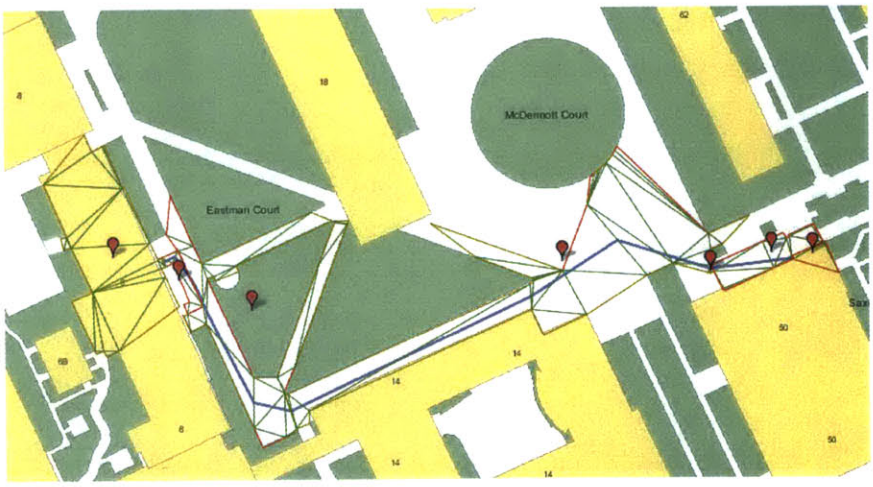


Fig.3-9: Outdoor route from Building 50 to Building 6.

Given a source and destination space, the optimal sequence of spaces is determined using the inter-space path finding methods from section 3.3.1. The graph search is course-grained, considering spaces to be nodes, and portals to be edges. Figure 3-10 shows the resulting path modeled as a traversal of space centroids.

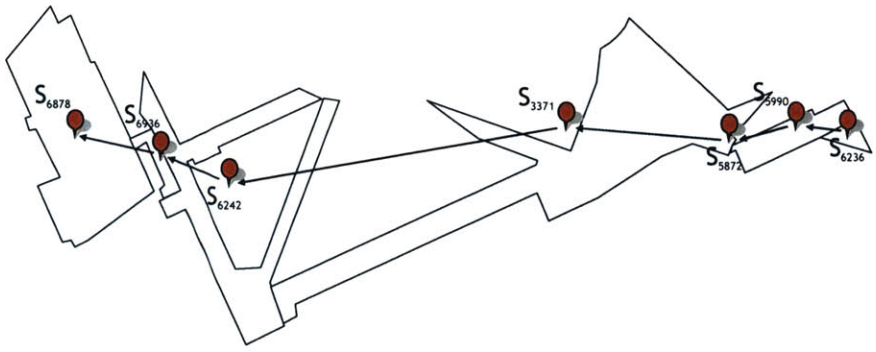


Fig. 3-10: A course search between space centroids (red tacks) first finds the optimal sequence of spaces connecting the source and destination.

The second search is performed on the union of intra-space graphs (as described in section 3.3.2) for each space in the sequence. The graphs are combined by merging corresponding portal nodes (nodes incident on the space contour) between each pair of adjacent spaces. Figure 3-11 shows an example for two adjacent spaces S_1 and S_2. Every portal node in S_1 that has space S_2 as its destination is merged with a portal node in S_2 that has space S_1 as its destination. When multiple matches are available, nodes are paired by geometric proximity.

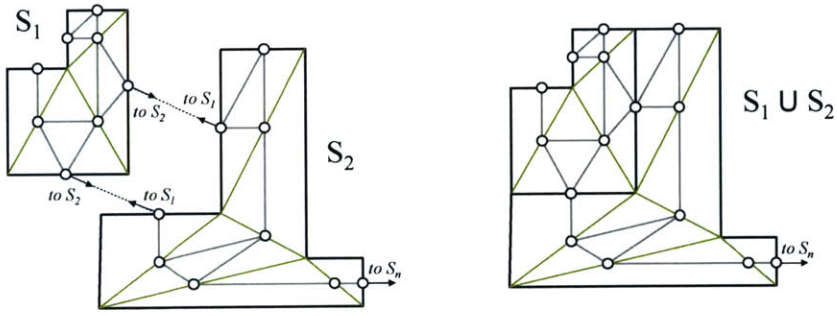


Fig.3-11: Combination of internal graphs for spaces S1 and S2. Gray lines are graph edges, circles are graph nodes, and green lines are space triangulations. Nodes incident on the space contour represent portals. The two graphs are connected at corresponding portal nodes.

Dijkstra's algorithm is then run on the resultant graph to determine the actual polyline path. The search terminates when it reaches a portal node leading into the destination space, as shown in Fig. 3-12.

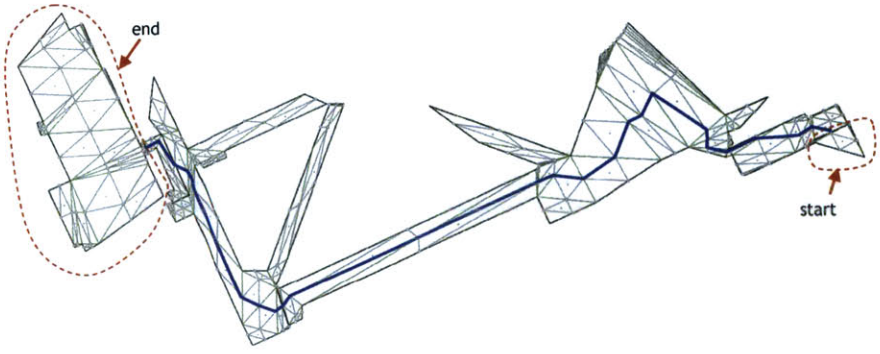


Fig. 3-12: Dijkstra's algorithm is run on the combined internal graph to find the actual path through the sequence of spaces.

3.3.4 *Path Relaxation*

Once the polyline path has been determined, a final shape simplification process is applied. This stage reduces the number of segments in the path while leaving the overall shape of the route intact. The main motivation is to yield a cleaner looking map, removing artifacts present in the medial axis representation. A simpler route polyline may also increase the speed of subsequent rendering routines in our web interface.

Our approach to simplification considers the path through each space independently. In a step-wise fashion we remove interior points from the medial axis path, checking to ensure that the removal does not cause an intersection with any of the space's boundaries. This method is similar to work by Agrawala [2001] in shape simplification of road maps, with the difference that we maintain overall shape by constraining the route within the space boundaries. The process is demonstrated in Figure 3-13.

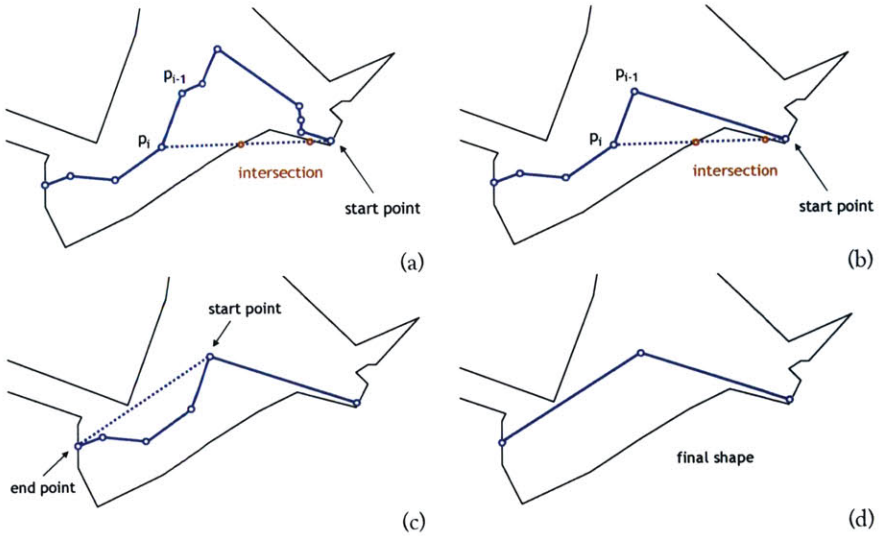


Fig. 3-13: Path relaxation process removes interior points, ensuring that removals do not cause an intersection with the space boundary.

We step through the path forming a ray between the start point and the current point p_i. If the ray intersects the space boundary (Fig. 3-13a), we mark the previous point p_{i-1} as irremovable, and collapse all points between the start and p_{i-1} to a single straight line segment (Fig. 3-13b). The process repeats with p_{i-1} as the new start point, and continues until we reach the last point in the current space. The final simplified shape is shown in Fig. 3-13d.

3.3.5 *Route Constraints*

Route constraints are implemented by selectively restricting undesirable space and portal types in the campus graph. In the edge relaxation step of Dijkstra's algorithm, connections with restricted types are ignored, effectively removing the edge from the graph. For example, paved routes

prohibit portals leading to grass or construction on the basemap, but allow streets, sidewalks, and any indoor space type. Rolling routes are additionally constrained to elevator portals and ramps when moving vertically within buildings. On the other hand, walking routes are free to cut across fields and traverse any indoor space, and are consequently shorter than highly constrained paths.

3.4 Results & Discussion

3.4.1 Route Optimizations

In rare cases, the optimizations built into the route-finder make it impossible to find the shortest path. This occurs when the best route requires leaving a space, and then entering the space again at a different point. Figure 3-14 illustrates one example with the U-shaped sidewalk segment. The problem occurs during the first phase of the route-finder which searches for a sequence of spaces. The optimal route in Fig. 3-14 would result in a cycle.

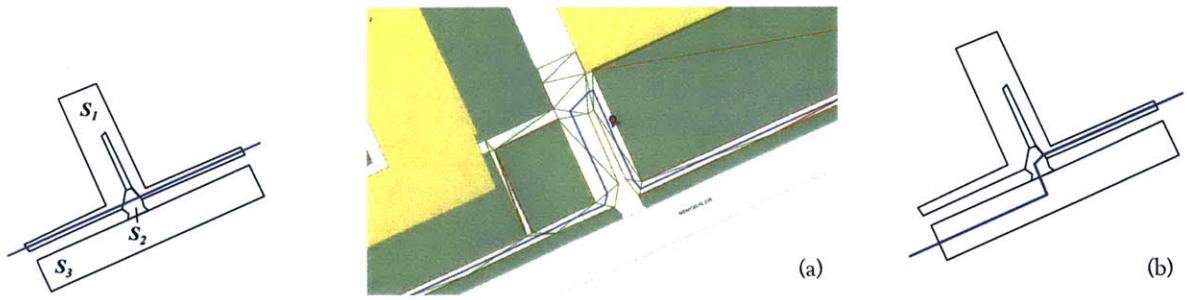


Fig.3-14: Concave basemap spaces. The optimal route requires a cycle in the space sequence (S_1, S_2, S_1). (a), (b) Two alternative routes.

Shortest-path graph search algorithms prohibit cycles, and therefore the optimal route is not found. Instead, the path is forced to stay within the oddly-shaped space (Fig. 3-14a), or find an alternative route (Fig. 3-14b).

A possible solution is to split basemap spaces with large ratios of perimeter to area into more balanced components, or more rigorously, to break up all concave spaces into convex components.

3.4.2 Medial Axis & Path Relaxation

The path relaxation methods discussed in section 3.3.4 do not consistently produce better results than the medial axis path. There are two distinct cases where each method produces the more natural appearance:

1) When the direction of travel is across the main axis of a space contour (e.g. traversing the short distance across a rectangular space, as in Fig. 3-15a), the medial axis rendering pulls the path toward the center of the space, away from the intended destination. Iterative shortening substantially improves the appearance of the path.

2) For street, sidewalk and hallway segments – paths following the centerline of the space with approximately constant width – the medial axis produces a more natural appearance. This is particularly evident in winding sections (e.g. Fig. 3-15c, d).

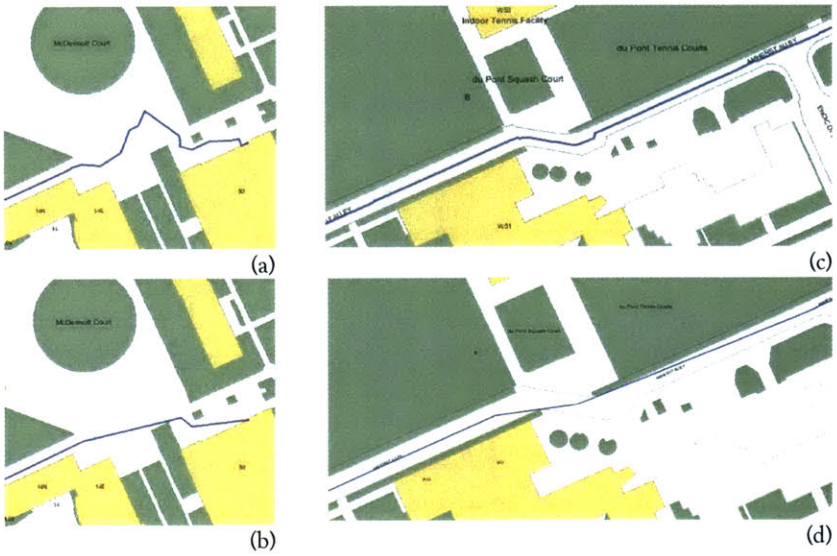


Fig.3-15: (a) Path through McDermott Court with medial axis rendering. The relaxed path in (b) is smoother. (c) Medial axis path along Amherst Alley follows the curves of the street. (d) The relaxed path appears to bounce off the boundaries.

A possible remedy could be to take a denser sampling of contour points when constructing the CDT, which would more closely mirror the exact medial axis. Alternatively, the CDT could incorporate portal positions, for example, by constraining a triangle edge to span the width of a door frame rather than the full length of the door's incident wall.

3.4.3 Robustness & Space Geometry

For a practical implementation of the geometric algorithms used in this project, problems in numerical errors and geometric degeneracies needed to be addressed. Numerical errors are uncertainties resulting from the use of data of varying precision. For example, interior measurements may be accurate within fractions of a foot, while the position of the building itself may be known only to within a few feet. This results from the great variations in the scale of the site: the campus coordinate system has an order of magnitude of 10^5 ft., yet walls separating individual rooms are only inches thick. Double precision floating point values are used in all computations, with epsilon tolerances to determine when two points coincide.

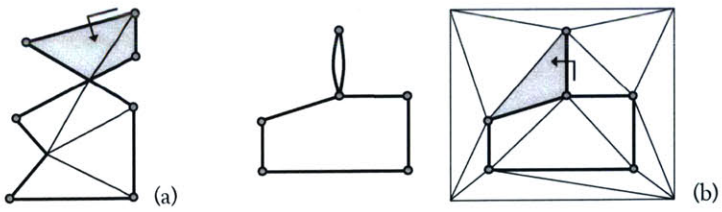


Fig.3-16: Geometric degeneracies present in basemap spaces: (a) Self-intersecting polygon. Performing a depth first search on the CDT finds the triangulation for only one simple polygon component. (b) Repeated edge. Both right and left face triangles are outside the polygon.

Geometric degeneracies were prevalent in the basemap. Partitioning of the basemap in [Kulikov 2004] resulted in instances of self-intersecting polygons and repeated edges (cf. Fig. 3-16). This caused a number of problems when determining triangulations. Specifically, self-intersecting polygons result in an incomplete triangulation, since the search algorithm (separating interior and exterior triangles) finds only the triangulation of one simple polygon component. Repeated edges are interpreted as a single constrained edge in the CDT since they share source and destination coordinates. As illustrated in Fig. 3-16b, if the search algorithm chooses the bad edge as a starting point, the root triangle will be outside the polygon, and the triangulation of the outer mesh will be returned in error. To alleviate this issue, a filtering script pre-processes all basemap spaces to remove any repeated edges from the space contours.

Fig.3-17: Example of generated basemap route in [Nichols 2004].

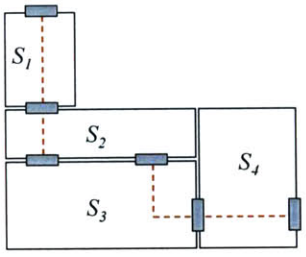


Fig.3-18: Discontinuous path.

3.4.4 Path discontinuities

The Location Server described in [Bell 2003] and [Nichols 2004] used a significantly different optimization scheme than presented in this work. Their method was to pre-compute shortest path lengths.

For every sequence of three adjacent spaces $\{S_1, S_2, S_3\}$, pre-computations determined the best pair of portals $\{P(S_1, S_2), P(S_2, S_3)\}$ providing the shortest route through S_2. Routes were then constructed by simply appending the set of pre-computed paths inside individual spaces, once the high-level sequence of spaces was obtained.

The problem was that continuity is not guaranteed, resulting in irregular paths as shown in Fig. 3-17. Consider a sequence of four spaces $\{S_1, S_2, S_3, S_4\}$. The first three spaces optimally connect with the portal pair $\{P(S_1, S_2), P(S_2, S_3)\}_1$, and the last three spaces optimally connect with a second portal pair $\{P(S_2, S_3), P(S_3, S_4)\}_2$. When adjacent spaces have more than one common portal, $P(S_2, S_3)_1$ is not guaranteed the same as $P(S_2, S_3)_2$ causing the path discontinuity illustrated in Fig. 3-18.

4 MIT WikiMap

4.1 Introduction

An expressive representation for location is an important component of many applications. Semantic properties focus on the meaning of a feature, such as its cultural, historical or functional significance. While the previous two chapters reasoned about space at the level of coordinates, containment relationships and adjacency networks, these representations have no way to express the semantics that define how a particular space is used. This chapter presents the MIT WikiMap, an application that models the geographical relationships between spaces as well as the functional significance or other meanings of a given space.

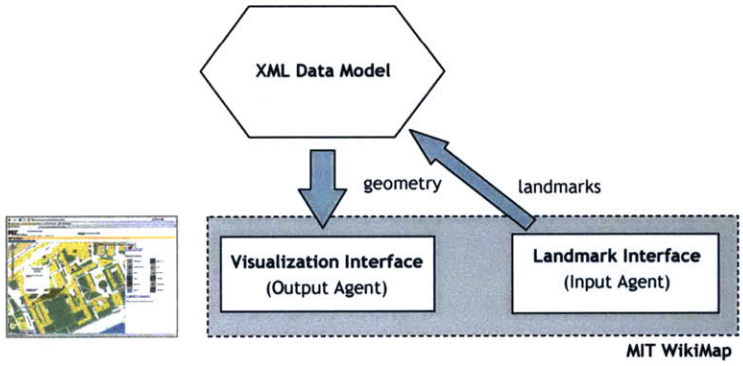


Fig.4-1: MIT Wikimap components. A map visualization interface is combined with UI controls for adding landmarks to the data model.

The broad-view motivation for this work is landmark-based navigation. As the semantic layer becomes populated with distinct visual entities from around campus, route-finding algorithms may provide directions or plan paths based upon particular landmarks. Further, route visualizations may provide richer information to travelers in the form of visual markers supplementing map geometry, or even landmark descriptions integrated into textual route instructions.

Material in this chapter appeared in a report for course 6.831 User Interface Design & Implementation instructed by Professor R. Miller [Whiting, Giovine and Stoltzman 2005].

4.2 Motivation

Complex public spaces, such as a college campus, are host to a wealth of interesting and practical locations that are too often neglected or underutilized simply due to the community's lack of awareness. As a collective, the denizens of a space encapsulate this information, but there is currently no convenient way to gather this information and disseminate it to the individual.

The MIT WikiMap is proposed as a solution. The WikiMap is an interactive, web-based application that allows collaborative, distributed tagging of geographical points on the MIT campus. The WikiMap will serve as a collective record of the public's knowledge of campus: any user may add an item to the map, at which point the item will be world-viewable. Any user may update or edit previously added items at any time, so an effectively-used WikiMap can be perpetually correct and up to date.

The users fall into two main groups: MIT community members and MIT campus visitors. MIT community members have varying levels of familiarity with the campus, and will be the primary contributors to the WikiMap, actively adding entries about locations with which they are familiar and updating those of others. Further, we expect that community members will also reap the most benefit, given the amount of time they spend on or around campus.

MIT campus visitors will generally be viewers of, rather than contributors to, the WikiMap. Our system offers visitors "self-guided-tourism"—the map will offer a wealth of information regarding the unique academic, cultural and artistic facets of MIT and where to find them. Also, the WikiMap offers pragmatic uses, for instance pointing out cafés or places to board public transportation.

The WikiMap offers 3 basic actions to the user: 1) add an item to the map; 2) edit an existing item; and 3) view an existing item. Users' tasks largely consist of these operations. Important tasks include:

- *browsing the map* – a user may simply want to explore the campus by casually perusing the WikiMap. He may explore by location (e.g. West Campus) or by category (e.g. MIT history).
- *sharing a point of interest* – any time a user encounters a novelty or amenity of campus not already present on the WikiMap, he may access the WikiMap and add it.
- *choosing destinations based on proximity* – users may find locations which offer multiple amenities, e.g. food near a lecture hall, or a computer cluster near bike racks.

4.3 User Interface Design

Usability was the primary concern in the interface design. Principles of intuitive user interface design were considered at all stages of development focusing on Nielson's Usability Heuristics [1990]:

- visibility of system status
- user control and freedom
- error prevention
- recognition rather than recall
- aesthetic and minimalist design

The following sections describe each component of the user interface, summarizing design decisions and the alternatives considered during various stages of development.

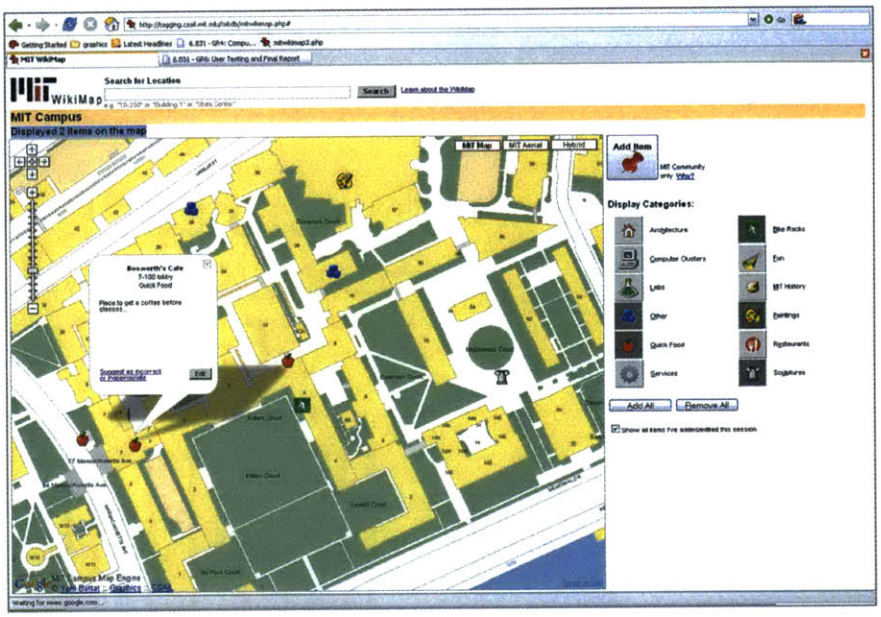


Fig.4-2: WikiMap user interface, shown while viewing items

4.3.1 Browsing

- *Navigating the Map*

The interface incorporates the same map navigation tools as implemented in the MIT Maps route-finder application. Direct manipulation controls allow the user to drag the map to pan and double-click to re-center. A zoom bar is also provided to change the map scale.

- *Category Selection*

We chose to implement category selection as a set of toggle buttons. Our user tests clearly showed this was desirable, and in designs which pre-dated this selection idiom, users would ask why we didn't have this.

Fig.4-3: Toggle-button widget for category selection.

The buttons offer a clear affordance for clicking and are better mouse pointer targets than, say, hyperlinks. Including icon images on the buttons acts as a visual attraction and makes clear the connection between buttons and map icons. Toggle buttons also offer easy undo: the user clicks in exactly the same place to reverse a display or hide action. To increase efficiency, we implemented "Add All" and "Remove All" options, along with keyboard shortcuts for every button.

An alternative "K of N" selection model can be seen in our original selection UI, which uses two list boxes: one list box to display the set of N

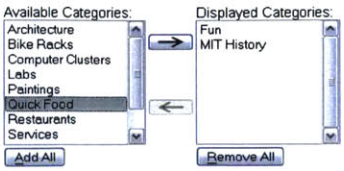


Fig.4-4: Alternative "K of N" widget for category selection – one list box for the K selected choices, the other listing all N choices.

fixed choices, and a second list box for the K selected categories. This UI scales better with the number of categories, addressing a concern we had in early designs. However, this UI has many drawbacks. Adding a category requires at least a double click, and undoing an action would require the user to move the mouse between the two list boxes. Further, the mapping between category names and icons was established by a small legend, which led users to erroneously click on the icons in the legend hoping to display items from that category.

- *Search Box*

Users may submit a location in the search field at the top of the page. A drop-down menu was incorporated with incremental search of all possible location names on campus. This ensures users will select a valid search item before submitting the query. A successful search re-centers the map and highlights the selected location (room, building or green space).

In earlier iterations, the search box was intended for multiple query types. For example, a valid query would be "bldg 10 food bike racks" in an attempt to display all bike racks and places to eat in the area surrounding building 10. We decided implementation of such a sophisticated search tool was beyond the scope of this project. Complications would arise in recognizing which part of a query corresponds to location, and which part to category, and how to provide error recovery when search queries cannot be resolved.

4.3.2 Adding a New Landmark

- *The Tack: Initializing a Landmark*

Fig.4-5: Draggable tack used as metaphor for tagging information points on the map.

For the Add-Item task, we introduced an affordance for pinpointing a location. We chose a tack because it is a well-understood metaphor for representing information on traditional paper maps. It also provides a visual representation for new items that is distinct from existing category icons. Using direct manipulation, the tack is simply dragged across the map to designate the new item location. Tacks are created via a prominently placed button at the top corner of the map. Multiple features are implemented for user freedom and efficiency:

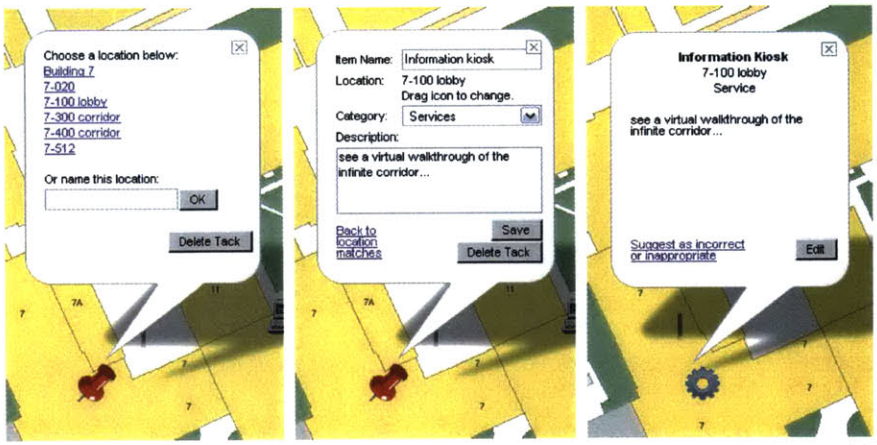
1) Every time the tack button is pressed, an additional tack is added to the map. This allows users to plan multiple items. For example, many tacks can be positioned at their intended locations before entering descriptive information for each one.
2) We included a "Delete Tack" button which removes the tack from the map and cancels an Add-Item in progress.
3) New tacks are positioned in the center of the viewable region of the map. This increases efficiency when used in conjunction with the search box. A location search followed by an Add-Item action will position the tack directly on top of the desired room.

The earliest design iterations included separate modes for adding and viewing items, but this approach had poor learnability. Users were not familiar with the operations available on the WikiMap, and modes restrained exploration of all functionality in viewing, adding and editing items. The result was frequent mode errors, for instance, attempting to add items while in view mode and vice versa.

- *Selecting Landmark Location*

We treat the campus as 2.5D (layers of 2D stacked on top of each other), e.g. by floors within a building. Consequently, choosing a location may sometimes be ambiguous. We chose to alleviate this issue with a location-selection bubble that provides a user with all the possibilities at a particular 2D point. For instance, dropping a tack on 10-250 also offers 10-455 and the hallway below the lecture hall, among other possible rooms. The user may alternatively choose a broader space destination (e.g. Building 10) if the entry pertains to a larger area.

In order to speak the user's language, we incorporate room types into location choices. For instance, instead of the formal space code "7-100LA," the location bubble displays "7-100 lobby." A text field is also available if the user prefers to enter a colloquial location name.



(a) (b) (c)

Fig.4-6: Stages in adding WikiMap items: (a) choosing a location; (b) adding descriptive information; and (c) the final display.

If a user were to type a valid location name in the text field, we considered automatically moving the tack to that location. This would act as an alternative to dragging the tack across the map. In the end, we decided against this feature because it would be disorienting to users and confused with the ability to submit colloquial names.

4.3.3 Displaying Added Items

A consistency issue arose when prototyping the Add-item feature: What is displayed if the category of the added item is not selected as a Displayed Category? For example, the user adds a Sculpture item to the map, but only Quick Food and Bike Racks are selected. To deal with this issue, we decided to include the check box "Show all items I've added/edited this session" that decouples selection of display categories from the user's personal contributions.

In every round of user tests (since the paper prototype), we found that users frequently re-check items immediately after saving to ensure the information is displayed as expected. As such, we decided added item icons should always be displayed. This provides visual feedback for a successful save, and allows users to easily view and edit their contributions (i.e. user control).

One considered alternative was to enforce consistency by automatically selecting the category of the added item as a Displayed Category. We decided it would be disorienting for a user's category selections to be over-ridden. Instead, users are given complete control over category display.

4.3.4 Editing Landmarks

- *Changing Location of an Entry*

In the spirit of the Wiki, entries may need to be moved to new locations, while still retaining the rest of their data. We address this 'user freedom' feature by allowing the entry icons to be dragged. Upon a drop of an existing entry, we present the user with a location-selection bubble (as when adding an item for the first time). A special case arises when the user drags an icon while editing the entry. Here, we store the current state of the edit so that it is once again available upon drop. Edit state is also maintained if the user closes the edit bubble, or views other existing items before saving.

- *Category Selection*

For the sake of consistency we decided to restrict category edits to administrators, for example, to prevent redundant item groupings such as "buildings" and "architecture". Future extensions may include hierarchal category lists to allow for greater variety of display selections and a form for user suggestions of categories.

An alternative was to allow custom categories. Although this follows our original goal of having all content controlled by the user, the danger is a long, cluttered category list with inconsistent or absent icon images.

4.3.5 Deterring Vandalism

The ability to add and edit items is restricted to members of the MIT community. This distinction is made for two reasons: (1) community members are assumed to have sufficient familiarity with the campus that they can appropriately add items; and (2) this allows the WikiMap to deter vandalism.

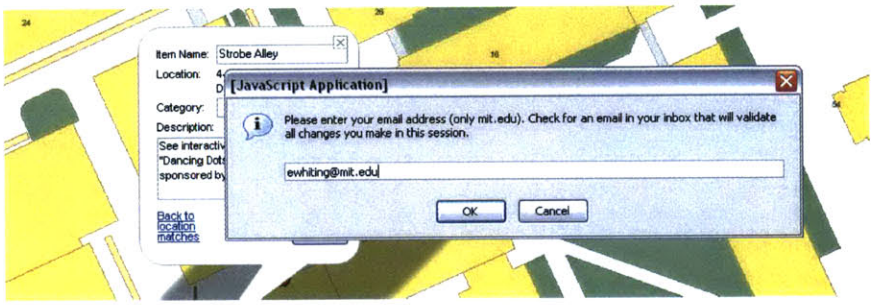


Fig.4-7: Email confirmation dialog. After adding or editing a landmark for the first time, users are asked to submit an MIT email address. A confirmation email is automatically generated and sent to the address provided.

Several measures were taken to deter vandalism. First, users are made accountable by requiring a valid MIT email address before finalizing a user's edits and additions. This allows the WikiMap administrators to associate every change to the system with a member of the MIT community so that proper actions may be taken against those who confirm inappropriate items.

Second, the power to delete an entry lies exclusively in the hands of the administrators. Any user may flag a WikiMap entry for deletion, but the action doesn't occur until an administrator approves it.

For efficiency reasons, users with add/edit permissions (MIT community members) will get only one email asking them to confirm all changes they made during a WikiMap session. This email is sent after completing the first change, but the confirmation will apply to all changes during the session, no matter when the user confirms. Only after this confirmation will a user's changes be publicly visible on the WikiMap.

4.3.6 System Information

- *System Status*

Some actions, such as displaying all sculpture items, may have no visible effect on the map, either because no such items exist, or the items are outside the viewport extents. To ensure users receive immediate feedback, status messages are displayed prominently above the map. A blue background hue (contrasting with map colors) and bold type add to visibility. This feature gives confirmation an action was completed successfully and speaks the user's language. Displaying a category will return the message "Displayed n items on the map." Pressing save on an edit will be confirmed with "Item successfully saved." Messages are

removed after approximately 10 seconds to avoid screen clutter or messages taken out of context.

- *Help & Documentation*

For comprehensive information and instructions for use of the WikiMap, users are one click away from our background and help page.

4.4 Implementation

4.4.1 Languages

The MIT WikiMap is built using Javascript, PHP, and MySQL aiming for a lightweight implementation that is easily loaded into a browser. The tradeoff is restricted functionality by Javascript's narrow range of capabilities.

One example where usability was compromised is that the map does not scroll when an icon is dragged outside the visible region. Scrollable maps are much easier to implement in a Java applet, however, this would add a large overhead on the initial load of the system.

4.4.2 Database

The MIT WikiMap has a MySQL database for its backend. Data is stored persistently in the database as users add and edit items, organized in three tables:

1. **"wikiobj"** stores the data for each landmark object.
2. **"wikiconfirm"** tracks which entries are awaiting confirmation.
3. **"wikicategories"** binds category names to icon images.

We decided that we wanted the system to be as real-time as possible. We took advantage of many of the asynchronous capabilities of Javascript. When a user clicks a category to load it onto the map, an asynchronous call is made to our database, and XML is returned. This XML is then parsed and displayed to the user appropriately. This system design means that the user never needs to reload the page in order to view changes; they are all available immediately.

Furthermore, when a user clicks an icon to load its information, it will first display a local version of the information (stored client-side in Javascript variables), and then will query the database to find the most up to date information for that item. If another user changes the information for a particular icon, that change will be immediately visible to other users (after clicking on that icon) - no page reloads are necessary. Note this only occurs if a user is viewing, rather than editing an item, since we would not want to overwrite a user's edit.

This real-time nature leads to a slight usability issue – a flicker upon opening an item's information. This is caused by the call to the server asynchronously coming back and refreshing the information displayed to the user.

4.4.3 User Information

The implementation relies on session variables for storing user information. When a user accesses the web page, a session variable called `overallnonce` is generated that uniquely identifies that user during the session. The session expires only if the browser window is closed. If the page is refreshed or the user presses back/forward in the browser, the session will persist. This was driven by a design decision to increase user control and freedom.

Once a user adds or edits an item for the first time, she must enter an email address. Since we are using a session variable, this step needs to be completed only once. A confirmation email is then generated and sent to the address provided. The new item is stored in the database, with the "confirm" column of the entry initially set to 0 (off). Once the user confirms the object, the entry's "confirm" column updates to 1 (on).

Email confirmation is flexible. The user may click on the confirmation at any time. For example, a user may add/edit 10 different items then click on the link via email to confirm. Since all of the objects were changed in the same session, they will all be confirmed at once. Alternately, a user may add/edit an item, then click on the link provided in the email, and continue editing items. Future adds/edits in this session will be automatically confirmed, since the user already confirmed his/her identity.

4.4.4 Coordinate Locators

When an item's location is changed (after the user drags and drops an icon), the location matches for the new point are displayed. This information is retrieved by doing a point query, returning matches for the provided layer of data. There are four layers that we use in order to return these locations - rooms, greens, parking, and landmarks. For the rooms layer, we query a script that finds all rooms in our data model containing that x,y coordinate. As a consequence, multiple rooms will be returned if the coordinate goes through multiple floors. For the greens, parking, and landmarks layers, we query the IMS server maintained by MIT's Department of Facilities [http://ims.mit.edu/help]. The greens layer allows points such as Killian Court or McDermott Court to be identified. Parking is for parking lots and garages, and landmarks are for a small set of commonly known locations, such as 77 Mass Ave or the Harvard Bridge.

One complication is that IMS returns space codes rather than colloquial names. For example, IMS calls Killian Court "G6". In order to resolve this, an additional table stores all known bindings between space codes and colloquial names. After doing a point query to the various layers, we send off another asynchronous call to a script that returns these bindings as XML, and then replace the space codes with the colloquial names if available. Similarly, we make sense of the space codes when we know a more human-readable form for the location. We did this for lobbies, corridors, stairs, and elevators. Instead of returning "10-100LA" to the user, we return "10-100 lobby".

4.4.5 Saving Item Edits

When an item is edited, previous versions of the item in the database are left intact. The only part that changes is the "active" column of those entries. Only one entry in the database for a particular object (identified uniquely by a nonce) may be active at any time. This facilitates rolling back an entry if a user inappropriately edited an item.

4.4.6 Item State

Finally, data entered by the user is persistent. When a user clicks to edit an item, makes a change, then closes the edit bubble without saving, the item's state will be the same when the user returns to that item's information. This is done by maintaining two sets of the item's data – one that is editable and one that is not. Any time a change is detected (using `onKeyUp` and `onMouseUp` events), the editable version will change to reflect what the user did. If a user saves his/her changes, the editable version of the data will overwrite the non-editable version. Alternately, if the user cancels changes, the non-editable version will overwrite the editable version. This can be used even for location changes. Therefore, if a user drags an item to another location, then decides to put it back, there is a link he/she can click on that will jump the item back to its original location. We made this design decision in order to reduce errors and increase user control and freedom.

4.5 User Testing

4.5.1 Procedure

User tests were conducted by finding volunteer users, briefing them, and then observing their ease of use while completing prescribed tasks at a computer. Since the WikiMap is web-based, the only equipment requirement was a computer with access to the Internet.

To represent the MIT community, we requested participation from several friends and acquaintances, both undergraduates and graduates. The bulk

of our users were from this group, which is reflective of our anticipated demographic for WikiMap usage. To represent MIT visitors, we asked a college student who was visiting MIT for a day.

We began our user briefing with an overview: "The MIT WikiMap is a web-based, collaborative way of tagging features of the MIT campus by location." We then asked our users if they were familiar with the concept of a Wiki. Those who were not familiar were briefed on how a Wiki allows public editing of common resources. Next, we asked our users if they had used Google Maps, after which we modeled our map zooming and panning UI. All users had used Google Maps.

We did not provide a demo, since we hoped to observe the learnability of the interface. Before performing tasks, most users preferred to have a few moments to explore and experiment with the interface, which was granted.

We asked each user to perform 3 tasks. MIT community members were asked the following:

1) Find a place to eat with bike parking nearby.
2) Add an item to the map at a specified location (different items and locations for each user).
3) Edit an existing item on the map.

Non-community members currently do not have add/edit privileges so their tasks differed:

1) Locate 26-100 exactly.
2) Find a place to eat with bike parking nearby.
3) Find something interesting to see (artwork, sculpture, etc. at the user's discretion) on the eastern side of campus.

To encourage a relaxed testing environment, the users were told that we were "testing the interface, not the user."

4.5.2 Results

The results of user testing were classified as cosmetic, minor, major or catastrophic usability problems. In the final design no cosmetic or catastrophic usability concerns were raised. Minor and major concerns are summarized below with proposed solutions:

Minor: *A user complained some icons (e.g. "Fun") blend into the background.* This could be solved by redesigning the icons, for example to have drop shadows.

Text asking a user to enter an email address to validate the session was not easily understood at first read. We solved this by rewording the dialog box to be more concise.

Major: *Many users were unconsciously reluctant to zoom the map.* All users had used Google Maps before, so all users knew that the map was zoom-able and how they could accomplish this. Despite this, new users tended to remain at the default zoom level, regardless of the number of items they displayed on the map or the area they were interested in. This could be alleviated by reminding users that they may zoom the map whenever more than a certain number of icons become displayed. Alternatively, zooming could be made more accessible, say, by having the scroll wheel control the zoom level.

Users were often quick to enter their own place names. When presented with a list of locations in the location bubble, many users went straight to the "Name this location" field. Sometimes the user did this correctly (e.g. to put the item "DDR machine" in the "Game Room"), but other times users entered a room location simply because the tack was in the wrong place and they did not see their room listed. The users may have expected the tack or item to relocate to the correct location, but we made the decision not to do this as it could be disorienting, especially if the entered location was off-screen. We tried to mitigate this mistaken usage by explicitly stating to the user that their best action may be to reposition the tack.

4.6 Discussion

Fig.4-8: An early paper prototype.

Upon reflection, the iterative design process was critical to the success of our interface. We can all remember how pleased we were with our initial design, and we now all look back at it aghast at how much more usable and elegant our current design is.

We chose to paper prototype virtually all of our front end. This exercise helped us recognize elements of our back end which were unrealistic (e.g. an intelligent search box that would parse complex search expressions). The paper prototype session also had its drawbacks. For instance, until the final user testing, we had a false sense of security that our status messages would guide the user. Indeed, they did in the paper prototype, but that probably owed to the fact that they were physically placed onto the interface, thus drawing attention to them. In our user testing, we found that users barely noticed the status messages, let alone took their advice.

5 Future Work & Conclusions

5.1 Future Work

5.1.1 Landmark Salience

A compelling challenge is to integrate local landmarks into route-representations. Research in spatial cognition has shown that landmarks can be a powerful tool for communicating and visualizing directions [Lovelace et al 1999]. Examples include identifying origin and destination points, identifying decision points (points of reorientation, or junctions where current orientation is maintained), verifying route progress, and influencing expectation [Raubal and Winter 2002].

The main challenge is to develop a system to automatically define and extract salient landmarks from the existing campus model. Drawing from the semantic dataset described in Section 4, a measure of salience could be incorporated by analyzing landmarks according to such features as singularity (contrast with the surroundings), prominence/visibility, or content (having meaning or cultural significance).

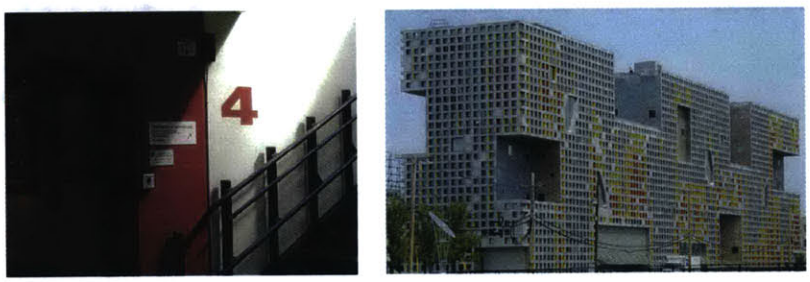


Fig.5-1: Visually salient locations on campus. (Left) a red wall marks the entranceway to building 10; (right) the shape factor and visibility of façade contribute to Simmons Hall's landmark status on campus.

- Visual Salience

Some landmarks fit naturally into the mechanisms developed for describing model geometry in generic walkthrough systems: e.g., interior windows, unusual entranceway dimensions, distinctive floor surfaces or wall colors or textures. Such regional differentiating features provide contrast with their surroundings and contribute to a measure of visual salience. [Raubal and Winter 2002] also suggest visibility of façade and shape factor (deviation of façade area to bounding rectangle) as salient qualities.

- Structural Salience

Structural salience corresponds to the elements defined by Kevin Lynch [1960] that structure a city, classified as nodes, boundaries, and regions. The topological model presented in this thesis affords a number of possibilities for extracting structurally salient locations on campus. For example, comparing the relative connectivity of spaces in the space-graph

may reveal important nodes in the structure of MIT campus. In Figure 5-3 below, hallways emerge as structurally salient spaces due to the many classrooms to which they provide access.

Fig.5-2: Structurally salient locations on campus. (Left) the entrance to Lobby 7; (right) navigational signs posted inside Lobby 10.

Connectivity comparisons could be further enhanced by weighting edges based on predefined notions of importance. For instance, a connection to a corridor or elevator is more useful for movement through a building than a connection to an office. Thus, a lobby linked to two corridor spaces might rank higher than a classroom with two portal edges to a lab and storage space.

Fig.5-3: Floor plans of MIT buildings 10 and 7, superimposed with a graph representation. Hallways emerge as nodes with high connectivity.

5.1.2 Route Preferences

As an alternative to hard constraints (e.g. rolling routes that cannot ascend staircases), future work could incorporate route *preferences*. For example, during the winter a student may prefer an indoor route to class, but will agree to take a short detour outdoors if it reduces his travel time by five minutes. Soft constraints such as this could be implemented through edge weight adjustments - any graph edge leading to an outdoor space is weighted more heavily, depending how strongly the traveler specifies his inclinations.

5.1.3 Route Visualization

The problem of visualizing routes inside buildings presents specific challenges. In particular, an extra dimension (the *z*-axis) is required to illustrate vertical movement such as ascending a staircase. Our current 2D map does not make use of height information; instead, all features are projected onto a plane which may result in a cluttered and ambiguous path when traversing multiple floors (see Fig. 5-4).

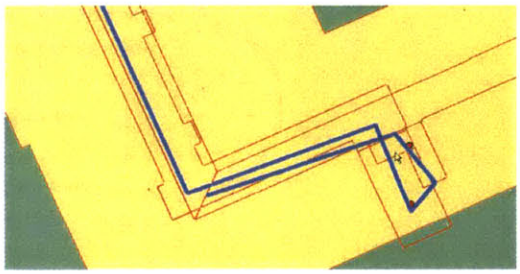


Fig.5-4: Example vertical route inside a building. The path goes through 1st and 2nd floor corridors that overlap in plan view.

A possible solution is to display route maps in 3D. However, this requires a display mechanism allowing viewers to simultaneously see interior spaces and exterior structure of the environment. Standard viewers for three-dimensional building models are suited to display exterior structure, but occlude indoor spaces. On the other hand, walkthrough interfaces reveal inner structure, but only for individual rooms.

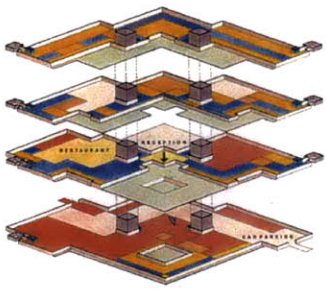


Fig.5-5: An exploded view of a multi-story building showing both interior and exterior structure [Niederauer et al. 2003].

One technique used by illustrators is to create exploded views separating buildings into individual floors. The work by [Niederauer et al. 2003] presents a system for interactively generating such views of 3D architectural environments. Incorporating such a display interface into the MIT Route Finder would greatly enhance usability.

Furthermore, the Niederauer visualization system provides interactive control. Allowing users the additional ability of visualizing routes from multiple viewpoints may have great benefits to their spatial cognition, enhancing the mental map they form of a route.

5.1.4 Route Granularity

The route-finding applications described in this thesis offer a fine-grained, human-centered approach to navigation services in built environments. If integrated with other higher-level mapping services, this could lead to applications which model multiple levels of granularity in urban environments, providing a continuous representation between traffic networks and interior spaces. For example, defining interface points between Google Maps and MIT Maps could enable the following scenario:

> A student's parents are visiting for the weekend. Their hotel is near Boston Commons and their son's architecture studio is in 7-403. A

A student's parents are visiting for the weekend. Their hotel is near Boston Commons and their son's architecture studio is in 7-403. A query to MIT Maps automatically redirects the first part of the search to Google Maps for a route from the hotel address to the parking lot nearest Building 7. MIT Maps determines the remaining path as a walking route from the lot to 7-403. The final display presents one continuous route with an icon to mark the parking lot location, and color coded paths indicating walking and driving segments.

5.2 Conclusion

The principal motivation of this work was to develop an intuitive, human-centered approach to landmark-based navigation systems in a large urban space. The work in this thesis presents three main contributions towards that goal:

1) *Framework for generating a topological model of complex environments*

Methods have been presented for constructing a topological representation of built environments from floor plan geometry. The MIT campus was used as a test-bed containing over 160 buildings, over 800 floors, and approximately 36,000 indoor and outdoor spaces. An exhaustive classification of adjacency types was provided for the university infrastructure.

2) *Prototype application for efficient route generation*

An MIT route finder was developed to provide efficient computation of paths throughout the MIT campus with coverage of interior and exterior environments. Improved path rendering methods were introduced, combining an approximated medial axis path with shape simplification techniques.

3) *User interface for generating a repository of local landmarks*

The MIT WikiMap application was developed to provide for collaborative tagging of geographical locations on the MIT campus according to functional, historical or cultural features. The resulting repository of "points of interest" on campus will serve as a collective record of the university community's knowledge of campus.

The methodologies developed in this thesis may contribute to novel design tools for complex environments. The ability to map and navigate interior and exterior spaces at human scale provides tools to answer numerous practical questions in architectural design. For example, what are the common navigation paths and do they provide adequate capacity? Are landmarks effectively placed in the environment to aid navigation? Does a building provide appropriate facilities for access and navigation by people with disabilities? The WikiMap may also lead to studies on the

usability of spaces. Simple measurements such as the frequency of searched locations may provide insight on features of functional or culturally significant spaces.

This work leads to many different directions for future research including measures of landmark salience, improved route visualization mechanisms, and integration of local environment models with global urban features.

Bibliography

Agrawala, M. and Stolte, C. *Rendering Effective Route Maps: Improving Usability Through Generalization.* In Proc. of SIGGRAPH 2001, pp. 241-249, 2001.

Battat, Y. M.Eng. Thesis, Massachusetts Institute of Technology (In Progress).

Bell, J. *An API for Location Aware Computing.* M.Eng. Thesis, Massachusetts Institute of Technology, 2003.

Bern, M. and Eppstein, D. *Mesh generation and optimal triangulation.* In Hwang, F. and Du, D. (eds.), Computing in Euclidean Geometry, pp. 23-90, World Scientific, 1992.

Bray, T., Paoli, J., Sperberg-McQueen, C., Maler, E. and Yergeau, F. *Extensible Markup Language (XML) 1.0 – 3rd edition*, originally published 2004. [http://www.w3.org/TR/REC-xml/].

Cham, J. In Piled Higher & Deeper, originally published December 1, 2005. [http://www.phdcomics.com/comics/archive.php?comicid=656].

Cormen, T., Leiserson, C., Rivest, R. and Stein, C. *Introduction to Algorithms – 2nd edition.* The MIT Press and McGraw-Hill, 2001.

Darken, R. and Peterson, B. *Spatial Orientation, Wayfinding, and Representation.* In Stanney, K. (ed.), Handbook of Virtual Environments: Design, Implementation, and Applications, pp. 493-518, Lawrence Erlbaum Associates, 2002.

de Berg, M., van Kreveld, M., Overmars, M. and Schwarzkopf, O. *Computational Geometry: Algorithms and Applications.* Springer-Verlag, 2000.

Funkhouser, T., Séquin, C. and Teller, S. *Management of Large Amounts of Data in Interactive Building Walkthroughs.* Computer Graphics: SIGGRAPH Symposium on Interactive 3D Graphics, pp. 11-20, March 1992.

Gold, C. *Simple Topology Generation from Scanned Maps.* In Proc. of Auto-Carto 13, ACM/ASPRS, pp. 337-346, Seattle, April 1997.

Guibas, L. and Stolfi, J. *Primitives for the Manipulation of General Subdivisions and the Computation of Voronoi Diagrams*, ACM Transactions on Graphics, Vol. 4, No. 2, pp. 75-123, 1985.

Haunert, J.-H. and Sester. M. *Using the Straight Skeleton for Generalisation in a Multiple Representation Environment.* In Proc. of ICA Workshop on Generalisation and Muliple Representation, Leicester, August 2004.

Joan-Arinyo, R., Perez-Vidal, L. and Gargallo-Monllau, E. *An Adaptive Algorithm to Compute the Medial Axis Transform of 2-D Polygonal Domains.* In Brunet, P. and Roller, D. (eds.), CAD Tools for Products, Springer-Verlag, 1996.

Klippel, A., Tappe, H., Kulik, L. and Lee, P. *Wayfinding Choremes – A Language for Modeling Conceptual Route Knowledge.* In Journal of Visual Languages and Computing, Vol. 16, No. 4, pp. 311–329, 2005.

Klippel, A. and Winter, S. *Structural Salience of Landmarks for Route Directions.* In Cohn, A. G. and Mark, D. M. (eds.), Spatial Information Theory, International Conference COSIT, pp. 347-362, Springer, Berlin, 2005.

Kulikov, V. *Generating a Model of the MIT Campus Terrain.* M.Eng. Thesis, Massachusetts Institute of Technology, May 2004.

Latombe, J. *Robot Motion Planning.* Kluwer Academic Publishers, 1991.

Lee, D.T. *Medial Axis Transformation of a Planar Shape.* IEEE Trans. Pattern Anal. and Mach. Intelligence PAMI-4, pp. 363-369, 1982.

Lee, J. *A Spatial Access Oriented Implementation of a Topological Data Model for 3D Urban Entities.* GeoInformatica, Vol. 8, No. 3, pp. 235-262, 2004.

Lischinski, D. *Incremental Delaunay Triangulation.* In Heckbert, S. (ed.), Graphics Gems IV, Academic Press, pp. 47-59, 1994.

Look, G., Kottahachchi, B., Laddaga, R. and Shrobe, H. *A Location Representation for Generating Descriptive Walking Directions.* IUI'05, January, 2005.

Lovelace, K., Hegarty, M., and Montello, D. *Elements of Good Route Directions in Familiar and Unfamiliar Environments.* Spatial Information Theory, pp. 65-82, Springer, Berlin, 1999.

Lynch, K. *The Image of the City.* The MIT Press, 1960.

MassGIS, Office of Geographic and Environmental Information, Commonwealth of Massachusetts Executive Office of Environmental Affairs. *Datalayers/GIS Database Overview.* March 2006. [http://www.mass.gov/mgis/spc-pts.htm].

Nichols, P. *Location-Aware Active Signage.* M.Eng Thesis, Massachusetts Institute of Technology, January 2004.

Niederauer, C., Houston, M., Agrawala, M. and Humphreys, G. *Non-Invasive Interactive Visualization of Dynamic Architectural Environments.* In Proc. of ACM SIGGRAPH'03 Symposium on Interactive 3D Graphics, 2003.

Nielsen, J., and Molich, R. *Heuristic Evaluation of User Interfaces.* Proceedings of ACM CHI'90 Conference on Human Factors in Computing Systems, pp. 249-256, 1990.

Nothegger, C., Winter, S. and Raubal, M. *Computation of the Salience of Features.* Spatial Cognition and Computation, Vol. 4, No. 2, pp. 113-136, 2004.

Raubal, M. and Winter, S. *Enriching Wayfinding Instructions with Local Landmarks.* In Egenhofer, M.J. and Mark, D.M. (eds.), Geographic Information Science. Vol. 2478, pp. 243–259, Springer, Berlin, 2002.

Richter, K. and Klippel, A. *A Model for Context-Specific Route Directions.* Spatial Cognition IV, pp. 58-78, 2005.

Roush, W. *Killer Maps.* Technology Review, Vol. 108, No. 10, pp. 54-60, October 2005.

Sorrows, M. and Hirtle, S. *The Nature of Landmarks for Real and Electronic Spaces.* In Freksa, C. and Mark, D. (eds.), Spatial Information Theory, pp.37-50, Springer, Berlin, 1999.

Timpf, S and Frank, A. *Using Hierarchical Spatial Data Structures for Hierarchical Spatial Reasoning.* In Hirtle, S. and Frank, A. (eds.), Spatial Information Theory, pp. 69-83, Springer, Berlin, 1997.

Teller, S., Funkhouser, T., Khorramabadi, D. and Sequin, C. *The UCB System for Interactive Visualization of Large Architectural Models.* Prescence, Vol. 5, No. 1, January, 1996.

Varadhan, G. and Manocha, D. *Out-of-Core Rendering of Massive Geometric Environments.* In Proc. of IEEE Visualization, 2002.

Whiting, E., Giovine, G. and Stoltzman, W. *MIT WikiMap.* 6.831: User Interface Design & Implementation, Final Report, Massachusetts Institute of Technology, December 2005.

A Project Build Instructions

This chapter describes how to checkout, build and execute the applications described in this thesis, including the CDT generator, vertical portal linker, dangling portal linker, and the location server. The instructions assume an MIT CSAIL account and a LINUX command-line environment.

A.1 Checkout Instructions

The applications described in this thesis are stored in the CSAIL SVN repository as part of the `walkthru/mit` source tree. To check out the entire directory, first move to the directory where your local checkout of the `walkthru` source tree will be hosted, then type one of the following commands:

From a CSAIL machine with local access to the repository:

```
% svn checkout file:///${REPOSITORY}
```

With remote access to the repository through ssh:

```
% svn checkout
  svn+ssh://login.csail.mit.edu/${REPOSITORY}
```

The variable `REPOSITORY` is the path to the repository, which currently resides at: `/afs/csail/group/rvsn/Repository/walkthru/mit`.

A.2 Build & Run Instructions

Once the source code has been retrieved from the SVN repository, the entire project can be built and run in batch mode with a single pipeline script. First move into the directory where your local checkout of the source tree is hosted, and type:

```
% python pipeline.py
```

It is assumed that all floor plans have been processed by the DXF Parser and are accessible from a central location. To run each application separately, step-by-step instructions are provided below.

1. Run CDT generator

To compile the CDT generator, move to the directory `/mit/src/cdt/` and type:

```
% make cdtxml
```

The following command will process all spaces in the campus data corpus:

```
% python run.py [floors_file] [input_dir] [output_dir]
```

e.g.

```
% python run.py ../orderedFloors.xml
  /var/www/maps.csail.mit.edu/output.latest/ ../output.cdt/
```

The `floors_file` is the ordered list of floors for each building (see C.1). The input directory is the path to the floor data files (see C.2). In the output, each space is given a set of "triangle" child nodes representing the constrained Delaunay triangulation for the space's contour.

2. Run vertical portal linker

Move to the directory `/mit/src/vertPortals/`. The command-line arguments to invoke the vertical portal linker are:

```
% python run.py [floors_file] [input_dir] [output_dir]
```

e.g.

```
% python run.py ../orderedFloors.xml ../output.cdt/
  ../output.vert/
```

The `floors_file` is the ordered list of floors (including mezzanines) for each building (see C.1). The input directory is the location of the floor data files. The portal linker processes each floor in the inventory, finds all instances of vertical spaces (i.e. stairs and elevators) and finds their match in neighboring floors. Floors are assumed to be neighbors if they are listed sequentially in the `floors_file`.

3. Run building-basemap dangling portal linker

Move to the directory `/mit/src/danglingPortals/`. The command-line arguments to invoke the dangling portal linker are:

```
% python run.py [floors_file] [input_dir] [output_dir]
  [radius]
```

e.g.

```
% python run.py ../orderedFloors.xml ../output.vert/
  ../output.final/ 30
```

The `floors_file` is the ordered list of floors for each building (see C.1). The input directory is the location of the floor data files, which must also contain the basemap data files. The `radius` parameter sets the tolerance, measured in feet, when searching for basemap spaces proximal to each dangling portal.

4. Run Location Server

Once the triangulation and portal data has been generated for each space, the output can be loaded into the location server. The location server is invoked with the following command-line arguments:

```
% java -Xmx[heap size] -D[rmi codebase] -D[policy file]
  [class] [mode] [db file] [input_dir] [floor ... ]
```

The `mode` parameter specifies whether the location server is run in batch processing mode, where the parameter is `BATCH_OUT`, or quick start mode, where the parameter is `QUICK_START`. In batch processing mode, the location server will load and pre-process the list of named floors, then output this state to the specified `file` before binding to the Java RMI port. The `input_dir` parameter is simply the path to the `floor` data files. The `floor` parameter names one or more XML files, where each file contains all space and portal information for the entire floor.

For example, to load all spaces and portals on floor 0 and 1 of Building 1 in batch mode, the command is:

```
% java -Xmx1500m -Djava.rmi.server.codebase=file://./
  -Djava.security.policy=locationserver/java.policy
  locationserver.JavaLocationServerRMI BATCH_OUT full.db
  ~ewhiting/walkthru/mit/output.final/ 1-0.xml 1-1.xml
```

To actually compile and invoke the location server, first move to the directory `LocationAwareXML/locationserver` then type:

```
% rmiregistry &
% make all
% make full
```

Alternatively, to load only the basemap spaces, type "`make basemap`" instead of "`make full`". The location server will then load the campus data from the local file system and publish itself on the default Java RMI port. The set of floors to load is listed in the Makefile.

B Portal & Space Types

The following are lists of type codes used to define spaces and portals in the XML data model.

Table B-1: Portal types.

Portal Class	Portal Type	Code
vertical	stair	STAIR
	elevator	ELEV
horizontal	explicit	EXPLICIT
	implicit	IMPLICIT
	basemap	OUTDOOR
	slope	SLOPE

Table B-2: Basemap space types [Kulikov 2004].

Space Type	Code
sidewalk	SDWLK
street	HGWAY
grass	GRASS
construction	CNSTR
slope	SLOPE
building footprint	BLDNG
unknown	UKNWN

Table B-3: Indoor space types as defined by MIT's Department of Facilities [https://floorplans.mit.edu/mit-explore.html].

Space Type	Code
ALTER/CONVERSION	ALTER
ANIMAL QUARTERS	AN QTR
ANIMAL RSCH LAB	AN LAB
ANIMAL SERVICE	AN SV
APARTMENT	APTMNT
APARTMENT SVC	APTSVC
ATH LOCKER ROOM	ATH LK
ATH SHOWER ROOM	ATH SH
ATHLETIC FACIL	ATHLET
ATHLETIC SERVICE	ATH SV
BRIDGE/TUNNEL	BR/TUN
CLASSROOM	CLASS
CLASSROOM SVC	CLA SV
COAT ROOM	COAT
COMPUTER FACIL	CMPUTR
COMPUTER SERVICE	CMP SV
CONFERENCE ROOM	CONF
CORRIDOR	CORR
DARK ROOM	DK RM
DAY CARE	DAY CR
DAY CARE SV	DC SVC
DIAGNOS SVC LAB	DS LAB
DRAFTING ROOM	DRAFT
ELEC/TEL CLOSET	EL/TEL
ELECTRIC CLOSET	ELEC
ELEVATOR	ELEV
EXHIBITION FACIL	EXHIB
EXHIBITION SVC	EXH SV
FEMALE LAVATORY	F LAV
FOOD FACIL SVC	FOODSV
FOOD FACILITY	FOOD

GUEST ROOM	GUEST
HEALTH CARE SVC	HC SV
HOUSEMASTER APT	H MSTR
INSTRUCTION SHOP	INSTRC
INSTRUMENT ROOM	INSTRU
JANITOR CLOSET	JAN CL
JANITOR LOCKER	JAN LK
JANITOR STORAGE	JAN ST
LAB SUPPORT SHOP	LAB SP
LABORATORY SVC	LAB SV
LAUNDRY FACIL	LAUN
LECTURE HALL	LECT H
LIBRARY PROCESS	LIB PR
LIVING QUARTERS	LIVING
LOBBY	LOBBY
LOUNGE	LOUNGE
MAIL ROOM	MAIL
MAINTENANCE SHOP	M SHOP
MALE LAVATORY	M LAV
MEDIA PRODUCTION	MEDIAP
MEDIA SERVICE	MEDIAS
MERCHAND FACIL	MERCH
MERCHAND SVC	MER SV
MULTI-PURPOSE RM	MULTI
MUSIC PRACTICE	MU PRA
NON-ATH LOCKR RM	N-A LK
NURSE STATION	NURSE
OFFICE	OFF
OFFICE SERVICE	OFF SV
PATIENT BATHROOM	PBATH
PATIENT BEDROOM	PBEDR
PRINT/DUP SHOP	PR/DUP
PUBLIC LAVATORY	PB LAV
PUBLIC WAITING	P WAIT
PVT CIRCULATION	P CIRC
PVT LAVATORY	P LAV
RECEIVING ROOM	RCVG
RECREATION FACIL	RECREA
RESEARCH LAB	RS LAB
RSCH LAB-OFFICE	RES LO
SECY/RECEPTION	SECY/R
SHAFT SPACE	SHAFT
SHOP SERVICE	SHP SV
SLEEP/STD W/BATH	SLPBTH
SLEEP/STUDY SVC	SLPSVC
SLEEPSTD W/OBATH	SLEEP
STACK/STUDY	STKSTD
STAIRWAY	STAIR
STORAGE FACILITY	STOR
STUDIO	STUDIO
STUDY ROOM	STUDY
SURGERY	SURG
TEACHING LAB	TC LAB
TELECOM CLOSET	TELE
TERRACE	TERR
TOILET OR BATH	BATH
TREATMNT/EXAM RM	TRT/XM
UTILITY/MECH RM	U/M
VAULT	VAULT
VEHICLE STORAGE	VEH ST

C File Formats

C.1 Floor Inventory

For batch processing, the applications described in appendix A require a list of all available floor plans in the data corpus. The applications take an XML file as input, containing an ordered list of floors for every building on campus. The expected format is as follows:

```
<Project name="MIT">
    <Buildings>
        <building id="W70">
            <floor id="1"/>
            <floor id="2"/>
            <floor id="3"/>
            <floor id="4"/>
            <floor id="5"/>
            <floor id="6"/>
        </building>

        ...

        <building id="4">
            <floor id="0"/>
            <floor id="0M"/>
            <floor id="1"/>
            <floor id="1M"/>
            <floor id="2"/>
            <floor id="3"/>
            <floor id="4"/>
            <floor id="4M"/>
            <floor id="5"/>
        </building>
    </Buildings>
</Project>
```

The `id` attribute specifies the building or floor name. Floor lists must be ordered numerically from lowest to highest and include mezzanines. The mezzanine naming convention is `[parent floor]M`, where `4M` is the mezzanine level above floor `4`.

C.2 Floor Geometry

Space and portal geometry is currently stored in XML files grouped by floor. Files are named according to the convention `[Building]-[Floor].xml`. For example, all spaces and portals contained in the second floor of Building 10 are stored in 10-2.xml. The file format is as follows:

```
<ROOT>
    FLOOR
    SPACE0 SPACE1 SPACE2 SPACE3 ...
</ROOT>
```

A top level node ROOT is the parent element for all spaces on the given floor. The first child node FLOOR provides geometry of the floor contour in the form:

```
<floor name="FLOORCONTOUR">
    CONTOUR
</floor>
```

Each element $SPACE_n$ has the structure:

```
<space name=SPACE_NAME type=SPACE_TYPE>
    CONTOUR
    TRIANGLE_0 TRIANGLE_1 TRIANGLE_2 ...
    PORTAL_0 PORTAL_1 PORTAL_2 ...
</space>
```

And CONTOUR elements are represented as:

```
<contour>
    CENTROID
    EXTENT
    POINT_0 POINT_1 POINT_2 ...
</space>
```

as described in chapter 2. For complete descriptions of the XML representation for each element, refer back to the "Data Representation" sections 2.1.3 for floors, 2.1.4 for spaces and 2.1.5 for portals.