Spatial Reasoning for Building Model Reconstruction Based on Sensed Object Location Information

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Abstract: The continuous collection of data on the state of facilities appears increasingly feasible due to advances in sensing technologies. In this context, we explore the application of tag-based location-sensing to reconstruct models of existing buildings. We describe tag-based building representations, which are complete under certain conditions for the automated conversion to boundary-based building representations. The latter have a rich structure and are useful for various construction-related applications. We describe and demonstrate with a system prototype how spatial reasoning methods facilitate the conversion process.

1 INTRODUCTION

There is a growing interest in the continuous data collection of buildings, driven in part by recent advances in sensing technologies. Although commercial solutions are available for monitoring and preventative maintenance of mission-critical HVAC, lighting, security or circulation systems, these cover only a small fraction of the information that may be useful in assessing building performance. What is still lacking is a systematic and comprehensive approach to collecting state information throughout the building life-cycle. If overall facility performance is to be tracked, analyzed, and improved, it appears that 'inert' or 'grey' matter in buildings such as surfaces, furniture, manually operable windows and doors should be included as well. Although generally thought of as static, these entities change considerably over time. For example, studies on churn rates and churn cost in office buildings suggest that significant physical changes can occur in workplace configurations over relatively short time periods (Ryburg 1996). Through appropriate sensing infrastructures, entities affected by such changes could be made available for detailed performance analysis.

Automated reconstruction and recognition of objects or scenes from sensor data has been researched extensively in computer vision and related fields (Hebert 1998). Most work assumes only minimal or no a-priori knowledge about a target scene.

However, progress with respect to potential applications in the building domain, has been slow. On the other hand, the availability of smart sensing technologies - some of which employ computer vision techniques - suggests the feasibility of scenes enhanced by markers tracked by sensors. Richer models could be derived from such scenes. The work presented in this paper adopts the latter approach and demonstrates how seemingly unrelated object data collected by a tag-based location-sensing system (and possibly other sensor sources) may be enriched through spatial reasoning into comprehensive, three-dimensional building models.

In the following sections, we first describe which objects in a building are marked with tags for location sensing. We assume that each sensed object's identity is known and may be linked with additional information in remote product databases. Key issues include the minimization of the number of tags to mark objects as well as the amount of information required and maintained at the back-end. We use the term tag-based building representation to refer to a building model obtained by a combination of tags and product databases. Such a representation in itself, however, exhibits little explicit structure and is thus of limited immediate use to most applications. We describe a procedure that converts a tag-based into a boundary-based building representation through spatial reasoning. Boundary-based building representations are useful for a variety of potential applications, including quantity surveying, inventory management, building controls, augmented reality, mobile robotics and context-aware computing (see, for example, Mahdavi 2001, Harter et al. 1999).

2 TAG-BASED BUILDING REPRESENTATIONS

Current location-sensing systems often rely on tags, that is, small markers mounted on objects to be tracked. In contrast to tag-less technologies such as laser scanners, one benefit of tags is the encoding of object identification and, sometimes, additional information. We assume that a tag's pose is sensed and represented as a coordinate system transformation. TRIP is a tag-based location sensing system that provides this kind of information (Lopez de Ipina 2002, Icoglu et al. 2004). As TRIP uses computer vision techniques to derive tag locations, only those objects with line-of-sight between tags and sensors can be tracked. We further assume ideal sensor data, that is, there is no deviation between measured and true values.

In the present context, it suffices to define *buildings* as an aggregation of *spaces* (class names are italicized). The concept of architectural space is relevant for a number of construction applications. It is included in emerging building product model standards such as the Industry Foundation Classes (IFC) (IAI 2004). We use and adapt the space object terminology introduced by Bjoerk (1992) because it is more specific than the IFC model for the purpose of this work. Spaces as well as buildings are abstract concepts, but they may be described in terms of their physical or imaginary boundaries. *Physical-envelope-boundaries* or *physical-space-boundaries*, that is, boundaries of enclosing structures such as façades or roofs, and, respectively, floors, walls, and ceilings, may be marked with tags. These are grouped by space (analogously those for the envelope). There is a one-to-one correspondence between such a tag-set and a space object (Figure 1 upper-left box). For simplicity, we use the term *space-tag-set* to refer to these two related objects. Semi-bounded spaces or spaces with *imaginary-space-boundarie*s may be modeled as *holes* in physical-space-boundaries. A hole-tag is placed on the physical-space-boundary in which a hole is contained and otherwise treated as an opening-tag (see below). A *physical-building-boundary* is an aggregation of envelope- and space-boundaries and thus an abstract concept. For the remainder of this paper, we will omit the term 'physical' for convenience.

A space-boundary-tag may be placed anywhere on the interior of a space-boundary (that is, neither on a corner or an edge). Again, there is a one-to-one relationship between a tag and a space-boundary. This facilitates flexible placement and minimizes the number of space-boundary-tags. Flexibility is important as space-boundaries may be partially obstructed and line-of-sight between tag and sensor may be required. Envelope-boundaries are marked similar to spaces. In the following, we will often use the terms envelope and space interchangeably.

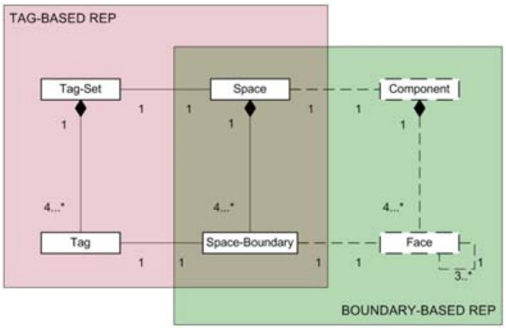

Figure 1 Tag-based and boundary-based space representations (dotted lines indicate derivation by spatial reasoning)

An *opening* such as a *door* or *window* may fill a hole in a space-boundary, implying a containment relation. An *opening-tag* is placed on a pre-defined opening spot. Additional tags may be required if multiple movable opening parts are tracked.

Infrastructure-objects include *tables*, *light-fixtures*, *cabinets*, *blinds* and other movable or fixed objects in a space. Placement of *infrastructure-object-tags* is analogous to opening-tags.

3 CONVERSION FROM TAG-BASED TO BOUNDARY-BASED BUILDING REPRESENTATIONS

This section describes a procedure that converts a tag-based into a boundary-based building representation. The geometry related to a building object is a non-simple *polyhedron*, whose *components* are associated with the envelope and spaces (in contrast to a simple polyhedron, a non-simple polyhedron may have holes and multiple components). Similarly, each envelope- or space-boundary has a *face*, which is part of a component. Faces in turn have adjacency relations among themselves (see lower-right box in Figure 1). Once a building-polyhedron is known, opening geometries are generated and matched with component faces. This step gives rise to a space connectivity graph based on openings. Finally, infrastructure-object geometries are generated and associated with spaces.

3.1 Space-boundaries

Space-components are bounded by space-boundary-faces. The shape of these faces is initially unknown and determined by a geometric modeling procedure. Since tag-representations for non-simple polyhedra with a one-to-one correspondence between tags and faces are incomplete (Suter 2004), a divide-and-conquer approach is chosen whereby the boundaries of individual components are evaluated first. In the present context, the number of components is known because space-boundary-tags are grouped by space. The resulting component boundaries are subsequently combined into a single non-simple polyhedron by boolean intersection. Components are treated as flat-faced simple polyhedra, for which a conversion procedure has been developed. A detailed description is given in Suter (2004) and summarized in the following. The procedure is closely related to existing work on sampling representations in solid modeling, especially tag-enhanced ray representations (Menon and Voelcker 1995).

A tag representation of a simple polyhedron *A*, or tag-rep(*A*), is converted in two stages into a boundary-representation of *A*, or Brep(*A*) (Figure 2). The first stage relies on known procedures from constructive solid geometry (CSG) to derive a disjunctive decomposition of 3-space from the set of half-spaces induced by the position and normal vectors associated with the tags in tag-rep(A) (Shapiro and Vossler 1990). Tag positions are also used in point classification procedures to identify cells in the disjunctive decomposition whose point set represents a subset of *A*. The result of this procedure may or may not include all cells, which, if merged by boolean union, would be equivalent to *A*. The success of the first stage is influenced by a combination of factors, including tag placement and the shape of *A*.

If the first stage does not result in a valid polyhedron, the conversion procedure enters its second stage, which involves a generate-and-test search process. The objective is to incrementally evaluate the boundary of an evolving polyhedron, *B*, until it is equivalent to that of *A*, that is, *bB* = *bA* (*b* denotes boundary). Two tests are performed on *bB*. First, *bB* is inspected for general polyhedron well-formedness conditions (Requicha 1980). Second, each tag in the tag-rep needs to be matched with exactly one face. This condition enforces the one-to-one correspondence between tags and faces mentioned earlier. Unmatched as well as multiple tags matching a face result in a conflict, in which case a new face alternative is generated and added to *B*. A vertex-edge graph and constraints on vertices, edges, and faces - all derived from the disjunctive decomposition using known boundary evaluation algorithms (Requicha 1985) - guide this highly recursive search process to evaluate *bB*.

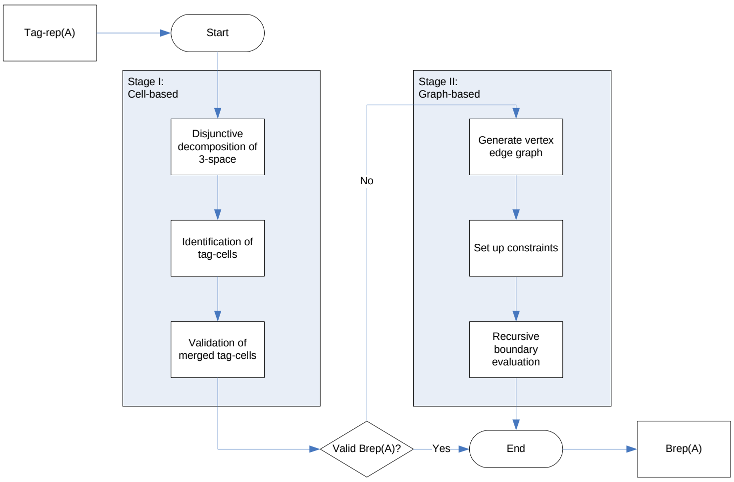

Figure 2 Flow diagram of the procedure converting a tag-rep(A) to a Brep(A)

Note that in most cases neither of the two stages alone would achieve the conversion between tag-rep and Brep. Whereas the first stage may only generate a partial Brep(A), the search space in the second phase would often be unmanageable unless narrowed by the constraints obtained from the first stage.

3.2 Merge of Space-components

As space-tag normals point toward the interior of a space, the space-components obtained by the conversion outlined above are semi-bounded. Thus the combination of space-components occurs by boolean difference operation (Figure 3a). Note that the polyhedron resulting from such an operation is still semi-bounded. The same intersection operation is used when one of the components to be merged is the (bounded) envelope-component (Figure 3b). The result of that operation is a bounded polyhedron. As boolean intersection is commutative, the order in which space- and envelope-components are processed does not matter.

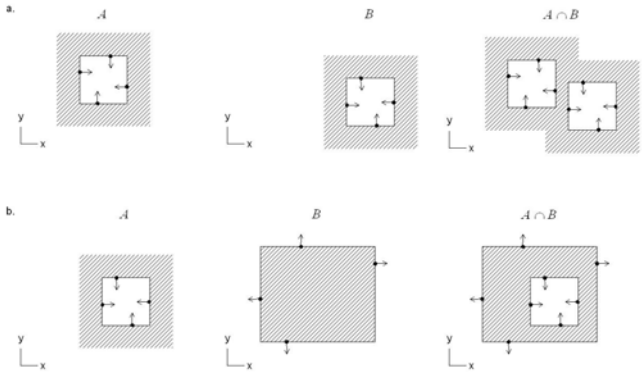

Figure 3 Merge of bounded and semi-bounded components by boolean intersection. a. Merge of two space-components; b. Merge of an envelope-component and a space component

3.3 Openings

Relations of an opening with space-boundaries are not readily derived from a tag-based building representation. However, tests for relations can be performed when space-boundary-faces are known. Assuming that an opening connects two spaces (or a space and the outdoor environment), the relation of a given opening-tag and space-boundary-face pair is determined as follows (Figure 4a). First, tag and face normals are compared. If they are not parallel, there is no relation. Otherwise, the distance between the tag position ***p*** and its projection ***p'*** on the surface, in which the face is embedded, is computed. If the distance is greater than a certain maximum distance (about 50cm should be sufficient to reliably derive relations even in case of thick walls), then there is no relation. Otherwise, the last test involves point classification of ***p'*** with respect to the face. If ***p'*** lies on the interior of the face, then there is a relation between tag and face, otherwise there is not. With relations between each opening, its space-boundaries, and hence spaces known, it is possible to derive a space connectivity graph based on openings (Figure 4b, 4c).

The next step in the generation of openings is to actually evaluate an opening shape and integrate it within its space-boundary context. First, the shape is retrieved from the product database by opening-tag ID. This could be a simple two-dimensional profile, a three-dimensional solid, or the latter computed from the former with thickness information. The opening geometry is then transformed from local to global coordinate system based on the opening-tag pose. The level of detail required depends on application needs, therefore we just give examples of common opening representations.

The decision regarding opening representations could have far-reaching consequences for the building geometry and topology. For example, a hole or void-opening, modeled as a profile obtained from the product database, swept by the distance between two related space-boundaries and subtracted from the building-polyhedron, would connect two previously separated space-components (Figure 4d). On the other hand, simply converting the profile into faces and subtracting these from corresponding space-boundaries would not affect the number of components (Figure 4b, 4c). In either case, it appears desirable to preserve the state of the building-polyhedron prior to the integration of openings because it represents a view of the building that is more abstract and may have different topological properties than the view that includes openings. Simultaneous accommodation of multiple object views or representations has been mentioned frequently as a crucial requirement for building information models (see, for example, Rosenman and Gero 1996).

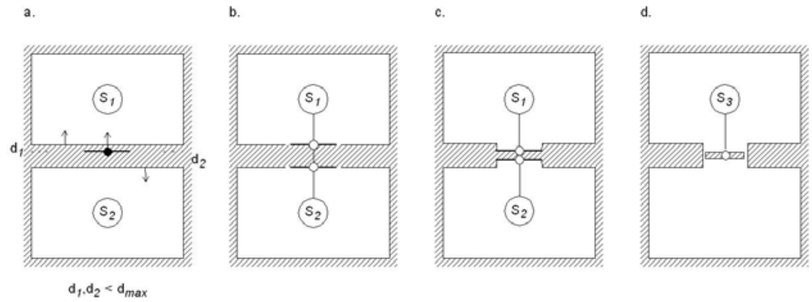

Figure 4 Opening representations and space connectivity. a. matching of opening-tags and space-boundary-faces; b. opening-faces co-planar with space-boundary-faces. c. recessed opening-faces; d. disjoint opening-solid filling a hole connecting two space-components.

3.4 Infrastructure Objects

Infrastructure-object geometries are evaluated similar to opening-object geometries. The containment relation between an infrastructure-object and a space is of interest here. It may be derived only when at least space-boundaries are known. Consideration of an infrastructure-object-tag position rather than explicit or approximated shapes should be sufficient for most applications. A given infrastructure-object-tag and space-component pair is tested for containment by point classification of the tag position with respect to the space-component. A containment relation exists if the tag position lies outside or on the boundary of the component, that is, in or on the void enclosed by it. There is no containment relation if the tag position lies in the component.

It is possible that an infrastructure-object can not be associated uniquely (e.g. a table geometry extending beyond a single space) or at all (e.g. a chair completely contained by a void opening) with respect to a space-component. In such cases, hole geometries and approximated shapes such as bounding boxes for infrastructure-objects and space-components should be considered to minimize processing overhead.

4 EXAMPLE

A proof-of-concept prototype system was implemented to demonstrate the conversion from tag-based to boundary-based building representations. Envelope- and space-boundary evaluation is currently performed with only a limited set of constraints (the cell-based first stage is skipped altogether). Most of the geometry processing is done in the ACIS API, a commercial solid modeling environment (Spatial 2004). Figure 5 illustrates the conversion from tag-rep to Brep for an F-shaped space that is part of an office environment. The vertex-edge graph (upper-left image) provides the basis for recursive evaluation of face alternatives. There are several intermediate states (states 77 and 165 are shown as examples) of the evolving space-component, most of which result in local failure, which may require backtracking to higher levels in the search tree. In the example, the boundary of the target space is validated after 246 steps. Figure 6 shows two views of the office environment at different abstraction levels. The first is a high-level view of space-boundary-components. The second view includes detailed representations of openings, blinds, and infrastructure-objects. Note the difference in the number of components in the building-polyhedron: seven in the first view, one in the second – that is, envelope- and space-components are merged into a single component. Providing such flexible views or interpretations of a building is relevant with respect to the disparate information needs of various applications.

5 DISCUSSION

We have introduced the concept of tag-based building representations and a procedure to convert these to boundary-based representations. Several issues should be addressed in future work. First, various steps in the conversion involve spatial queries that are computationally expensive. This suggests the exploration of spatial indexing schemes to improve the scalability of tag-based building models. A by-product of such an effort could be the automated derivation of zones or floors. Secondly, in a realistic setting, pre-processing would be required to account for tolerances in location sensing data. In the work presented here, we have assumed ideal sensor data. Deviations between recorded and true sensor values could cause significant problems in evaluating tag-based building models, resulting in global failure in the worst case. For example, deviations in tag positions or normals due to sensor tolerances could cause certain faces not to be included in a Brep derived from a tag-rep (see Hoover, Goldgof and Bowyer 1998 for a description of similar problems in validating face adjacency graphs).

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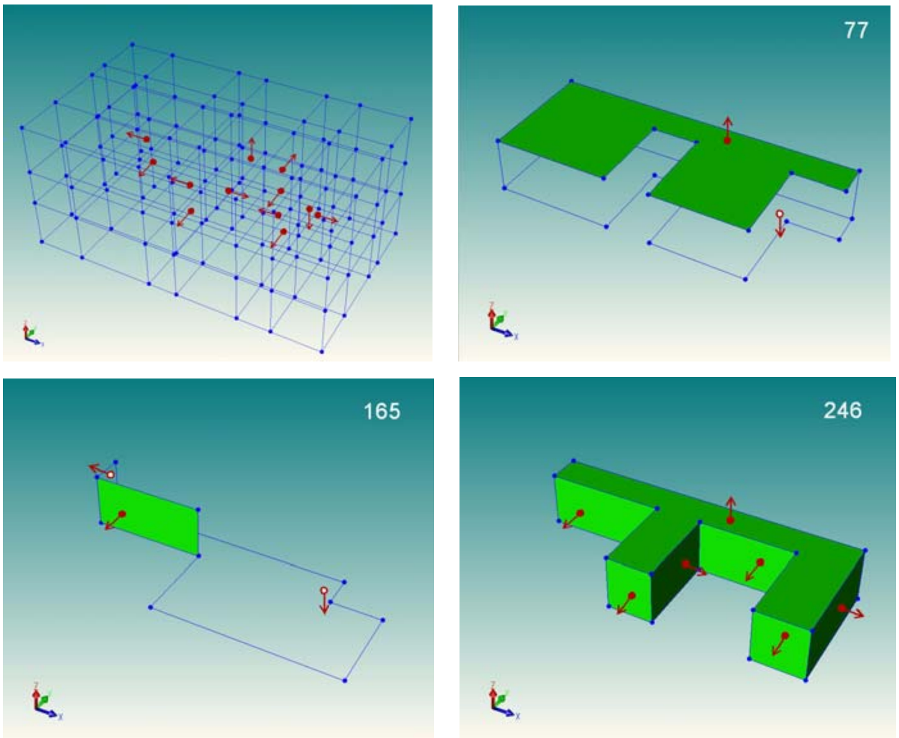

Figure 5 Illustration of a conversion procedure from a tag representation to a boundary representation of a space (shaded areas and dotted lines indicate derivation)

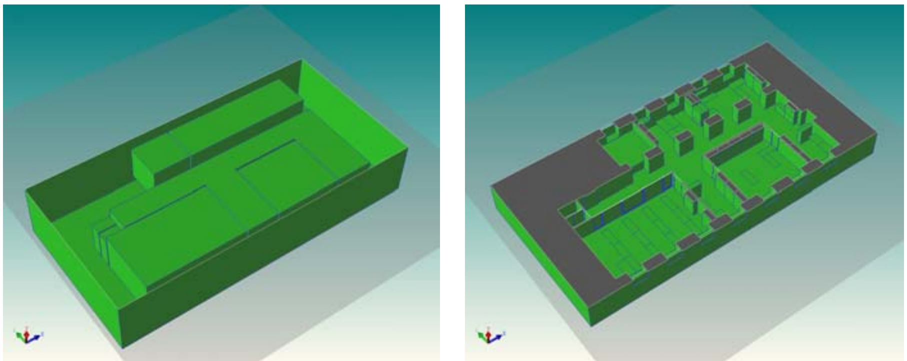

Figure 6 Two views of the building representation: space-boundary view (left) and total building model view (right)

REFERENCES

Björk, Bo-Christer. 1992. A conceptual model of spaces, space boundaries and enclosing structures. *Automation in Construction* 1(3): 193-214.

Harter, Andy, Andy Hopper, Pete Steggles, Andy Ward, and Paul Webster. 1999. The anatomy of a context-aware application. *Wireless Networks* 8: 187-197.

Hebert, Martial. 1998. *Shape recognition: recent techniques and applications*. Proceedings of RFIA '98, 15-31. Clermont-Ferrand: Université Blaise Pascal de Clermont-Ferrand.

Hoover, Adam, Dmitry Goldgof, and Kevin Bowyer. 1998. The space envelope: a representation for 3D scenes. *Computer Vision and Image Understanding* 69 (3): 310-329.

Icoglu, Oguz, Klaus Brunner, Ardeshir Mahdavi, and Georg Suter. 2004. *A Distributed Location Sensing Platform for Dynamic Building Models*. In *Second European Symposium on Ambient Intelligence,* eds. P. Markopoulos, B. Eggen, E. Aarts and J.L. Crowley: Vol 3295, 124-135. New York: Springer.

Lopez de Ipina, Diego. 2002. *Visual sensing and middleware support for sentient computing*. Ph.D. diss., University of Cambridge.

Mahdavi, Ardeshir. 2001. Aspects of self-aware buildings, *International Journal of Design Sciences and Technology* 9: 35–52.

Menon, Jai, and Herbert Voelcker. 1995. *On the completeness and conversion of ray representations of arbitrary solids*. Proceedings of the third ACM symposium on Solid modeling and applications, 175-186. Salt Lake City: ACM Press.

Requicha, Aristides. 1980. Representations for rigid solids: theory, methods, and systems, *ACM Computing Surveys* 12: 437-464.

Requicha, Aristides. 1985. Boolean operations in solid modeling: boundary evaluation and merging algorithms. *Proceedings of the IEEE* 73(1): 30-44.

Rosenman, Mike, and John Gero. 1996. Modeling multiple views of design objects in a collaborative CAD environment. *Computer-Aided Design* 28(3): 193–205.

Ryburg, Jon. 1996. *New churn rates: people, walls, and furniture in restructuring companies*. Ann Arbor, MI: Facility Performance Group.

Shapiro, Vadim, and Donald Vossler. 1990. Construction and optimization of CSG representations. *Computer-Aided Design* 23(1): 4-20.

Spatial. 2004. www.spatial.com. Accessed 2 February 2005.

Suter, Georg. 2004. *Tag representations of simple polyhedra* [Technical Report]. Vienna: Vienna University of Technology.