Developing a Spatial Context-Aware Building Model and System to Construct a Virtual Place

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Abstract: The current notion of space seems to be inappropriate to deal with contemporary and future CAAD applications because it lacks of user and social values. Instead of using a general term called 'space', our approach is to consider the common unit in architectural design process as a place composed of space, user and activity information. Our research focuses on developing a novel intelligent building data model carrying the essence of place. Through our research, the needs of using virtual architectural models among various architectural applications are investigated at first step. Second, key characteristics of spatial information are summarized and systematically classified. The third step is to construct a semantically-rich building data model based on structured floor plan and the semantic location modeling. Then intermediate functions are created providing an interface between the model and future applications. Finally, a prototype system, PlaceMaker, is developed to demonstrate how to apply our building data model to construct virtual architectural models embodying the essences of place.

1. INTRODUCTION

1.1 Space vs. Place

Space is the basic element a designer starts with while designing any object. The first scratch on paper of sketchpad in CAD system is about space and it organization both in 2D and 3D. (Mourshed, Kelliher, et al., 2001) Due to this fact, architects usually refer their works to building design processes.
containing space and spatial configurations among building components. This notion of space, nevertheless, seems to be inappropriate to deal with contemporary and future CAAD applications because it lacks of user and social values. They are crucial since building design is a complex process involving knowledge not only of the building or the built environment but also the user organization activities. (Ekholm 2001) In addition, digital convergence brings about the mergence among distinct disciplines such as computer science, medical science and entertainment into environment in which architecture is located. A lot of researches and studies have been done to investigating a new kind of interaction between space and users so called “Human Space Interaction”. Consequently, these increase an important role of user entity in architectural design. Architecture described by conventional building data model in CAAD domain has to be modified or supplemented. Instead of using a general term called ‘space’, our approach is to consider the common unit in architectural design process as a place. Places differ from mere spaces in that they embody social and cultural values in addition to spatial configurations. It is the concept of place, not space, that connects architecture to its context and makes it responsive to given needs. (Kalay, 2004)

1.2 The need of virtual place

The term ‘virtual place’, here, is differed from Kalay’s definition (Kalay, 2004) in that we interpret virtual place as the output from architectural design process embodying the notion of ‘place’. Hence, virtual place refers to a building model, an instrument for creating a real place. By supplement existing building models, it is feasible to build ‘Spatial Context-aware Building Data Model’ which can be applied to various CAAD applications as described later. ‘Spatial Context-aware’ means that the established data model conveys rich information regarding context that can describe what can happen in a space which could not be provided in traditional building model. In particular, the created data model is not only for representing the physical objects but also for embodying spatial information in various levels: component level, space level, and building domain level. In other words, it contains spatial reasoning. Based on this basic spatial context structure, the developed intermediate functions serve as an interface between building model and applications. As a result, the level of intelligence and interactivity of architecture can be leveraged on the application level. This brings about change in the status of architecture to be more dynamic and enhancing the efficiency in the architectural design. This paper, above all, reveals a research on developing a novel intelligent building data model carrying the
essence of place. In turn, the output of architectural design process is indeed considered as a virtual place.

1.3 Methodology

Throughout our research, the needs of using virtual architectural models among various architectural applications are investigated at first step. Second, key characteristics of spatial information are summarized and systematically classified. The third step is to construct a semantically-rich building data model based on Structured Floor Plan and the Semantic Location Modeling. Then intermediate functions are created providing an interface between the model and future applications. Finally, a prototype system, PlaceMaker, is developed to demonstrate how to apply our building data model to construct virtual architectural models carrying the essences of place.

2. RELATED WORKS

In this chapter, some related and relevant researches assisting the development of spatial context-aware building data model are investigated and explained.

2.1 Building product models

In order to create a spatial context-aware building data model, it is necessary to build the model by supplement existing models instead of starting from the scratch. Here, building data model slightly differs from building product model (Eastman, 1999) in that building product model is potentially a richer representation than any set of drawing can be implemented in multiple ways. In particular, it is mainly developed to set up a standard for seamless interoperation among CAD/CAM applications focused on drawing using by stakeholders in building design and construction processes. On the other hand, building data model refers to an object-oriented data structure maintaining the relationships among spatial components focused on modeling for architectural design purpose. Both can be concurrently considered as spatial modeling. Among them, Björk (1992) used physical obstacles to define a space based on its complete separation from the others. Eastman and Siabiris (1995) constructed their spatial model based on three major components; constructed form (material), bounded space and activity. Ekholm and Fridqvist (1997) proposed a complicated model focus on construction entity. None of them, however, embodies the full essence of a
place described as the relationships among space, users, objects and activities. In spite of previous models, the theoretical framework used in this development project is based on Choi’s ‘Structured floor plan’. Choi suggested a model composed of building components and spatial information. The model suits for constructing spatial-context aware ability because of its semantically-rich structure carrying spatial topological network and real-time editing capability.

2.2 Structured Floor Plan

‘Structured floor plan’ (Choi, 1997) is referred to a floor plan composed by the designer in which its components are well structured and thus effectively express its architecturally meaningful structure. The key issue of this study is to construct semantically-rich architectural forms with minimum input from the designer in the interactive, instant, automatic manner. It is also an important issue to manage spatial design information as well as information about building components. According to this research, managing both types of information, spatial and formal is very important for any intelligent architectural CAD systems. Our research is developed based on the knowledge of this research.

2.3 Semantic Location Modeling

Another related project is the development of ‘Semantic Location Model’. (Lee, Lee, et al., 2004 & Lee, Choi, et al., 2005). This project is also developed based on the concept of Structured Floor Plan. The developed model embodies geometrical and topological information focusing on entity location. The structured floor plan functions as the fundamental data structure suitable for applying the concept of context-aware system since all building components have been bound each other with their spatial relationships. The developed prototype is capable of defining architectural
spaces appropriately and managing them easily for constructing the ubiquitous computing environment. Given an inhabitant position, the system can trace and report the semantic location rendering the spatial relationships between the user and the space such as orientation of user’s eyes, the closest spatial components; opening, wall and column. Our spatial context-aware building data model is developed based on this system.

3. SPATIAL CONTEXT-AWARE BUILDING DATA MODEL

This paper proposes a new spatial context-aware building data model based on our previous research. The kernel of our data model is structurally well-defined and contains hierarchical components. Each component is composed of geometric and spatial information pursuing the interactivity with environment in certain situations. In particular, the model is ‘Semantically-rich’ which means that the established data model conveys rich information regarding context that can describe what can happen in the space. Here, we consider a building in terms of its functional properties and structural components, and these alone or in combination will be referred to as building semantics. (Babalola, Eastman, 2001) As shown in figure 3, what differential our model from the others is that the created data model is not only for representing the physical objects but also for embodying spatial information in various levels. Our data model is composed several modules providing different functions. Total model, spatial context-aware building data model, comprises of three sub models; building data model, object data model and spatial data model. The details and functions for each model are explained as follows;

Figure 2. The conceptual level of spatial context (Left) and the graphic user interface of PlaceMaker (Right).
3.1 Building Data Model

Mostly derived from structured floor plan, this object oriented data model contains the spatial information of building components and space. The hierarchical relationships are constructed from building (the largest entity) to surface (the smallest entity). Among them, space is the most important class acting as a hub. It connects the entities inside building data model with spatial data model and object data model. Another powerful characteristic is topological network. The spatial relationships among spaces and among building components are stored automatically once spaces have been instantiated.

3.2 Object Data Model

Object refers to furniture, appliances, lighting and equipments that can be utilized a place. Due to the distinction in stored information and mobility, we separate object data model from building data model. However, the relationships with other models are also maintained through space and activity class.

3.3 Spatial Data Model

The model provides novel characteristics enabling context-aware capability, particularly, in order to convey an essence of a place. It combines other models and constructs spatial reasoning. The model contains building type domain and space type characteristics indicating characteristic for space, user and activities that could be happened in a place. The main members of spatial data model are described as follows;

- **User and user group entities**: they provide all user information which can be transferred to avatars or agents in the system. As discussed in the introduction, user entity is one of the major missing parts in conventional architectural building data model. In order to establish the model capable of dealing with human-space interaction or human-centered design, this entity is crucially needed. User entity also includes behavior information empowering an ability to let agents or avatars perform predefined actions in certain contexts.

- **Location entities**: these entities provide the both semantic and geometric relationship among objects, buildings and users in a place stored as a location. Key location entity stores geometric locations of activity. Based on semantic location modeling, semantic location entity contains semantic relationship of each object in our data model. Location entities are
the key component for location based service in which tangible user interface is applied in space.

- **Activity entity:** The concept of activity embodies the characteristic of ‘place’ since it contains and combines user, place, location and action. Like space in building data model, activity is the main class of spatial data model connecting with other data models.

- **Spatial domain and space type entities:** These entities, basically, provide the information of each type of building and space having different attributes and constraints. Serve as libraries during the design process; it helps architects to create places rigorously.

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**Figure 3.** The spatial context-aware building data model.
4. SPATIAL CONTEXT-AWARE HIERARCHY

Apart from the data structure described previously, the detail of spatial context-aware hierarchy is discussed in this section. The essence of our research relies on the way spatial context is bound with each instance. According to the structure of spatial context-aware building data model, such spatial context can be divided into three levels; component level, space level and building domain level as shown in figure 4 (left).

1. **Component level:** component refers to object entity and building components such as door, window and wall in spatial context-aware building data model. In turn, each object can has its spatial context which contains its attribute, location and user. Unlike space and building domain level, components have their behavior to interact with other instances. Constraint and spatial connectivity are not included in this level.

2. **Space level:** This intermediate level is the most critical part in spatial context hierarchy. Space level provides all spatial contexts; attribute, constraint, user, activity, location and spatial relationship among its components. Figure 4 (right) shows the example of spatial contexts for a living room.

3. **Building Domain level:** This top level contains spatial context of a whole building. Different building domains have their own spatial context such as constraints and properties. It also embodies the relationship among spaces or rooms within the building.

For each level, spatial context can be divided into sub categories; attribute, constraint, user, behavior or activity, location and spatial connectivity. **Attribute** stores the basic properties of an instance such as color, size and area. **Constraint** contains the rules for spatial configurations. For example, a room must contain at least one door. Location stores the positions of each instance. It refers to both geometry and semantic location. In particular, **key location** stores geometry position for each activity. **User** means the possible users for such instance. Consequently, some components may have behaviors to interact with user whereas space and building domain will have their information of possible activities. Finally, **connectivity** means the relationship among instances in one space or among spaces with the same building.
5. **PLACEMAKER: A SPATIAL CONTEXT-AWARE CAAD TOOL**

For the sake of system evaluation, our semantically-rich object oriented CAAD tool, **PlaceMaker**, has been developed to demonstrate how the intelligent building data model bound with the spatial context can be applied. As a user creates a component, spatial context is automatically generated from library along with the geometric data. The system is designed to be capable of elaborating various kinds of building domain and space type. Buildings created within different domain contain different spatial characteristic and spatial context. Figure 5 shows the entire interface of PlaceMaker. Currently, there are three mode of visualization; two-dimensional mode, three-dimensional mode and print mode. Users can freely switch the visualization mode back and forth among all modes. The functions for each mode are described as follows;

5.1 **Two-dimensional mode**

By default, two-dimensional mode (2D mode) is set as an input mode. Here, a user can create a space by drawing enclosed walls. A space can be composed of building components such as wall, opening, furniture as described in spatial context-aware building data model. All instances can be modified through their parameters in real-time manner from dialogs. All basic CAAD modeling and operation tools are also provided. Unlike other modeling tools, users have to bind each space with spatial context by specifying space type from space dialog. Once the spatial context has been bound, some spatial functions can be performed to gain benefit from spatial
context-aware building data model. Such functions and benefits will be explained in next section.

5.2 Three-dimensional mode

Basically, three-dimensional mode (3D mode) is used for simulating three-dimensional environment especially when a building contains more than one story. A user can also navigate the created space through walk-through function. A human-like agent can be inserted here to perform specific functions and simulations such as 3D way-finding. By means of procedural modeling technique, various types of visualization can be displayed in this mode. This will be described in details in the following section.

![Figure 5. The graphic user interface of PlaceMaker: 2D mode (left) and 3D mode (right).](image)

6. THE BENEFITS OF SPATIAL CONTEXT ON CAAD APPLICATIONS

By means of the spatial context in our spatial context-aware building data model, several useful features are developed and utilized. Note that such features can also be employed in other applications. So far, we have been developing some simulation tools utilizing building model created by PlaceMaker containing spatial context and spatial reasoning information. Apart from architectural modeling tool, figure 6 shows brief benefits of spatial context-aware building data model upon several CAAD applications; evacuation simulation tool, ubiquitous computing space scenario design tool, facilities management tool as well as other structure and energy simulation tools. This section explains how to apply those intermediate features through spatial functions in PlaceMaker. They are grouped into four categories;
constraint-based design, spatial network, context awareness and procedural modeling.

Based on ‘Building Complier’ (Park, Choi, 2003), the constraint-based design shows how to gain benefits from spatial attribute for each instance in spatial context hierarchy. Since our data model contains much information in depths, such information can be used for setting the constraints enhancing the efficiency in architectural design and simulation. For example, one can set a constraint for a toilet according to building code. A toilet must have a door and at least an opening for ventilation. If a user creates a toilet without any opening, the system will check the design with stored constraints and let the user know about the violation. This will be done after the user perform building compile functions. In short, the 2D and 3D building models can be created according to the constraints previously set by a user. Note that this building compile function is still under construction. Figure 7 shows the graphical user interface for this function.
6.2 Spatial network

The relationships among architectural components can also be easily traced. Spatial network refers to the spatial relationship among space and objects as shown in figure 8 (left). Such knowledge can bring about the applications of way finding, architectural simulation as well as constructing the multi-story spatial connectivity. Our data model supports multi-story buildings. That means spatial context and network are maintained throughout the whole building by means of stair entity. Consequently, it is possible to perform multi-story simulation such as three-dimensional wayfinding as shown in figure 8 (right). In particular, a path from one to another location can be rapidly traced. Our system can analyze all possible paths and the shortest path. Thus it can be applied to both a simple spatial exploration application and an advance pedestrian simulation system.
6.3 Context awareness

As mentioned earlier, user information is the main part to design a place as well as to pursue human space interaction. Thus, user context, primarily focused on activity and location, plays the key role for elaborating context awareness capability. Activity entity combines all information from user, space and location to form a place. In other words, it is possible to retrieve information about available activities, their locations and users which are useful for any context-ware or location based systems. Figure 9 (left) shows a snapshot when a designer creates an activity and defines its key locations. As shown in activity dialog (see Figure 9 middle), key location refers to a set of location to perform an activity stored in each object including space in our database. Each instance can have more than one key location set to perform different kind of applications. It can also be used by another simulation such as lighting calculation, evacuation simulation as well as scenario simulation. Furthermore, our system can deal with the dynamic user location by integrating semantic location with agents or avatars. However, this feature is still under construction. As shown in figure 9 (right), possible path for each user can be visualized since each activity also include its users. Above all, activity data encompassing the information of location, user and time is created and linked with a space providing spatial context awareness capability and the essences of place.

![Figure 9. Snapshot of activity and key location (left), activity dialog (middle) and graphical user interface of user tracing function (right).](image)

6.4 Procedural modeling

Since our data model contains semantically-rich information, the concept of procedural technique is also implemented to deliver only the relevant
information to users according to their needs. Based on the same data internally stored, our system can generate different types of visualization suitable for handling with complex information. Figure 10 shows different type of visualization in 3D mode; full model, half model and half-paper model modes. Full model mode is suitable for normal visualization and walkthrough function. In contrast, half mode and half-paper mode are appropriated for 3D simulation that needs to observe the interior spaces among stories such as evacuation simulation.

![Figure 10. Snapshots of full model mode (left), half model mode (middle) and half-paper model mode (right).](image)

7. **CONCLUSION**

In this paper, a new characteristic of building data model containing spatial context and spatial reasoning has been firstly introduced. Through PlaceMaker, numbers of intermediate functions are developed to gain the benefits from such spatial context. Figure 11 illustrates the conceptual diagram of spatial context-aware framework for building design and simulation. Moreover, the output building models can also be imported and used by other tools. In addition, a set of applications has been applied to verify those benefits of our intelligent building data model. In fact, “XML” parsing module will be integrated to provide interoperability with other CAAD tools in further development. At the moment, 3D building models generated by PlaceMaker can be imported into “V-Placelab” (Kim, 2006) as a smart virtual place (stage) for simulating scenarios to utilize ubiquitous computing interior space. As shown in Figure 12, snapshots of V-Placelab reveal the utilization of activity, key location and spatial connectivity. By means of these spatial contexts, the demonstrated projects render the advantages of our building data model. As the level of semantically rich information is increased, the interaction among agents including inhabitants, space and building services can also be leveraged. Thus, the efficiency in architectural design is also improved. Not only restricted to the scenario
simulation system, but our semantically-rich data model can also be applied with other CAAD domains including computer aided facilities management, data driven simulation and ubiquitous computing space design.

Figure 11. The conceptual diagram of spatial context-aware framework.

Figure 12. Snapshots from a Scenario Design tools called V-Placelab.

8. ACKNOWLEDGEMENTS

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9. REFERENCES


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