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Generalized Descriptions for the Procedural Modeling of Ancient East Asian Buildings

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Abstract
Many ancient East Asian buildings are noted for their immense beauty and intricate design. We introduce a graphics modeling library based on a generalized procedural description we formulated to describe East Asian architecture. By setting the desired parameters, a user can create a building in any of the many different styles, such as Chinese, Japanese or Korean. Different building types, such as palace halls, commoner houses, temples, pagodas, pavilions, ceremonial gates and fences, are described by our modeling system. This large range of traditional East Asian styles and structures is significantly more than those supported by existing systems.

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1. Introduction

Traditional East Asian architecture has rich aesthetic value, and many historical sites have been designated UNESCO World Heritage Sites. To study and preserve these sites, researchers have begun to build graphics models and digital descriptions of these ancient buildings. For example, the Virtual Forbidden City project (www.beyondspaceandtime.org), a partnership between the Palace Museum and IBM, allows users to immersively explore a virtual 3D model of Beijing's Forbidden City. Furthermore, because of the beauty of ancient East Asian architecture, many fantasy worlds in 3D computer games and movies require the construction of elaborate 3D models of East Asian architecture.

We have developed a procedural modeling system to create buildings in ancient East Asian styles. We have formulated a description of the basic elements of traditional East Asian architectures, so that a user can quickly create buildings based on these architectural styles. Ancient Chinese, Korean and Japanese architecture share many common characteristics and yet have fundamental differences. We show that, by varying some parameters, users can conveniently create buildings of the different styles using our graphics modeling library.

In this paper, we show examples of palaces, houses, gates, temples, pagodas, pavilions and fences created with our system. By setting the dimensions and parameters of a building, the user can create 3D models of most of the existing ancient East Asian building structures, and can also create novel ones using different parameters.

The main contributions of our work include: (1) the formulation of a generalized procedural model that is able to describe a wide range of traditional East Asian architecture, including Chinese, Korean and Japanese temples, palaces, houses, ceremonial gates, pagodas and pavilions, and (2) the construction of procedural 3D models of roofs and brackets with unprecedented realism. The generalized mathematical descriptions of the roofs of the different styles quantifies the differences between the different artistic styles, for example, contrasting between the Japanese and the southern Chinese styles.

Compared to existing systems, our system is particularly useful for two important purposes: (1) by setting the parameters, the artist can control the shape of the building, to design a building in any one of the many East Asian styles, and (2) by randomly setting different shape parameters, a program

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can efficiently create many different buildings of the same style with different variations in appearance

2. Related Work

Procedural Modeling is a very effective method to efficiently create realistic 3D models of many objects, and there are many existing work on procedural trees, plants, terrain and cities. Birch et al. [BBJ*01] introduced one of the earlier works on procedural modeling of architectural structures. They are able to generate many different 3D models by using a large library of prototypes. They also describe window-splitting and curve-generation components, as well as integration with a scene-graph.

Chan et al. [CTDQ03] modeled the Temple of Heaven in Beijing, as part of the effort to preserve historical architectural knowledge. This project did not make use of procedural modeling, instead they relied on taking photographs of perpendicular elevations of the buildings.

Liu et al. [YCZY04] described their semantic modeling project, where they built 3D models of vernacular houses in the Southeast China style. In their paper, they emphasized the importance of creating digital architectural models for the understanding and preservation of cultural heritage. They are able to model the vernacular house to significant detail, with elements like roofs, windows, and various types of walls.

Liu et al. [LWH*05] introduced a procedural modeling technique based on Chinese Ancient Architecture design theory. They formalized the design patterns into a set of Constructive Grammar rules. They are able to generate some buildings in the traditional Chinese style.

Wonka et al. [WWSR03] presented a method for modeling architecture using split grammars. These split grammars are able to generate non-trivial volumetric shapes. They set up a large database of rules and modeled different designs from the same rule database. With a parameter-matching system, users can specify high-level design parameters to influence the output. They also introduce control grammars, which grow buildings according to architectural principles. Lipp et al. [LWW08] later extended this work to create user-friendly interactive tools that allow the artist to interactively edit and control the output of the grammar-based procedural architecture system.

CGA shape [MWH*06] is a shape grammar introduced by Muller et al. It has production rules that iteratively generates building models with increasing detail. This powerful grammar is able to generate complex building models not restricted to axis-aligned shapes, and includes advanced roof surfaces. They are able to create buildings and streetscapes with buildings of varied designs and styles of significant complexity and realism.

Our system is the first to formulate a unifying mathematical model able to describe the structures of the vast majority of Chinese, Korean and Japanese temples, palaces, houses, ceremonial gates, pagodas and pavilions. This is a significantly more extensive procedural description of East Asian architecture than that provided by existing work. Our work also models complex East Asian roofs with much more detail than other existing systems dedicated to East Asian architecture.

3. Modeling East Asian Architecture

Our system is based on traditional East Asian architecture principles, as described in books such as *Great Architecture of the World* [Nor75], which explains the historical origins of Chinese, Korean and Japanese architecture, and how they are related. We also note examples of historical buildings. Ancient official Chinese architecture, for example, all follow strict rules laid out in *Yingzao Fashi* (circa A.D. 1100). During the Tang Dynasty in China, Chinese architectural styles began to influence Korea and Japan, and this forms the basis of virtually all major existing traditional Korean and Japanese palace and temple architecture. Throughout the following centuries, architecture in different parts of East Asia evolved differently, and developed their unique styles, and we highlight some of these differences in this paper.

The basic structure of our model is shown in Figure 1. From these basic components of a storey, a general building can be built by specifying the parameters or presence of each component of each storey. For each storey, the various components are optional. For example, to create the double roof of the fourth storey of the Japanese pagoda shown in Figure 6, we actually create two storeys, with the upper one having no walls. To create a storey that is supported by bracketed beams, simply create another storey below it with no walls and no roof. An example is the third storey of the Japanese pagoda shown in Figure 6. The optional panel component of the top beams is used for example in the Chinese gate shown in Figure 13. The diagram also shows in parentheses the three different types of top beams supported by our system.

Some of the basic parts, such as the roof and wall, of a general building structure is shown in Figure 2. The *width* of the building defines the width of the building up to the wall. The user sets the positions of additional parts of the building, such as the external pillars, beams, floor and roof, by setting the *margin* parameters, labelled on the diagram. For example, the *floor margin*, defines the distance between the wall and the edge of the floor.

3.1. Basic Roofs

The roof is one of the most important but complicated parts of a traditional East Asian building. Virtually all traditional East Asian roofs are slanted. Together with the intricate bracketed beam structure, the roof is the most ornate and aesthetically important part of major buildings. We have formu-

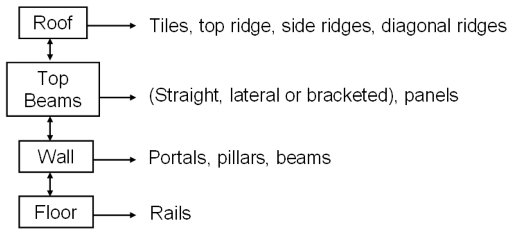

Figure 1: *Basic structure of a storey: Each component is optional, for example, some storeys do not have a wall or a roof.*

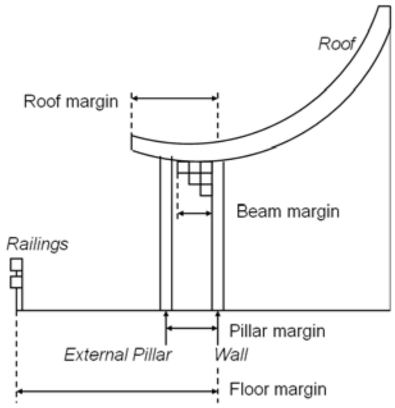

Figure 2: *Some basic parts (in italics) of a building structure, and the margins set by the user*

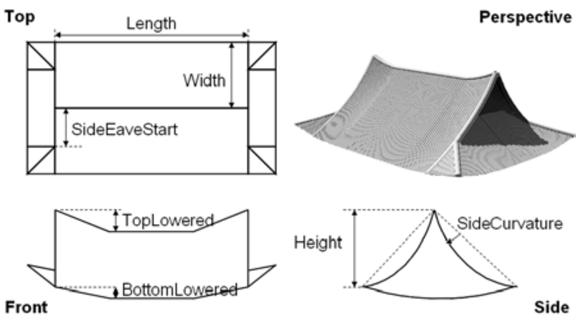

Figure 3: *Model of a general roof: Some user-defined parameters are listed.*

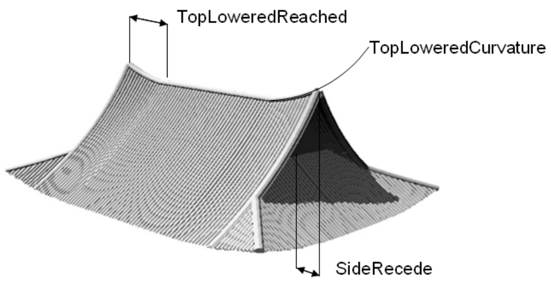

Figure 4: *More user-defined roof parameters*

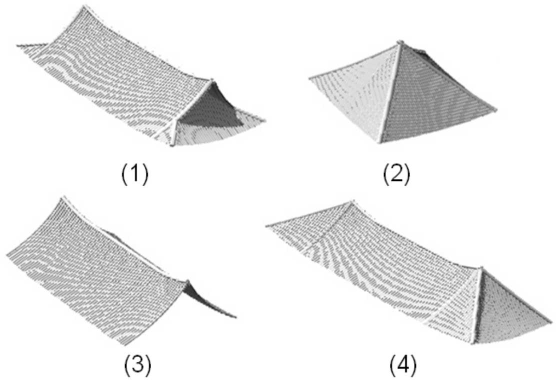

Figure 5: *Basic types of roofs: (1) Regular double-sided roof, (2) Special case: Length=0, SideEaveStart=0, (3) Special case: SideEaveStart=1 (no side eave), and (4) Special case: SideEaveStart=0*

lated a versatile generalized description of the roof, shown in Figure 3, that covers the vast majority of East Asian roofs. The figure shows some of the parameters that can be set by the user to control the appearance of an individual roof, such as *Length*, *Width*, *Height*, *SideEaveStart*, *TopLowered*, *BottomLowered*, and *SideCurvature*. *TopLowered* refers to the difference between the height at the side of the roof and at the middle of the roof, since many palace and temple buildings raise the roofs at the sides.

There are some additional related parameters the user can set, shown in Figure 4. For example, the user can set *TopLoweredReached*, which specifies the distance from the side that the roof first reaches its lowered height, and also *TopLoweredCurvature*, which specifies whether the slanting part of the top ridge is straight or curved. Another user-set parameter, *SideRecede*, specifies the distance the side roof wall recedes from where the side eave meets the main eave. Similarly, the parameters *BottomLowered*, *NottomLoweredReached* and *BottomLoweredCurvature* determine the shape of the bottom edge of the roof.

Figure 5 shows the four basic types of roofs found in East Asian buildings. Roof Type 1 is a double-sided roof design that is commonly used for important palace and temple buildings. This design consists of a triangular prism on top of a rectangular frustum. In our roof description, we use the double-sided roof as the general roof design; the other three basic roof types are simply special cases of the general roof design.

Roof Type 2 is a pagoda roof, a regular pyramid. This is accomplished by setting Length=0 and SideEaveStart=0. To create a pagoda/pavilion roof which is not four-sided, such as the one shown in Figure 6, the user specifies the height, radius and number of sides of the roof. Roof Type 3 is a single-sided roof commonly used in houses and simple buildings, and a model is constructed by setting SideEaveStart=1 (no side eave). Finally, Roof Type 4 is a double-sided roof where the side eaves extend all the way to the top. This design is also used in some palace buildings such as the Tang Dynasty Ta-Ming Palace.

By controlling parameters such as Length, Width, Height, Curvature, and SideEaveStart, a designer can create roofs with a wide variety of styles. Figure 6 shows an example of the contrast between a Japanese pagoda and a Chinese one. The Japanese roof is typically straighter, and is four-sided, in contrast to Chinese roofs, which are often six- or eight-sided. Chinese roofs also tend to have more elaborate ridges. A ridge is a thick elevated tube on the roof. For the basic Type 1 roof, there is typically one ridge that runs across the top of the roof. There are ridges down the sides of the upper prism part of the roof, and there are ridges down the diagonal that separate the four sides of the lower frustum part of the roof. These ridges are labelled in Figure 9.

Ridges and other decorative items such as finials can be added to the 3D model by artists. Artists can import custom-designed 3D models to make even more elaborate structures, and display these models through the *MakeFinial()* and *MakeRidges()* procedures. In Figure 6, for example, a typical nine-ringed finial has been constructed to top the Japanese pagoda, while a lotus bud finial is made for the Chinese pagoda. Another notable difference in styles is that white and plain walls are common in Japanese and Korean halls and pagodas, but never in Chinese ones. User-set colors and textures are used to further enhance the difference in styles. In this example, white walls and red beams and pillars are used on the Japanese pagoda, while darker wood is used on the Chinese one. In general, white walls and red pillars are common in Japanese temple buildings, while Chinese buildings are often a darker shade of wood, or are sometimes built with stone or brick instead of wood.

For multi-storeyed buildings, the lower floors often have eaves extending from their ceilings. These eaves are like truncated roofs and are therefore made with the same basic structure in our models, except that a *FloorStart* parameter controls where the roof ends.

Figure 8 shows how a description of a curved roof is derived from user-set parameters. From the Width and Height dimensions set by the user, the angle that the straight roof makes with the horizontal plane θ is obtained. The user sets the desired curvature α of the roof.

The program then calculates the center and radius of the circle that circumscribes the curved slanted roof, according to the formulae given in Figure 8. The top of the roof is taken to be the origin. When the circle center (C_x,C_y) and radius R that describes the rounded roof has been found (according to Figure 8, given the distance d from the top of the roof, the height h of the point on the roof is given by:

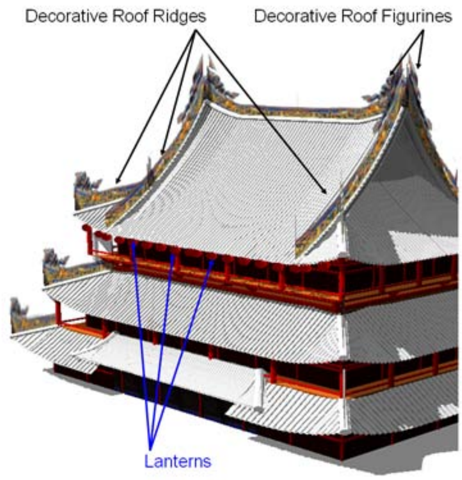

Figure 7: *The user can import custom-designed models for for decorative roof figurines, ridges and lanterns. Such elaborate designs are common in temples in Southern Chinese style.*

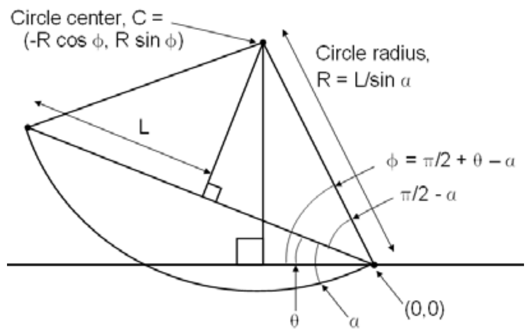

Figure 8: *Modeling a curved roof: The straight roof makes an angle θ with the horizontal plane, and the user sets the curvature α. The program calculates the Circle Center C and Radius R*

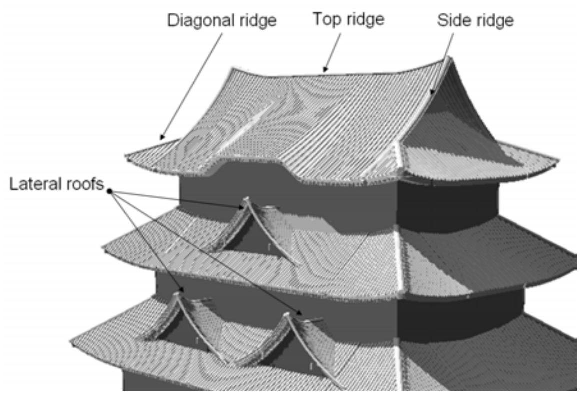

Figure 9: *Japanese roof with raised arch and auxiliary perpendicular roofs, modelled after the Himeji Castle*

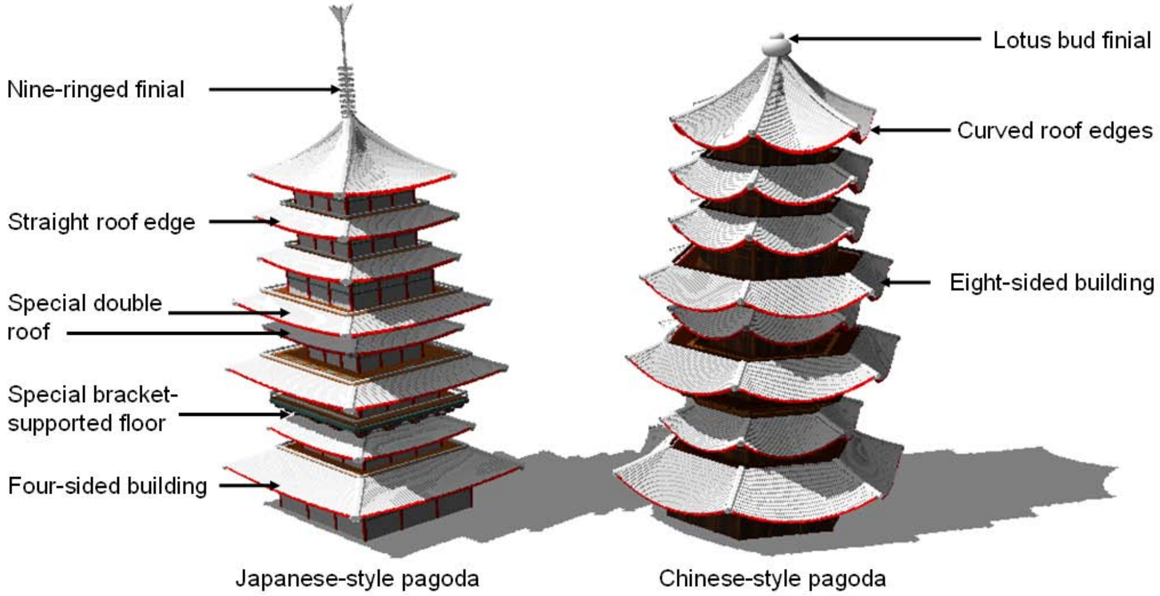

Figure 6: *A Japanese pagoda (left) is typically four-sided, has straighter roofs, and has a nine-ringed finial. A Chinese pagoda (right) can be eight-sided, often has a lotus-bud finial, and has more elaborate roof ridges.*

$$\theta = asin((C_x - d)/R) \quad (1)$$

$$h = C_y - rcos(\theta) \quad (2)$$

Note that the top and bottom lines of the roof are not necessarily straight, as shown in the lower Front elevation diagram in Figure 3. Therefore, our program creates many circles to describe the curved roof along the entire length of the roof. At each point along the length of the roof, the top and bottom coordinates are found, and are used to obtain the Height of the roof at that point, and then to calculate the circle as described above.

In temple buildings, Japanese and Korean roofs tend to be straighter, simple and elegant. Northern Chinese roofs are slightly curved, while southern Chinese temple roofs tend to be even more curved and have very elaborate carvings of dragons and other animals on the roofs.

Our system does not create these elaborate carvings, instead it is up to the artist to design these models using existing tools and import them. Also, southern Chinese temples tend have colorful and complex designs on their walls, pillars and beams as well. Figure 7 shows the import of models to add decorative ridges, figurines and lanterns on southern Chinese style temple buildings, common in some places outside Mainland China such as Taiwan and Singapore. Our system does not generate these custom-designed components procedurally, but support the import of textures. As another example, the Chinese Gate shown in Figure 13 uses some imported textures.

3.2. Special Roofs

While the basic roofs described above describe the vast majority of East Asian roofs, some modifications need to be made to include a few special types of roofs.

First, some Japanese roofs have a raised arch in the center. This is shown in Figure 9, modelled after the Himeji Castle. The top roof in this building has an example of a raised arch. To create and model the raised arch, the user specifies the (1) *Height*, (2) *StartCurve*, and (3) *EndCurve* of the raised arch. Along the edge of the bottom line of the roof, from 0 to StartCurve, the bottom line is not modified. From StartCurve to EndCurve, the bottom line is increased by $Height \times (0.5 + 0.5 \times sin(\pi/2 + \pi \times (x - StartCurve)/(EndCurve - StartCurve)))$, where x is the coordinate along the bottom line of the roof. From EndCurve to the miNon-Photorealistic Rendering Applied to a Commercial CAD Systemddle of the roof, the bottom line is increased by *Height*.

Figure 9 also shows auxiliary perpendicular roofs in the lower storeys. These additional roof additions are sometimes found in East Asian palace and temple buildings. They are simply modeled as regular roofs and then juxtaposed with the main buildings. These auxiliary roofs can be found in many of the larger buildings in China, Korea and Japan.

Another modification is the rounded roof-top. Some Chinese buildings, such as traditional commoner's houses in Beijing, have rounded roof-tops. An example is shown in Figure 10. To model such a roof, the user sets the *WidthRound*, which specifies the width of the rounded part of the roof. The program finds the angle the original roof makes with the horizontal plane at that width. A circle segment is then fitted to make the rounded roof. Figure 11 explains how this circle is found.

When the circle center (C_x,C_y) and radius r that describes the rounded roof has been found, given the distance d from the top of the roof, if $d < WidthRound$, then the height h of the point on the roof is given by: $h = \sqrt{r^2 - d^2}$.

The example of a commoner's house in Figure 10 also shows the Side Wall, an optional feature in a building with a Type 3 roof. Side Walls that go all the way up to the roof-top are usually not found in large, ornate temple and palace buildings, but are often found in houses.

Another modification we allow is to create gaps in the roofs. Many East Asian temples have a gap in the first-floor roof above the main entrance. This is to create a grander and higher main entrance. Often, the entrance has an elevated roof, higher than the regular roof. This is shown in Figure 12. By calling the procedures *SetGap* and *SetElevatedRoof*, and setting the dimensions of the gap and elevated roof, a user can create the entrance shown in the figure.

Gaps in the roof are also convenient for modeling another structure: the Chinese ceremonial gate, an important structure found at the entrances to major ancient Chinese towns and important monuments. Chinese gates are also a familiar feature in historic Chinatowns in the West. An example is shown in Figure 13. This Chinese gate has three "storeys". The lower two storeys each has a gap. In this way, a Chinese gate can be modeled using the basic building structure, by setting gaps, and setting the *drawWall* flag to "no". For this gate, the artist has also added additional decorative panels and imported textures for the panels.

3.3. Beams and brackets

The system of wooden beams and brackets is a hallmark of East Asian architecture. We have created a procedural system that models the standard bracket system. The user specifies the following parameters: (1) *BeamMargin*: the horizontal distance between the wall and the outer-most beam, (2) *NumBeams*: the number of beam/bracket levels, and (3) *BeamWidth*: the width of the beam as a fraction of the width allocated for each level. Given these parameters, our system will find the height of the roof at the BeamMargin, and then calculate the positions of the beams and brackets accordingly.

The system creates beams extending from the walls outwards and upwards towards the roof. The user specifies the

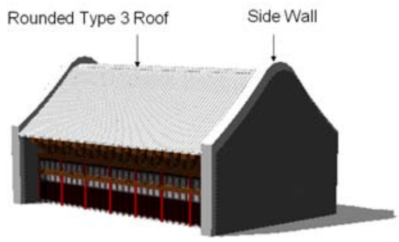

Figure 10: *A Chinese commoner's house showing rounded roof-top*

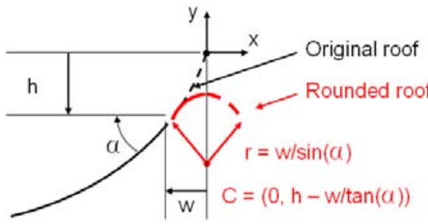

Figure 11: *The user specifies d=WidthRound, the width of the rounded roof. The program finds h and α and the finds C and r, the circle describing the rounded roof.*

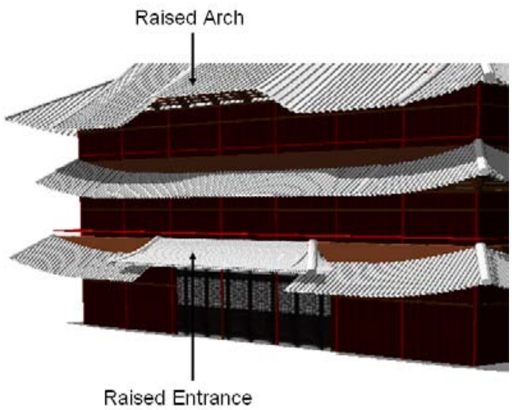

Figure 12: *Modification to allow a gap and raised roof on the first floor*

Figure 13: *This three-storeyed Chinese gate can be described by the general procedural building.*

Figure 14: *Colorful beams and brackets characteristic of Korean temple buildings. This example also shows a storey supported by bracketed beams.*

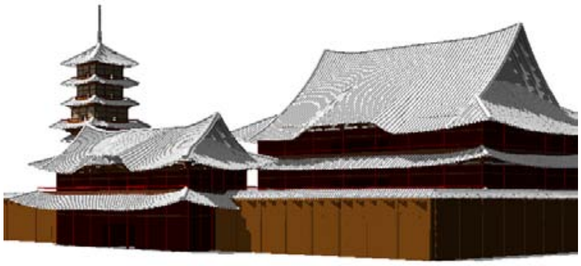

Figure 15: *A Japanese temple enclosure showing a gate and fence in the foreground*

positions along the walls to construct the brackets, and at each position, the system creates a series of brackets that support the beams up to the roof. At the corners of the building, additional brackets are constructed at 45-degree angle outwards. Examples are shown in Figure 14.

A simple bracket consists of a base, with one arm extending to the left, and another extending to the right, along the wall. The third arm extend outwards from the wall. The outer tip of an arm either supports a beam or another bracket base. In this way, a system of brackets grow upwards and outwards, to support the roof.

Temple and palace buildings often have elaborate and unique bracket designs, although the vast majority of them are built in the same structure. One characteristic of many Korean buildings, for example, is their unique colorful brackets and beams. Our system only creates the structure of the brackets. The position, dimensions and orientation of each bracket is generated and fixed by the program, and each bracket is drawn using the *DrawBracket* function. To create brackets with custom appearance, the artist simply imports the custom-designed bracket 3D model and draw that model in the *DrawBracket* function. An example of Korean-style beams and brackets created by importing textures and modifying the geometry is shown in Figure 14.

Other simpler buildings such as small houses, hallways and pavilions do not use the bracket structure described above. Instead, they use simpler lateral or straight beams, sometimes with decorative structures. For each building, the user specifies the roof-beam type to use: (1) bracketed, (2) straight, or (3) lateral.

3.4. Other Building Types

Our generalized description of traditional East Asian buildings can be used as a template to create procedural models of a wide variety of ancient building types, such as pagodas and halls described in previous sections.

The pavilion is another common structure found in Korean and Chinese scenery, often as an integral part of a garden. Our sytem models pavilions as a special case of pagodas, except that the *drawWall* flag is set to “no” so that no walls are created. Typically, the beam structure used for a pavilion is the simple straight un-bracketed beam, and pavilions are usually single-storeyed with either one or two roof layers.

Figure 15 shows a Japanese temple complex with an entrance gate and fence in the foreground. On the exterior, this style of Japanese entrance gate is not very different from a regular Japanese hall. The major difference in the structure is that gates are typically smaller and much narrower than halls, and have wide open doors.

The corridor is another building type. Unlike regular buildings, the corridor need not be level or straight. Instead, the user can specify a list of control points for the corridor. Other parameters to specify include the inter-pillar interval and height. The program will construct a corridor along the path specified by the user. A corridor is seen in the foreground of Figure 16. The fence is simply a generalization of the corridor. The program creates a fence the same way as a corridor, except that the *drawWall* flag is set to “yes” so that a wall is drawn. An example of a Japanese fence is shown in Figure 15. Some Japanese and Korean fences have roofs, and some do not, and they are typically wooden. Walls also surround Chinese palaces, gardens, and residences.

We have created a procedure to create each of the basic building types: hall, house, Chinese gate, entrance gate, hallway (corridor), fence, pavilion, and pagoda. These procedures allow the user to set parameters that control the building, for example their dimensions, and the number of storeys.

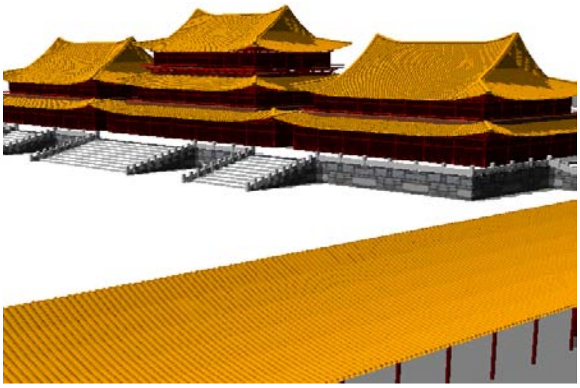

Figure 16: *Chinese palace buildings and corridors with their characteristic yellow-tiled roofs*

4. Future Work

We are currently working on a front-end interactive modeling tool to allow artists to design buildings without needing to access the library of procedures. Simultaneously, we are accumulating a more extensive collection of custom-design decorative 3D models and textures, such as door patterns and roof ridges. These will be useful for creating a large number of buildings with different appearances. Other future work includes modeling the basic building at greater levels of detail, modeling building interiors, and automatic procedural generation of ancient cities.

5. Conclusions

We have introduced a library of procedures for the easy creation of East Asian buildings built in the traditional ancient styles. The procedural description that we have developed also formalizes the structural definition of the rich aesthetics of traditional East Asian architecture. The difference in the range of parameters used in our system is also valuable in quantifying the difference between the different styles, for example, Japanese roofs tend to be straighter than southern Chinese ones. Our procedural modeling system is useful for the efficient generation of East Asian building models for use in 3D games, virtual movie sets, and educational tools to aid cultural preservation.

Compared to previous systems, our system makes the following important contributions. First, we are the first to introduce a general procedural description of East Asian buildings that is able to describe the wide range of building types, such as halls, houses, pagodas, pavilions, gates and fences. Furthermore, these buildings can be built in different styles, from southern Chinese to Korean to Japanese.

Compared to previous work, we also provide a more detailed and accurate models of the complex roof and bracketed beam structures that characterize ancient East Asian buildings. With our system, by calling functions with different parameters, users can instantly create roofs and brackets according to their individual specifications.

In this paper, we have demonstrated the unprecedented wide range of ancient East Asian structures that can be described by our single procedural model. A computer program can quickly create many buildings by: (1) specifying slightly different parameters for each building, such as width, height, roof curvature, number of pillars, and wall colors, and (2) optionally augmenting the appearance of the buildings with a large library of custom-designed geometry and texture for building parts such as doors, beams, brackets, roof finials and roof ridges.

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