ICA$^3$D – Intelligent Computer-Aided Ancient Chinese Architecture Design

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Abstract. ICA$^3$D is an implemented computer aided system that helps user design ancient Chinese architecture. With ICA$^3$D, the user can describe the building he/she wants to see in a domain specific Chinese natural language, and the system automatically generates an animation demonstrating the construction process of this building from scratch. This whole text-to-scene conversion is supported by a set of knowledge bases implemented by the Semantic Web technologies. Currently, ICA$^3$D covers more than 180 different types of Chinese traditional buildings. Compared with normal CAD systems, ICA$^3$D features the automatic generation of animation, natural language style user interface, and scalable knowledge infrastructure.

1 Introduction

Ancient Chinese architecture (Guo, 1998) represents a unique contribution to the world’s architecture heritage, with respect to both its technologies and arts. The complex of ancient Chinese architecture is a grand system incorporating theory, arts and techniques. It is one of the three major schools of world architectural systems. The other two streams are the European and Islamic architecture. The uniqueness of ancient Chinese architecture lies in its wooden structure. The number of ancient Chinese buildings (at least more than 300 years old) worth of protection amounts to 80,000. Among them, 2,541 have been declared by the Chinese government as national historical relics.

Meanwhile, there has been a serious lack of computer supported tools for representing, modelling and designing different forms of ancient Chinese buildings. This was the motivation of our research in designing and implementing the ICA$^3$D system. ICA$^3$D is an implemented computer aided system that helps user design ancient Chinese architecture style buildings. Currently it can support the design work of more than 180 different ancient Chinese architectures ranging from wooden structure, pagoda, Dougong to joinery (Zhang, et al., 2010).

2 The Overall Goals of the ICA$^3$D Project

In spite of the great efforts of Chinese people and government in preserving the ancient architecture buildings and techniques, more and more ancient buildings were damaged or even destroyed either by natural forces such as thunder hits, fires, and floods, or due to human factors such as city construction and water reservoir building. The protection of ancient architecture, including its theory, arts and techniques, has become an urgent task of the government. It was with this background that the Chinese Ministry of Science and Technology initiated in 2006 a project called “Study on the virtual restoration and Web representation techniques of ancient architectures”. Our research team was responsible for one of its subprojects called “computer assisted ancient architecture animation generation system based on semantic understanding”. Here, ‘semantic understanding’ means the system to be
built should be able to understand the semantics of the user’s natural language input in terms of the type and scale of the desired building and to further show its construction process. This has been the main motivation of our research.

Our second motivation is to provide a platform of computer aided ancient architecture design. With the rapid development of China’s economy, more and more attention of Chinese government and people has been directed to the cultural aspects. The point here is not only to maintain, but also to make use of our ancient heritage of building techniques and arts. On the one hand, many historically prominent but already destroyed ancient Chinese buildings are reconstructed one by one at different places. Moreover, the design of many new buildings needs to benefit from expertise of ancient Chinese craftsmen. Chinese architects have an urgent need of using computer aided systems when designing ancient style buildings. The third motivation is to make the (national or local) historical relics at different places accessible to a wide public even when these people do not have chance to visit these relics in person, or even when these relics have not been reconstructed yet and any memory on them remains only in ancient books or legends. People are looking forward to establishing virtual museums for demonstrating ancient Chinese architecture. Finally, our last motivation is to provide materials and services for e-learning courses to students of architectural departments.

3 The Full Life Cycle of Ancient Chinese Architecture Design

Our design philosophy is that the ICA^3D platform should support the full life cycle development of ancient Chinese architecture. This whole life cycle is divided into five main phases as follows.

The first phase is the requirement specification phase. The following decisions have to be made at this phase: for what purpose is the architecture? Is it an independent building of full ancient flavour? Or is it just an ancient flavour architectural decoration for a modern building? Is it a real building to be built and used? Or is it just a virtual building to be displayed as part of a virtual museum? What social level it serves? Is it a palace, temple, or pagoda? What is its architectural type?

The second phase is the beginning of design. The user needs to decide, for the case of the temple and palace, whether the building is of Wudian, Xieshan, Yingshan, or Xuanshan type (Guo, 1998), as shown in Figure 1. The system may also make some suggestions according to the information provided at the previous phase.

The third phase explores the structure of the architecture. The user needs to determine the extension and structure of the architecture. In case of Wudian structures which can only be used in imperial palaces and temples, one needs to determine the number of rooms and purlins. Other information includes whether there is a veranda around the outer walls. Moreover, the roof is very important for Wudian buildings. It has four slopes rather than two, and five ridges rather than only one compared to other simpler types of architecture. A further decision to be made is whether the user wants to have double eaves or just single ones.

The fourth phase determines more details, including information about Dougong, a typical product of ancient Chinese architecture used to support the eaves. A set of Dougong consists of two parts: the Dou which has the form of a wooden block, and the Gong which has the form of a bow-shaped arm. Various types of Dou and Gong are interlocked to form a bracket and various brackets form a Dougong layer set in between the column network and the roof.
The last phase of design is to determine the decoration of components. For example, the ridges of the roof may have decorations on them, mostly mythical small animal figures. The walls of a temple can also have wall paintings as their decoration. Also the detailed structure of different Dou and Gong should be determined, together with the way they are interlocked using tenons and mortises.

4 The Infrastructure of ICA$^3$D

In order to support the reasoning of architecture design, we need an infrastructure of data, knowledge and inference rules. The infrastructure of ICA$^3$D includes a model base ACAMB, a rule base ACARB, and a data base ACADB, as shown in Figure 2.
4.1 Model Base ACAMB

Similar to many other CAD systems (Modi, 2011; Thankur 2009), the most important part of the ICA3D infrastructure is its model base ACAMB. The models of ICA3D are constructed in tree form. Each node of the tree is a model. The lower level models inherit functions and properties from their ancestors. On the other hand, almost all models are compositions of their sub-models which form a hierarchy. We differentiate between the following levels of models, those at the level of building types, building structures, building components and component elements.

The first group of models includes palace, temple, pavilion and pagoda. The second group of models is actually a group of structure specifications. Each specification describes configurations of standard structures. For example, usually a palace of Wudian style consists of \( n \) sections from left to right and \( m \) purlins from front to rear, and satisfies that \( n \) and \( m \) must be odd numbers, \( n < m \), and \( m \leq 13 \). Moreover, a Wudian style building can also have a veranda or not. In ancient China, only imperial families were allowed to build Wudian palaces. The third group of models includes the major components of the building, such as roofs, walls, bases, columns, cross-beams and veranda. The fourth group of models includes elementary parts of components such as purlins, rafters, eaves, glaze animals and Dougong, which are all parts of the roof. Glaze animals are used as decoration on roof ridges, particularly the central ridge.

4.2 Rule Base ACARB

ACARB is composed of separate rule sets serving different reasoning purposes (Wei, et al., 2010). Firstly, component rules infer what types of components are needed for the specific building the user describes, and how many each of these components should be. Secondly, size and position rules compute the 3D size, position and rotation of each individual piece of wood in the animation scene. Thirdly, construction sequence of these pieces of wood is inferred so as to ensure that they can be jointed correctly by tenons and mortises. An example of rules is given as follows for computing the size of outer columns in a Wudian building. The left-to-right and front-to-rear size of an outer column are fixed values, while its vertical size depends on that of a type of tiebeam for supporting the Dougong.

```
(defrule size_OuterColumn
    ?f <- (OuterColumn)
    (Data (Name PingbanTiebeam) (Vertical ?cz))
    (Data (Name OuterColumn) (LeftToRight ?mk) (FrontToRear ?js))
    =>
    (bind ?cz (- 70 (+ ?cz *DG_XPTY*)))
    (modify ?f (VerticalSize ?cz) (LeftToRightSize ?mk)
        (FrontToRearSize ?js))
)
```

4.3 Data Base ACADB

What is specified in the model base and rule base is the knowledge about standard buildings regulated by the ancient Chinese central governments. However, the real world ancient buildings have never been exactly following these regulations. Therefore, measure data are important to illustrate the characteristics of existing real world buildings. We store such measure data in a data base called ACADB, including the exact shape and size of components.
of the building. When such data are used, only the reasoning of the construction sequence needs to be carried out. Of note, measure data of existing buildings are often incomplete, as parts of some components are hidden and cannot be captured by the measuring device. In such case, our knowledge bases become useful to suggest the hidden parts and infer the missing data.

5 The Working Environment of ICA³D

Based on the hierarchical model set, the user can freely construct part or whole of an ancient Chinese building in two different ways: the interactive way and the automatic way.

For the automatic way, we have implemented a natural language style interface particularly suited to paraphrase the major characteristics of the architecture required by the user, such as “I want to see a grand Wudian style building, with five sections from left to right, and seven purlins from front to rear. The building has a surrounding veranda, and for Dougong I want Wucai type.” The requirement in Chinese natural language style is parsed and information is extracted for deciding the necessary parameters. Afterwards, model base and rule bases are triggered to compute the target building. Once all the 3D size and position data are ready, the animation generation module, as shown in Figure 1, presents the motions in the animation scene. The motions are first represented in a qualitative language as follows.

moveTo (outerColumn1, fromPosition(above), toPosition(<10, 25, 10>), downwards, veryFast, t2, t3)

Then the quantitative description is generated, for example, outer column number 1 moves from position <10,45,10> to <10,25,10> from frame 120 to frame 210 (i.e., in about three seconds of time). Such motion data are transformed into the scene file format of Maya animation software, which is ready for rendering. What the user lastly gets is an animation showing the step-by-step construction process of the building he/she wants.

In the interactive mode, we provide the user with an easy-to-use interface for receiving user instructions of how should the building look like. The construction process consists of an instruction tree where a menu of instructions resides on each node helping the user to select the next step. The idea is to construct the building in a stepwise refinement way. The user is asked to first select a building type (palace, pagoda, etc.), then its structure (how many sections, etc.), then its component types and numbers (how many purlins, etc.), finally the types of elements of the components (type of Dougong, etc.).

We have implemented the first version of ICA³D. Semantic Web technologies (Berners-Lee, et al., 2001) were applied in modeling our knowledge bases. More precisely, the representation of model base ACAMB is an ontology in OWL DL (W3C OWL Working Group, 2009), including axioms such as \((\text{OuterColumn} \land \text{Column})\) and \((\text{Wudian} \land \exists \text{hasPart. OuterColumn})\). Such mechanism facilitates the knowledge sharing and reuse of Chinese architecture on the Semantic Web. Furthermore, we modeled the rule base ACARB in both SWRL (Horrocks, et al., 2004) and Jess (Friedman-Hill, 2008). The former is to follow the Semantic Web standards, and the latter, as shown in Section 4.2, for efficiency purposes. As output, in addition to Maya scene files that can be rendered into videos, we also transformed the quantitative animation description into VRML format to enable the real-time preview of the animation. Figure 3 shows some images from the animation automatically generated by our system.
(a) Animation of a Wudian wooden structure, from left to right showing the construction process

(b) Animation of Dougong, including partial ones under construction (the left and right image), and a complete layer of various Dougong installed together (center)

Figure 3: Animations generated by ICA3D

6 ICA3D versus Normal CAD Systems

Before deciding to design the ICA3D platform, a natural strategy for us would have been to use traditional CAD systems to construct ancient Chinese architectures. However, we did not find any CAD systems capable of dealing with all the functions listed as follows, while ICA3D has all these properties.

- Representing the domain knowledge and reasoning about ancient Chinese architecture, including complicated matching rules for composing ancient buildings from individual components, and elaborated algorithms for ensuring the construction sequence.
- Processing the Chinese natural language that the user inputs to describe the requirement;
- Processing massive sized measure data of real-world Chinese ancient architecture;
- Intelligent planning, i.e., given the user requirement, the system is able to do a hierarchical planning including structure planning, components planning, layout planning and construction process planning;
- Generating 3D animation, i.e., once the architecture planning is done, the animation module is able to transform it into a running animation first by qualitative and quantitative animation planning and at last by rendering.

Compared to normal computer-aided architectural design systems (CAAD), ICA3D features the automatic generation of animation to demonstrate the construction process of a building. In the domain of Chinese traditional architecture, construction sequence is of vital importance
as all pieces of wood were jointed together solely by tenons and mortises, and no glue or metal nails were used. A correct installation sequence of wood components ensures the final forming of the building. Although ICA³D provides full automation, the user interaction and intervention are also available. When unsatisfied with certain component or the construction sequence, the user can change the qualitative animation specification, which was purposely devised to facilitate friendly human intervention. Generally speaking, a normal CAAD system would have an extensive interactive interface where the user can choose components and install them in various flexible and convenient manners (Kim, et al., 2006). ICA³D functions could be used as add-ons for such CAAD systems, so that the user not only gets a static final 3D building model, but also an animation showing the whole construction process of the building from scratch.

7 Conclusion

With ICA³D, the user can simply input a few words in natural language about the building he/she would like to see, and the system automatically generates an animation to show this building. If the user changes the input, the system would immediately respond and generate a new animation with the updated building in it. This text-to-scene conversion is enabled with the support of a knowledge-based approach (Lu, et al., 2002; Lu, et al., 2006). The core is a model base where architectural structures and components are organized in a hierarchy. Moreover, rules are constructed to specify the number, size and position computation for components which finally leads to the animation. Measure data of real buildings can also be used in addition to rules for standard buildings. The infrastructure we deployed for ICA³D is scalable in the sense that, whenever a new type of architecture is modelled, only a new rule base should be added while the other modules of the system can be kept intact.

We used the Semantic Web standards in building our knowledge bases. Our future work would include incorporating architectural standards into ICA³D, to further its sharing and reuse. Moreover, linking with the state-of-the-art Web resources in architectural domain such as Google Earth² and advanced architecture design tools such as Revit³ would greatly improve the usability and interoperability of ICA³D.

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3 http://usa.autodesk.com/revit-architecture/
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