Interaction in an immersive virtual Beijing courtyard house

Qian Chen
Iowa State University

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Interaction in an immersive virtual Beijing courtyard house

by

Qian Chen

A thesis submitted to the graduate faculty
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Major: Human Computer Interaction

Program of Study Committee:
Chiu-Shui Chan, Major Professor
Carolina Cruz-Neira
Dirk Reiners

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2005

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Graduate College
Iowa State University

This is to certify that the master’s thesis of

Qian Chen

has met the thesis requirements of Iowa State University

Signatures have been redacted for privacy
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CHAPTER 1
INTRODUCTION

Virtual reality (VR), as an emerging technology, has been more and more involved in architectural researches, such as the heritage preservation (Zach, Klaus, Bauer, Karner, & Grabner, 2001; Gaitatzes, Christopoulos, & Roussou, 2001) and briefing clients (Patel, Campion, & Fernando, 2002). VR allows users to control the paths, speeds, camera views, or other factors while navigating through the 3D space at real-time, which is different from traditional architectural visualization methods. Users may actively participate in the simulation rather than just passively receive information.

In this project, an interactive VR simulation is developed for courtyard housing in Beijing, which is representative of traditional Chinese residential buildings. In addition to the static visualization, the structure of a major building is demonstrated interactively. Its major interaction mechanism is to show the constructional process step by step through menu selections. Each item uses the name of the components for naming purpose, and by clicking a menu item, the corresponding constructional step is shown in the VR environment.

Research Question and Objectives

Currently, the most frequently used methods of architectural visualization include physical model, digital still imaging, animation, and hand drawing. However, all of them have their own drawbacks.

Physical models are expensive, non-reusable, and non-editable. More importantly, they cannot provide a normal viewpoint at human height since their dimensions are always
smaller than the physical buildings. Consequently, the spatial perception from physical models may render incorrect information. For experienced architects, freehand sketching is often a convenient tool to quickly visualize their design concepts. However, in order to draw accurate and detailed sketches, longtime training is needed, which could be a challenge for novices. The digital media appeared in the middle of last century is a revolutionary visualization tool. Since it is generated programmatically by computers, its components including camera views, materials, and lightings are highly accurate. Almost all of them can be modified at unlimited times until the expected effects are reached. Furthermore, digital drawings are reusable in multiple files and can be shared as public resources. In computer-aided design (CAD) packages, drawings of a chair can be easily copied at multiple places, or referenced by external files.

There are at least two common problems for all of these visualization methods. Firstly, their presentations are usually not full-scale, which may bring problems to imagine the real buildings, especially for people without strong visualization skills. Secondly, these methods are pre-rendered or pre-produced, so that nothing can be changed at real-time after the raster graphics or physical objects are generated. There is also no interaction between their products and users. Lantz (1997) mentioned that a highly ornate architectural space is "static, but viewing it involves a great deal of eye, head, and body motion. Even our best large-format film displays are at a loss to reproduce the range of colors, dynamic range of intensities, field of view, and level of detail present in such a space" (Lantz, 1997, p. 38). Obviously, current digital imaging or animation is not capable of providing a most ideal environment to appreciate architecture.
Concerning the discussed two issues, it could be beneficial to explore a new visualization approach which can successfully overcome them. As a strong alternative, VR owns two major features: immersion and interactivity (Burdea & Coiffet, 2003). In a full-immersive environment, graphics are projected from all directions on large-display equipment. In such an enclosed virtual space, the perception of building’s scales can be more closely seen in its real dimensions. In addition to the navigation, users can also operate VR simulations interactively at real-time, such as moving an object’s position in the 3D space, which is hard to achieve by all other visualization tools.

Although VR has these advantages, so far no previous study has been found to explore whether they are helpful to present architectural knowledge. A related prior experiment from Ruddle, Payne and Jones (1999) revealed that the participants with immersive facilities performed better on navigation and spatial acquisition than non-immersive ones. However, their study did not contain rich architectural knowledge, but concentrated more on human performance. Besides, the immersive facility in their study was the head mounted display, which cannot generate a perfect full-immersion. Moreover, there is no systematic study on interactivity in architectural VR, either. Kim, Kesavadas, and Paley’s (2003) developed an interactive VR simulation, but the architectural knowledge embedded was not clear, nor had the contribution of interactivity in the architectural simulation been confirmed in the paper. In other words, it was not clear that the methods of their interactivity are beneficial on presenting architectural knowledge.

Therefore, this thesis study is designed to answer the following question: Can architectural knowledge, such as structure, be presented through a full-immersive and interactive VR environment?
The main objectives of this thesis are to research the Chinese courtyard housing, digitalize its features in a full-immersive VR environment, and explore if its architectural knowledge can be presented through this environment. The methods employed in this project to develop an interactive architectural VR simulation could also be used as a general guideline for other developers with similar research interests.

Methodologies

The methodological steps of this project consist of four major tasks: (1) architectural research of courtyard housing; (2) VR modeling of courtyard house and hutong (the narrow streets), including the model conversion from 3DS Max to VRML format for VR display; (3) simulating the constructional processes of wood structure through user-and-system interaction; (4) implementing the model and the interaction in C6, a full-immersive virtual environment at Iowa State University.

After studying the Chinese courtyard housing across different eras, the housing of Ming and Qing dynasties in Beijing was studied in detail, for it represents the highest and most mature dwelling type in ancient China. A traditional Chinese philosophy and aesthetics are reflected through its plan layout, materials, decorations, structure, etc. For example, in some locations, the eastern side of a building is little taller than the western one because according to the traditional Chinese philosophy, the direction of east is more highly regarded than west. From the multi-yard housing complex for top-level officials to the single-yard house for commoners, there existed various housing types matching with their dwellers’ social levels and financial powers.
The features of Beijing’s courtyard housing were analyzed in terms of its timber frame structure, plan layout, utilization of Fengshui, gate styles, and hutong. A four-yard house located in the Beijing Inner City and its nearby districts were used as the prototype for the digital modeling.

The VR modeling covers the task flow from geometric model building to file converting. An important step in the process is to find out how to optimize models for C6 display. It was found that the fewer nodes the VRML file has, the more efficient it is.

In the interaction planning step, the main hall’s structure was designed to be displayed according to its constructional process, because it best tells the concept that how the building is actually built. After that, the simulation was implemented in the C6 through VR Juggler Template Applications developed at Iowa State University.

Five viewers were invited to see the model and comment on the functionality of full-immersion and interactivity in this simulation. Overall, the results are positive that the full-immersive and interactive VR environment is potentially effective to present architectural knowledge. A major suggestion from the viewers is that more details can be added in the simulation, such as characters and furniture.

**Organization of the Study**

This thesis is organized into five major sections. Chapter one briefly introduces the research’s topic, research questions and objectives, methods, and products. Chapter two outlines the history of Chinese courtyard housing, and then focuses on the key features of Beijing’s style. Chapter three introduces VR and human-computer interaction (HCI). In this chapter, the definition, components, and features of VR are discussed, and the definition of
HCI and the interaction styles are introduced. Another purpose of this chapter is to review the precedent studies of interactive VR in architecture. Chapter four describes the methods used to generate the VR simulation, including 3D modeling, interaction planning, C6 implementation, and user feedback. The VR modeling is introduced in detail because it took the longest time in this project. For the conclusion, chapter five summarizes the limitations and proposes recommendations for future study.

Products

There are three digital products finished in this project. One is an interactive VR simulation for the C6 at the Virtual Reality Appliances Center, Iowa State University; the other two are a VRML model and a 3D animation (Appendix) which can be run on personal computers (PC). Since C6 is not a portable system, its simulation cannot be shared online at this moment, the VRML model and animation are options to be played through the Internet or a laptop computer.

There are some differences between the C6 and PC models. In order to improve the simulation speed, the C6 model has less polygons and textures. Also, its textures have smaller dimensions than the PC model. Many trials had been tested to achieve a best balance between visual fidelity and smooth running. The PC model uses more baked texture on its key components with shadows and subtle color transitions, which cannot be generated in VRML programmatically. Several cameras are pre-set in the VRML model in different yards, which can be switched fluently and conveniently in VRML players.
Compared to the C6 and PC models, the animation has the best graphics (Figure 1) results. Its shadows and lightings were set carefully to get high-quality renderings. Meanwhile, it is helpful to realize that the slightly different visual effects between VR models and animation are merely created by the available functions in different systems. Therefore, lightings in the animation were capable to be set on a moderate level on purpose, but VR cannot generate graphics with lighting effect as clear as pre-rendered animation. Another example, relating to the availability of techniques in systems would cause different production, is radiosity; which could generate highly realistic rendering but has not applied in this animation due to the lengthy time of creation.

The animation contains four major parts: navigation, plan, structure, and hutong. To match with their rhythms, different pieces of music were integrated into the animation.
CHAPTER 2
COURTYARD HOUSING IN BEIJING

Courtyard housing is an old habitation form in the world. In western countries, its prototypes were found as early as 2000 B.C. in Mesopotamia, where is between Euphrates and Tigris (Blaser, 1979). In China, courtyard housing had been a main dwelling type from three thousand years ago until the middle 20th century. Except for some extremely poor farmers and remote-area minority dwellers, most residential buildings in ancient China were courtyard style (Wang, 1999). Therefore, the research of courtyard housing is of great significance to explore the technology embedded in the traditional Chinese residence.

Definition of Courtyard Housing

In Chinese language, courtyard house is called Si (four-side) He (enclosed) Yuan (inner yard). Literally, it is the house with one or more inner yards enclosed at four directions. As an integration of function and form, courtyard housing is connected tightly with local customs, aesthetics, philosophy, and natural conditions. It is an architectural reflection of Chinese traditional courtesy, which systematically ruled the family members.

In this study, the courtyard housing is defined by synthesizing both physical and cultural factors as: the low-rise residential housing with rectangular-shape inner yard enclosed by buildings and walls, which is typically occupied by one family across generations, and with certain rules applied in the design. These rules include the symmetry and axis of plan, hierarchy of form, and principles of Fengshui utilized in determining the functionality and space, etc.
Typology of Courtyard Housing at Different Eras

Chinese architecture did not change vigorously in its history in terms of structure, material, aesthetics, etc. From Western Zhou (ca. 11th century - 771 B.C.) to nineteenth century, the features of courtyard house had persisted for thousands of years.

The earliest courtyard house found so far is the palace site of Western Zhou excavated at Fengchu Village, Qishan, Shanxi Province (Figure 2). The tortoise shells and oracle bones uncovered at the site indicate that it used to be a ceremonial complex for authorities (Fu, Guo, Liu, Pan, Qiao, & Sun, 2002). Along the axis, there lies the shadow wall, gate, front inner yard, main hall, covered corridor, and bedrooms. As the housing complex’s focus, the main hall displayed its superiority in all aspects including size, height, and position. Along the axis, the main hall was located in front of the bedrooms, so the public and private spaces were separated from each other. There were corridors built on the inner sides of surrounding buildings. Consequently, the house was very open inwards while close outwards. Seeing the cycle of day and season, the cosmos could be perceived by dwellers through the inner yards. An old Chinese philosophy concept, “the harmony of nature and human”, was fully exhibited through such an architectural form.

Han (206 B.C. - 220 A.D.) was the first peak of China’s civilization in history. There were courtyard houses depicted on bricks, murals, and burial articles in this period (Figure
3). In Han, the bricks, stones, and limes were used more extensively with diverse types and sizes of different kinds of buildings; also, the improvement of timber frame technology made the multiple-story constructions possible (Chinese Academy of Architecture, 1982), which can be proved by the guiding tower on Figure 3. A distinction from Western Zhou is that the inner yards were enclosed by corridors and walls, but not by buildings.

Song (960 - 1279 A.D.) had a thriving economy, art, and literature. Three of the four Chinese grand inventions, gunpowder, compass, and reusable printing, were all conceived in Song except paper. A significant architectural achievement in this era is the Yingzao Fashi (Construction Rules), the oldest book compiled by Jie Li, which fully described the architectural standards of ancient China. There are many courtyard houses found in Song’s paintings (Figure 4). It can be seen from those paintings that the courtyard houses in Song also had the covered corridor connecting two buildings in the middle, called “Gongzi Hall”,
which is similar to the style appeared in Western Zhou.
As Figure 5 shows, the front building A is closer to gate, so it has less privacy and thus could be used as public space such as the living room; on the contrary, the rear building B could be the bedrooms.

Established by the Mongolian, Yuan (1271 - 1368 A.D.) is particularly important for Beijing because in that dynasty, it became the capital of China for the first time. In Yuan, Beijing was called “Dadu”, which was planned based on the traditional ideal city model. The planning was significant for the development of courtyard housing in Beijing, because it established the urban grid, on

Figure 5. “GongZi Hall”

Figure 6. Reconstruction drawing of courtyard house at Houyingfang
(Lu & Wang, 1996)
which the courtyard houses were constructed. This urban grid still exists in Beijing due to its continuous use. The residential design in Yuan was mainly learned from Song (Lu & Wang, 1996). An example is the Houyingfang site excavated in Beijing (Figure 6).

After Yuan dynasty, courtyard housing developed into its most mature stage in the Ming and Qing dynasties (1368-1911 A.D.). Beijing’s style of this era (Figure 7) is often studied as the representative of Chinese courtyard housing. The technology of producing bricks improved dramatically in the Ming dynasty (Ma, 1999). In Nanjing, the world’s longest city wall was built, of which the bricks’ quality has been highly evaluated. Ming’s capital, Beijing, was developed based on Yuan’s Beijing city with some new districts added. After Manchu conquered China, they adopted the Chinese culture extensively and hired Chinese natives as key officials. The architectural style of Ming was completely inherited by the Qing government (Ma, 1999). Because of Beijing’s population boom in Ming, the land each family was allotted to build their houses was much smaller than Yuan. Consequently, the front yard of Ming’s courtyard house was much smaller than the front yard of Houyingfang site (Figure 6) of Yuan (Ma, 1999; Lu & Wang, 1996).
Comparing the courtyard houses of Ming and Qing with Song and Yuan, there is an obvious difference—the “Gongzi Hall” almost completely disappeared. An explanation given by Lu and Wang (1996) is the systematic large-scale immigration from Shanxi Province to Beijing organized by Ming’s government. As a result of this immigration, the building styles of Shanxi probably influenced Beijing profoundly.

Summarily, as Figure 8 shows, the courtyard housing in China did not change dramatically. Some key features, including symmetry, structure, hierarchy, and height, persisted without exceptions. The houses in Western Zhou, Song, and Yuan have more similarities. For example, all of them had the “Gongzi Hall”, middle gates, and building-surrounded inner yards. An obvious distinction of Han is that its yards were enclosed by corridors and walls, but not buildings. In Ming and Qing, the last two dynasties of China, the “Gongzi Hall” totally disappeared. In Qing, the gate moved to the southeast corner of the housing complex, which relates to the concept of geomantic omens in Beijing.

Figure 8. Plans of courtyard house at different eras
Significance of Beijing’s Courtyard Housing in China

Beijing was the political and cultural center of China in Ming and Qing. Its city was carefully planned based on the ideal city model of Chinese philosophy. The construction of official buildings gathered top-level carpenters and craftsmen. In Yuan, a rule was released by the emperor that wealthy families had the priority to move into the capital. In Qing, only the Manchu families who usually had better governmental financial support could live in the Beijing Inner City. Therefore, the typical dwellers in Beijing could be richer or of higher social level than other cities’ inhabitants. In fact, this could contribute to a better construction quality. With these advantages, Beijing provided a best platform on which its courtyard housing reached a most mature stage.

Features of Courtyard Housing in Beijing

In this section, the features of Beijing’s courtyard housing are discussed, including plan layout, structure, Fengshui, gate styles, and hutong. These features distinguish Beijing’s courtyard housing from the architecture of other cultures.

Plan Layout

The beauty of Chinese architecture often relies on the composition of building groups. Even though the individual buildings are often quite similar, the method to organize them to form a space is often appreciated.

The basic unit of Chinese architecture is “Jian”, which is the space between two columns. As early as the courtyard house of West Zhou (Figure 2), jian was clearly shown. Several jians form an individual building, usually in odd number. For a typical five-jian
building (Figure 9), the middle jian is called “Mingjian” (bright jian); the leftmost and rightmost ones are called “Shaojian” (rear jian); and the two between them are called “Cijian” (secondary jian). The width of Mingjian can be larger than Cijian, and Cijian larger than Shaojian (Lu & Wang, 1996).

Based on jian, a building is formed, and then a yard is enclosed by buildings. The more yards a housing complex has, the higher level it is. In Chinese, the word “deep” is often used to describe a house’s size. This depth is not vertical, but horizontal, which illustrates the perception of walking yard-by-yard.

A typical middle-size courtyard house in Beijing has three yards (Figure 10). From the front to rear, there are DaoZuoFang, first yard, ChuiHuaMen, second yard, ZhengFang, third yard, and HouZhaoFang. The main gate usually locates on southeastern corner. The DaoZuoFang is for visitors, male servants, and restrooms. Sometimes the first yard is divided into several smaller ones to create more complex spatial transitions. Usually with very delicate ornaments, the ChuiHuaMen is a key component which separates the public and family spaces. Traditionally, young female dwellers should not exit this gate. The eastern and western XiangFangs in the second yard are typically for sons. Around the inner yard, there is a circular corridor connecting buildings. When raining or snowing, dwellers could easily get
access to other rooms through this corridor. The ZhengFang (main hall) is the most important building in the housing complex, which is typically lived by grandparents and parents. The small buildings on its two sides are called ErFang, which can be used as reading room or kitchen. As a most private building, the HuoZhaoFang is for daughters and female servants. Along the axis, the privacy increases from the front to rear. Figure 11 illustrates the circulations of residents and the properties of each yard.

Figure 10. Plan of a typical three-yard courtyard house in Beijing (reprinted from Ma, 1999; diagrammed by the author)
Structure

Chinese architecture is well known for its timber frame structure, which has two major types, including Tailiang and Chuandou (Figure 12). For the Tailiang style, there are columns, beams, and purlines at different horizontal levels. Part of the roof is supported directly by purlines, beams, short columns, and finally conveyed to columns. For the Chuandou style, all columns support roof directly. Each of these two styles has its advantages and drawbacks. For example, the Tailiang style, which uses fewer columns than Chuandou, needs stronger and thicker timbers. So it was used more frequently in northern China where had the proper woods opposed to the Chuandou style which was used extensively in southern China.

Beijing’s courtyard house usually adopted the Tailiang style. In a typical structure of the main hall (Figure 13), there are four columns along the depth direction, YanZhu (Eave Column) at outside and JinZhu (Golden Column) at inside. The ShanZhu (Mountain Column) can be built on the two sides of a building if the distance between two golden columns is too large (Lu & Wang, 1996). Corresponding to the columns, the outside purline is YanLin (Eave Purline); the middle two are JinLin (Golden Purline); and the inside one is
JiLin (Ridge Purlin). Beams are along the depth direction with rectangular sections, which are called BaoTouLiang, WuJiaLiang (Five-Purline Beam) and SanJiaLiang (Three-Purline Beam) from outside to inside respectively. The numbers in their names indicate the number of purlines they support. From top to bottom, the roof’s structure is composed of tiles, WangBan, and ZhuanZi (rafter), which are the long timbers with small rectangular sections supported by purlines.

Utilization of Fengshui

Literally, Fengshui is composed of two Chinese words, feng (wind) and shui (water). It has been practiced by the Chinese to create a harmonious environment. Incorporated with philosophy, religion, psychology, ecology, astrology, geography, art, and other aspects of ancient science, Fengshui is a system exploring the relationship among natural environment, built conditions, and human beings.
Fengshui has a profound influence on Chinese architecture. It has a set of rules used by dwellers to select sites, plan layouts, arrange furniture, etc. It was believed by ancient Chinese that the successful utilization of these rules would bring good fortune to the house owner. To better employ these rules, there were professionals to provide instructions of Fengshui for construction projects. In Fengshui, the constructions for dead people, usually tomb, are called "Ying House"; the constructions for living people are called "Yang House". Therefore, the methods of Yang House were usually used in courtyard housing.

Fengshui was originated from the searching for ideal caves by cave dwellers on the Yellow-Earth Tableland (Ma, 1999). During Tang and Song, Fengshui evolved into two subsystems, "Xingshi Zong" and "Liqi Zong". Generally, "Xingshi Zong" was more
concerned with physical factors of environment, such as location and shape of mountains, water, etc. “Liqi Zong”, on the contrary, mostly deals with non-physical concepts such as “Bagua” (Eight Diagrams). In the construction of courtyard house in Beijing, both subsystems were involved (Ma, 1999).

Figure 14. Eight possibilities to locate the gate (Lu & Wang, 1996)

Figure 15. Standard layout according to Fengshui (Lu & Wang, 1996)
There was a formula of Fengshui to arrange buildings in Beijing, called “DaYouNian Rule”. This formula has eight sentences, and the first character of each sentence represents one direction, which is called “Fu Direction”; and the remaining seven characters of that sentence represent the fortune of other seven directions in clockwise order. It is a common sense that the important buildings should be built on good-fortune directions. To use this formula, the initial step is to determine the “Fu Direction”. In Beijing, this direction is usually the main gate’s position. Therefore, based on the “DaYouNian Rule”, there are eight possibilities of plan layout according to the main gate’s position (Figure 14). Among these eight alternatives, the gate on the southeastern corner is the best one. In this arrangement (Figure 15), the east, south, and north are good-fortunate directions, which are assigned to the east side building, DaoZuoFang, and main hall respectively. So, all of these three important buildings can locate on good-fortune directions. Therefore, placing the main gate on southeastern corner became a fixed pattern in Beijing.

**Gate Styles**

Gate in Chinese architecture not only works as entrance, but also as cultural metaphors. A courtyard house’s gate can be an architectural symbol representing the dweller’s social, official, and economical standings. For the inhabitants with different rankings, there were corresponding rules on gate styles such as decorations, colors, and materials, which strictly divide them into different levels (Ma, 1999). Also, the gate styles contain rich philosophical and cultural connotations. For example, in the emperor’s palace of Beijing, the number of pins on gate is usually nine per row and column (Figure 16), because
the number nine was the highest level of number in Chinese philosophy. Following the emperor, officials could use fewer pins according to their ranks.

The gate styles of courtyard housing are roughly divided into two major categories according to their architectural forms, "building-gate" and "wall-gate" (Ma, 1999). The first style is constructed based on buildings. In DaoZuoFang, one of its bays is used to build this kind of gate. Similar to buildings, a gate also has its complete structure including columns, purlines, and beams. Usually the "building-gate" is used in middle class or above housing compounds. The "wall-gate" is much simpler with smaller dimensions and less ornaments, which is often used by commoners. The constructions on its two sides are not buildings, but simply walls.

The "building-gate" style includes four sub-styles: "Guangliang", "Jingzhu", "Manzi", and "Ruyi", in the order from high level to low level. The depth and height of "Guangliang" gate are obviously larger than the depth and height of DaoZuoFang. After "Guangliang", "Jingzhu" has a little lower level. Both of their inhabitants should be the governmental officials above certain ranks. "Manzi" was usually used by prosperous merchants and families. As a most frequently used gate style, "Ruyi" was popular among

Figure 16. Gate with pins (provided by Chiu-Shui Chan, Iowa State University)
commoners. Compared to these four styles, “wall-gate” is quite simple, but some of them also have delicate decorations (Ma, 1999).

An obvious distinction of these styles is the position of gate (Figure 17). For

![Guangliang Style](image1)

![Jingzhu Style](image2)

![Manzi Style](image3)

![Ruyi Style](image4)

![Wall-Gate Style](image5)

Figure 17. Gate Styles (all images except the section view of the wall-gate style are reprinted from Ma, 1999; diagrammed by the author)
“Guangliang”, the gate is at the middle of the direction of depth. For “Jingzhu”, the gate is between the middle and outmost columns. Through such a layout, the gate could be felt more distant from passengers to clarify the house owners’ high social level. In other three styles, the gate is at the outmost columns.

As an important element in courtyard house, the shadow wall is tightly related to gate (Figure 18). It not only blocks the inside scenery from street, but also beatifies the entrance. There are three types of shadow walls according to their positions: (1) the shadow wall built inside the house which is also called screen wall, (2) the shadow wall built on the other side

![Figure 18. Shadow walls](image)

(reprinted from Ma, 1999; diagrammed by the author)
of the hutong facing the gate directly, (3) the shadow wall built on the gate’s two sides with some degrees.

**Hutong: The Narrow Street in Beijing**

Created from Yuan, hutong refers to the narrow alleys and streets in Beijing. There is still not a unified agreement that where this word came from (Weng, 2003; Lu & Wang, 1996). One explanation is that it was originated from the Mongolian word, “well”, because the well was very important for a residential district. Actually, the well was often a place for neighborhood affairs and activities in Beijing. Another explanation is that hutong came from the word “town” in Mongolian, but not “well”. In Mongolian, both of these two words have similar pronunciations to “hutong” in Chinese. After the establishment of Yuan, Chinese language absorbed the “well” or “town” gradually with a changed meaning.

Hutong is closely related to courtyard housing (Figure 19; Figure 20). It is an important element of urban fabric on which the courtyard houses were allocated. Since the typical main entrance of courtyard house faces south, hutong was usually constructed in the east-west orientation. But, the south-north and irregular orientations also exist.

In Yuan, the width of hutong was required to follow some specific regulations. The standard width of hutong was six steps; the width of the “small street” was twelve steps, and
twenty-four steps for the “large street”. In Yuan, 1 step equaled to 1.54 meters, so, theoretically, hutong had the standard width of 9.24 meters. However, such regulations were not executed strictly in the following dynasties. The typical center-to-center distance between two hutongs was 50 steps in Yuan, which is 77 meters; and the edge-to-edge distance was 67.76 meters (Weng, 2003). This distance is enough to build a four-yard courtyard house.

In addition to transportation, hutong also plays other roles in people’s everyday life. For example, it was a spatial transition which connected the house’s private space to the main street’s public space. Its comfortable and friendly space made it an ideal place for neighborhood communications. Besides, in some places of Beijing, such as the Qianmen district, hutong became the market for commercial activities.

Summary

In this chapter, the courtyard housing was first defined in terms of its architectural, cultural and social factors, followed by the discussion of its typology at different eras from Western Zhou to Qing, among which the Beijing’s courtyard house in Ming and Qing was
studied in details. The structure of Beijing’s courtyard house is timber frame, which is significantly different from western architecture. As Knapp (2000) stated, “such a structural system is a clear precursor of contemporary skyscraper construction, which is generally viewed as a modern innovation” (p. 77). Additionally, the courtyard house’ plan layout, utilization of Fengshui, gate styles, and hutong are also very unique features in terms of architecture, culture, and urban context. Based on a prototype in Beijing Inner City, a four-yard courtyard house was digitalized and displayed in the C6 facilities.
CHAPTER 3
VIRTUAL REALITY AND INTERACTION

As an emerging technology, VR has received intense interest recently. Figures with stereoscopic glasses are often shown on magazines or movies as symbols of cutting-edge technology. Compared with desktop systems, VR has a much richer diversity of interaction techniques. The way to make good interactions in VR relates closely to the advancement of computer hardware and software, psychology, design, and many other related fields. At this time, research of interactive VR is still far from satisfactory.

VR has a great potential to be incorporated in architectural research. It not only allows users to walk through virtual buildings, but also operate models dynamically. It is capable of providing a full-scale environment in which buildings are displayed closer to their physical dimensions.

Virtual Reality

VR is the computer-generated environment simulating our real world. It allows participants to experience “being there” through one or more sensory stimuli. Defined as “a high-end user-computer interface”, VR “involves real-time simulations and interactions through multiple sensorial channels. These sensorial modalities are visual, auditory, tactile, smell, and taste” (Burdea & Coiffet, 2003, p. 3).

The characteristics of VR can be summarized as “the illusion of participation in a synthetic environment rather than external observation of such an environment. VR relies on
three-dimensional (3D), stereoscopic, head-tracked displays, hand/body tracking and binaural sound. VR is an immersive, multi-sensory experience” (Gigante, 1993, p. 3).

The Five Classic Components of a VR System

Burdea and Coiffet (2003) depicted the five classic components of a VR system as VR engine, input/output (I/O) devices, software and databases, user, and task (Figure 21). As the computing component in a VR system, the VR engine “reads its input devices, accesses task-dependent databases, performs the required real-time computations to update the state of the virtual world, and feeds the results to the output displays” (Burdea & Coiffet, 2003, p. 116). The VR engine varies from PCs, graphic workstations, to parallel supercomputers. A key point of the VR engine is that it should be powerful enough to support real-time computations.

The I/O devices are the hardware equipment where users communicate with VR systems. These devices vary substantially in appearance, performance, purpose, and cost.

To create and implement virtual simulations in VR, developers often employ software packages such as modeling, texture editing, and scene graph programs. As a product operated
by humans, the VR simulation should be user-centered. Neglecting the issues of human factors could ruin a VR product completely.

Desktop VR Input Devices

For desktop VR, a 2D mouse and a keyboard are often used in simulations such as computer games or online virtual resources. A problem of the 2D mouse is that it can only move in horizontal directions. Using a mouse for 3D tasks may bring confusion and inconvenience, since it cannot directly match with the 3D movements of objects. Some techniques had been explored to improve 2D input in 3D tasks, such as the Virtual Sphere, which simulates the mechanics of a trackball capable of rotating on any axis (Chen, Mountford, & Sellen, 1988). The constrained 3D space in which the viewer’s navigation is limited at a proper level to avoid the loss of context and strengthen the focus of attention (Hanson & Wernert, 1997) has also been investigated.

As an alternative to 2D input, 3D input is capable of handling translation and rotation with six degrees of freedom (DOF), three for translation and three for rotation. In Hinckley, Tullio, Pausch, Proffitt, and Kassell’s (1997) study, which compared the 2D and 3D inputs, participants used 3D input to perform quicker in a rotation task. There was no significant discrepancy of accuracy between the two methods. Overall, 3D input demonstrated a better usability in their experiment.

There are two major types of 3D input devices, including desktop and free-space. The desktop 3D input is used on a stationary surface. The free-space 3D input usually employs the tracker or camera-based technology, so users can use it in the air. An example of desktop 3D input is the Logitech Magellan space mouse (Figure 22, retrieved December 4, 2004,
from http://www.id8media.com/Accessories_Product/MagellanPlus3D.htm), which can measure the forces and torques at three directions by the central sensing cylinder. The Logitech Magellan mouse can be used in computer-aided design, computer-aided manufacture, and any field in which 3D operation is extensively addressed.

**Advanced VR Input Devices**

In advanced VR systems, 3D trackers can send signals of positions and orientations of the objects they are attached at real-time. A related technology is motion capture, which can easily generate natural movements in animation. This has been used extensively in entertainment industries. Trackers have various types based on their technologies, including mechanical, optical, ultrasonic, and electromagnetic (Vince, 2004). There are several significant parameters associated with tracker’s performance such as latency, update rate, and accuracy. Latency is the time delay, where sensors detect the change of an object’s position after the change happens. A long-time latency may induce sickness, such as headache and nausea, in VR environments (Burdea & Coiffet, 2003). With 3D trackers, some natural interactions can be realized. For instance, when users move their heads, the 3D graphics will be updated simultaneously.
Although the free space 3D input may offer more freedom to users, it does not always necessarily bring better usability. As Zhai (1998) pointed out, these “flying” mice are easy to learn because of their natural and direct mapping, but, they also have many disadvantages, including the limited movement range, lack of coordination, fatigue, and difficulty of device acquisition. Users may easily feel tired after moving their arms or heads for a long period of time. Also, the sensors worn by users may be obstructive. Users always perceive them to be something “extra”. Furthermore, the cost of trackers is still too expensive to be widely adopted.

Another natural interaction method, a sensing glove, can recognize the user’s hand gestures to manipulate applications. With sensors embedded in gloves, each finger and wrist can be monitored at real-time. The CyberGlove is an example of sensing glove (Figure 23). It has two or three bend sensors on each finger, and other sensors on the thumb crossover, palm arch, wrist flexion, and abduction (Vince, 2004). A sensing glove has natural advantages, but also significant drawbacks. It needs user-specific calibrations for different hands, because users vary in hand size individually (Burdea & Coiffet, 2003). Moreover, the glove’s reliability is still not satisfactory (Vince, 2004) and accuracy is lacking (Ciger, Gutierrez, Vexo, & Thalmann, 2003).

In addition to commercial 3D mice and sensing gloves, there are other creative techniques from research labs. Zeleznik, LaViola, Acevedo Feliz, and Keefe (2002) developed the FingerSleeve with a six DOF tracker, worn on the index finger (Figure 24).
The button’s size is small and the pointer is aligned perpendicularly to the user’s finger to achieve a comfortable gesture in operations. Ehnes, Knopfle, and Unbescheiden (2001) tried the pen and puck on the virtual table for drawing and sketching tasks. In their system, there are virtual pieces of paper containing 3D objects. A pen is for the dominant hand and a puck is for the non-dominant hand, so that two hands can cooperate in manipulations.

A common drawback of 3D input with trackers is the high cost (Hinfiley, Tullio, Pausch, Proffitt, & Kassell, 1997). As a low-cost alternative, Olsen and Nielsen (2001) explored the standard laser pointer, which was said to be useful with large projected displays when personal displays are awkward. Although it may be an effective tool under certain conditions, the pointer is extremely constrained by its simple non-button interface. Also, since it is difficult to hold in a stable position or point precisely, the targets must be very large, which may lead to problems in interface design.

Another low-cost method explored by many researchers is the camera-based computer vision tracking technique that passive objects can be captured as input. Cao and Balakrishnan (2003) developed an interaction system composed of a simple plastic rod without any electronics and a pair of cameras. While the rod does not emit any signal actively, postures and gestures are tracked to control 3D manipulations (Figure 25). Lee, Ghyme, Park, and Wohn (1998) explored a continuous hand gesture recognition system to control the avatar motion in the virtual office environment. Tollmar, Demirdjian, and Darrell
researched interaction techniques by body tracking. Their system is capable of monitoring the upper body pose. So far, the vision tracking technology is still not mature enough to be used. For example, in hand gesture tracking, a major problem is that the starting and ending point of continuous gestures are difficult to locate, thus it would be difficult to filter the unintentional hand movements from the meaningful ones (Lee, Ghyme, Park, & Wohn, 1998).

Summarily, 3D input shows a richer diversity than 2D input. However, neither is a universal nor dominant one in VR. Each has its superiorities, but also vital limitations. Zhai (1998) demonstrated that none of the existing input devices, including the six DOF input, could meet all usability requirements of 3D manipulations. They are either too expensive or lack of stability. At this point, it is hard to say which input device is the best one for VR. The selection is usually made individually, based on the specifications of each task and system.

Output Devices

The output methods usually involve devices for graphics, sound, and haptic feedback. In Burdea and Coiffet's (2003) book, graphics output is briefly categorized into personal and large volume displays. The personal displays include head-mounted displays (HMD), hand-
supported displays (HSD), floor-supported displays, and desk-supported displays. Monitor-based and projector-based displays are the two major divisions of large volume displays. While the personal displays only allow for a single user, large volume equipment is open to multiple users.

Immersive and relatively affordable, HMD is a frequently used output facility (Figure 26). Its display equipment is the key to determining its performance, which usually uses either Liquid Crystal Display (LCD) or Cathode Ray Tube (CRT). Since the latter has a better graphic resolution, it is preferred by the professional-grade HMD, and the LCD is often used by a consumer-grade HMD (Burdea & Coiffet, 2003).

The BOOM is an example of a floor-based display, which employs a mechanical counterbalanced arm (Figure 27). Because of the arm’s support, the displays components can be complex to generate better quality graphics than other personal displays. With a low responding latency, the mechanical tracker is incorporated into the BOOM’s supporting structure. Compared to other trackers, it is not limited by the magnetic fields and ultrasound background noise (Burdea & Coiffet, 2003).

Large volume displays can be as simple as multiple monitors, two or more regular projectors, or a panoramic screen such as the Elumens Visionstation, which has a 1.5 meter diameter hemispherical screen coupled with a single projector (Vince 2004), the virtual table such as the Fakespace’s Immersive Workbench, and the immersive projection display.
The C6, an immersive projection display (Figure 28), is used in this project. The "6" indicates its six-side enclosed 10x10x10 feet space, which supports the wireless I/O devices. With shutter glasses, users can see the stereoscopic graphics projected on all four walls, the ceiling, and the floor. One of the walls is movable for users to enter or leave this enclosed space. Wand and digital glove are often used in C6 to control simulations. Besides graphics, stereo sound is also supported. Up to seven people can stay in C6 simultaneously, and one or two of them can drive the simulations.

**Features of VR - Immersion**

Immersion and interaction are often acknowledged as the two key features of VR (Burdea & Coiffet, 2003). Whether a system is immersive or not is sometimes used as a criterion to define if it is VR. Is the regular non-immersive video game a kind of VR? The answer may be different from various VR manufacturers. Usually the vendors of desktop VR prefer a more generous definition than the vendors of immersive VR equipment (Travis, Watson, & Atyeo, 1994).

In a non-immersive VR environment, the navigation through virtual spaces may be not as compelling as immersive ones. The field of view (FOV) on desktop monitors or other non-immersive displays is usually smaller than for immersive equipment. FOV is "a measure
of the horizontal and vertical visual range of the optical system, and ideally should approach that of the human visual system” (Vince, 2004, p. 83). The inadequate FOV on monitors may restrain users from constructing an accurate mental model of the space (Miller, Clawson, Sebrechts, & Knott, 1998). As Ruddle, Payne, and Jones (1999) pointed out, navigating with a limited FOV increases the angle and number of times that users need to rotate their heads; in a virtual environment without peripheral vision (with limited FOV), users probably walk past their targets unintentionally.

an experiment on the navigation in virtual buildings via HMD and desktop displays. Their results were compared in terms of navigation and spatial knowledge acquisition. The two virtual buildings for HMD and desktop had a similar number of rooms and the same navigation decision points (corridor intersections). There were twelve participants. All participants were asked to test both two virtual buildings. The results showed that on the average, participants navigated faster and farther when using the HMD than the desktop display. Also, employing HMD spent less time when altering directions to check the interior of rooms or to look down corridors at intersections. Additionally, HMD helped participants gain a more accurate sense of relative straight-line distance. Overall, participants had a better performance on HMD displays in their experiment.

As another study compared desktop and immersive facilities, Gruchalla (2004) conducted a project for a real-world industrial problem of oil well-path planning to explore and quantify the added value of immersion. The planning of oil well-paths involves heavy 3D spatial understanding and visualization tasks. A software package, Immersive Drilling Planner, was used in desktop and immersive environments with different interfaces but identical scenes and dynamics. The immersive environment was a four-sided immersive projection-based display driven by one Silicon Graphics Incorporated (SGI) computer. Participants wore shutter glasses to see stereoscopic images. The desktop equipment included a monitor, mouse, and keyboard, connected to the same SGI computer used in the immersive study. This desktop system also generated stereoscopic graphics, but did not have the head tracking system. Therefore, it did not have immersive effects.

In experiment, there were sixteen participants, four tasks, and two performance measures for each task, including completion time and correctness. In regard to correctness,
nine participants performed better in the immersive environment, one with the desktop, and six were identical. For the completion time, the difference was even more obvious. Only one participant took a longer time in the immersive environment. Therefore, participants involved with immersive facilities had better performances with both measurements.

Although these prior studies exhibited a superiority of immersive VR systems, it is not safe to assume they always work better than the non-immersive systems. There is no systematic study or framework exploring which type of 3D tasks is most appropriate for immersion. Gruchalla (2004) mentioned that the spatial complexity of the task could be a factor influencing the value of immersion, because the tests of simple spatial scenes did not show a significant difference between immersive and desktop systems. This indicates that immersion may be more helpful to simulations with complicated 3D scenes.

A viewpoint brought up by Travis, Watson, and Atyeo (1994) is that judging a VR system by immersion is specious, because the users should be the center of the evaluation, but they are often ignored. Travis, Watson, and Atyeo (1994) argued that HMD reduces a user's sense of security, freedom of movement, and eye contact. Thus, users become legally blind after wearing the HMD. If the simulation does not fit users' interests, they may not immerse. A scenario is that while reading books in subway, readers can be totally attracted by the contents no matter how noisy the environment. Even the book is obviously not an immersive media technically, but it provides exactly the information readers want. How to make VR products better meet user's requirements should be a concern, but not only constrained to the technologies employed.
Feature of VR - Interaction

Interaction is another important feature of VR. A most common interaction used in VR is the navigation. When users move their goggles, wands, or other devices, simulation can be updated to the correct perspectives. Some mechanisms have been created to simulate navigations in the physical world. For example, a virtual avatar can be applied with gravity, so he or she will always stay on the ground or jump within a certain distance. In architectural VR applications, navigation is used extensively to examine the spatial perceptions or for other purposes.

More advanced interactions allow users to move virtual objects or other manipulations, so that the virtual space becomes dynamic. An issue of the interactions is that they should be real-time, if the lags are not made on purpose. It was proved that the increased display lags and head motions could reduce the performance and cause perceptual instability (Allison, Harris, and Jenkin, 2001).

As more and more complex computing systems become, how to make them easier to use becomes an important issue. In which way can users most benefit from the communications with computing systems? This issue does not only exist in VR, but actually in all fields of computers. During the middle of the last century (Gaines, 1985), a new academic area was born—human-computer interaction (HCI).

Interaction with Computers

The starting point of concerning human factors can be dated to 1947, when Mauchly addressed the usability of subroutine facilities (Gaines, 1985). During the 1940s, human factors began to be researched intensively to solve the conflict between machine complexity
and the limits of human ability for safe operation (Butler, Jacob, & John, 1999). Since then, with the rapid growth of computers, related studies become more and more essential to allow people to easily adapt to the emerging technologies. The employment of a graphic user interface (GUI) dramatically freed users from command typing. This made computers more accessible for non-professionals. In such transitions, the role of human-computer interaction was irreplaceable. From websites, operating systems, television, digital cameras, cell phones, personal digital assistants (PDA), mouse and keyboard, to elevator and automobile, HCI can be found everywhere in daily lives. As a definition, Chen (2001) described HCI as:

"Human-computer interaction (HCI) is a multi-disciplinary subject that involves information technology, computer science, psychology, library science, education, business and management, human factors, industrial engineering and ergonomics. As more and more people’s life relate to interactions with computer systems, researchers, designers, managers and users have ever-stronger desires to understand the complexity, current situation and future development of HCI... The effective HCI has been recognized as a very promising and challenging area for both research and applications... In the context of human computer interaction, the relationship between a human and a computer involves many factors such as the computing environment, the nature of the tasks to be performed, as well as various characteristics of the users. The effectiveness of a human-computer interface system is influenced greatly by its ability to adapt to these factors. (Chen, 2001, p. i)"

The design of HCI is harder than many other engineering fields (Butler, Jacob, & John, 1999), as they noted in their paper, “the developer’s task of making a complex system appear simple and sensible to the user is in itself a very difficult, complex task” (p. 100). A
large-scale HCI work is almost always a team product by professionals with different backgrounds. For instance, a HCI team in software design can incorporate information architect, user experience researcher, interaction designer, visual designer, usability engineer, etc. Similarly, the development of a VR product can involve professionals in electronic engineering, computer science, art design, 3D modeling, and usability engineering. The more complex a VR simulation, the heavier demand it will have for a crew of diversity.

For desktop packages and websites, there are very mature guidelines and interface builders available by which developers can easily follow and use. For instance, the interface design guidelines on Apple computers (Apple, 2005) have specific requirements on user input, drag and drop, texts, icons, cursors, and more. If a new package is designed in this manner, then it will take a shorter time for experienced Apple users to learn it. To quickly work out the interface prototypes, there are interactive tools which provide libraries of icons, menus, buttons and their related codes, such as the Macromedia Dreamweaver (Macromedia, 2005). To generate a button, developers simply need to drag a button onto the screen, and that button will be exactly the same as the final button seen by end-users. Such a concept is usually called WYSIWYG (what you see is what you get).

However, in VR, there is still no interface or interaction standard. Neither is there any convenient interface builder. One reason causing this problem may be the diversity of VR equipment. Such diversity may restrain from developing a standard interface framework that developers can easily use on different equipment. A second reason may be the lack of a commercial driven force. VR equipment, especially immersive facilities, are still not affordable for common users. The small pool of potential clients may hold back the momentum in builders or companies to develop interface guidelines.
Interaction Styles

As previously stated, the interaction techniques for desktop computers are better developed than for VR. A well-known study of interaction styles for desktop computers by Shneiderman and Plaisant (2004) addressed them as direct manipulation, menu selection, and form fillin. In the following, these three interaction styles are selected as a means for discussing interaction mechanisms available in desktop VR and immersive VR environments, even though there are differences between the two platforms.

Direct Manipulation

Buttons and icons are two frequently used direct manipulations, which are universal interaction techniques for a desktop platform. Additionally, there are other directly manipulated objects in different packages. For example, images can be distorted or skewed in image editing programs, and models can be rotated or arrayed in 3D modeling programs.

“Direct manipulation is appealing to novices, is easy to remember for intermittent users, and, with careful design, can be rapid for frequent users” (Shneiderman & Plaisant, 2004, p. 71). But as they also pointed out, “for experienced typists, taking a hand off the keyboard to move a mouse or point with a finger may take more time than typing the relevant command” (Shneiderman & Plaisant, 2004, p. 233).

An issue of direct manipulation is that users must learn the meanings of visual representations on an interface (Shneiderman & Plaisant, 2004). Some large programs have hundreds of graphic icons, which could be a challenge for novices to recognize. As a solution, a professionally-designed interface usually shows a tip when the cursor stays on an icon. Also, some tests can be set to check the effectiveness of graphic representations. For
example, in an icon-matching test, users are asked to match each icon and its function. The results can indicate how accurately and easily the icons will be recognized.

By clicking, dragging, or simply moving the cursor on buttons or icons, users can receive visual or aural feedbacks as confirmations of their operations. In VR, the feedback, especially the tactile feedback, is often insufficient. In the real world, people always feel the haptic forces when their bodies come in contact with other objects. If this is lost in VR, the realism of direct manipulation can be harmed (Mine, Brooks, & Sequin, 1997).

While the direct manipulation with a desktop has proved its effectiveness, the manipulation of objects in VR is still not satisfactory. Poupyrev, Weghorst, Billinghurst, and Ichikawa (1997) explored a framework for studying manipulation techniques for immersive VR. They defined the basic direct manipulation tasks in VR as the same tasks that people perform in the physical world in positioning movements, which are “a combination of reaching/grabbing, moving and orienting of objects” (p. 22). Poupyrev, Weghorst, Billinghurst, and Ichikawa (1997) described the five basic interaction tasks as: “(1) Position – the task of positioning an object; (2) Selection – the task of identifying an object; (3) Orient – the task of orienting an object; (4) Text – the input of a string of characters; (5) Quantify – the input of a numerical value” (p. 22).

To accomplish a task, there are many conditions which may influence human performance significantly from case-to-case. Poupyrev, Weghorst, Billinghurst, and Ichikawa (1997) classified them as follows (p. 22):

- User-dependent: experience, cognitive, perceptual and motor abilities, anthropometrical difference, and so on.
• Input/output device dependent: attributes of the devices such as degrees of freedom, resolution, field of view, supported depth cues and others.

• Interaction techniques dependent: underlying metaphors of techniques, their design and implementation.

• Application dependent: configuration of the VE, size, shape and locations of objects, color, lighting and other.

• Task context dependent: required precision, initial and final conditions of a task, task constraints and others.

The input device in VR is often a problem for direct manipulation. In architectural simulations, usually the keys of walking forward, stop, acceleration, and turning directions are needed on a wand. Integrating so many functions could be troublesome, if the wand interface is not carefully designed. Some wands do not have effective visual indications on their interfaces. For instance, some numbers are simply printed on the buttons, but it is difficult to distinguish which one is for walking forward, and which one for stop. Even users can remember them the first time, but how long the memory can retain the information?

Menu selection

As mentioned by Shneiderman and Plaisant (2004), a great benefit of menu selection is that its structure is very easy for the operator's decision-making, because the menu items are listed one-by-one simultaneously and very convenient to compare. The terminologies on the menus must be chosen carefully and used consistently (Shneiderman & Plaisant, 2004), which can be helpful hints to their functions. Among the different menu systems (Figure 29), the single and linear menus are obviously the simplest ones, but they are enough to
accomplish certain tasks. The tree structure is the most frequently used, and the other two may be difficult for some users (Shneiderman & Plaisant, 2004).

Similar to the input device, there is no dominant menu system in VR either. Komerska and Ware (2004) compared the linear and pie menus in a Fish Tank VR environment. Among straight, slant, and pie menus, their results showed that the pie menu is faster and more accurate than the other two in selecting objects. Bowman and Wingrave (2001) compared the floating menu with a pen and tablet menu which uses a real cardboard and pen as a physical interface, and a menu system driven by digital gloves. The pen and tablet menu system was found to be faster than the other two. However, since it displays all the buttons at the same time, it may present problems when the number of buttons is too large. Furthermore, its physical interface can make users tired.

**Form fillin**

This is often used for data input. It could be a more difficult task than the other styles: “...with the form fillin interaction style, users must understand the field labels, know the permissible values and the data-entry method, and be capable of responding to error
messages. Since knowledge of the keyboard, labels, and permissible fields is required, some training may be necessary” (Shneiderman & Plaisant, 2004, p. 71).

Form fillin is rarely used in VR, since the text entry is extremely hard in an immersive environment. In a full-immersive environment, holding a keyboard in hand is very inconvenient. After wearing the shutter glasses, it is difficult to distinguish the keys on the keyboard clearly. McCaul and Suthlerland (2004) explored the predictive text entry with digital gloves, by which an average speed of nine words per minute was reached after twelve minutes of training. Experienced users could type over seventeen words per minute. Obviously, such a speed is still too slow for normal communication.

Shneiderman and Plaisant (2004) ranked the order of difficulty of each interaction style. Based on their conclusions, Table 1 is generated. From this table, it is noticed that the menu selection is an appropriate interaction technique for users at all levels. In this thesis project, there are many architectural terms translated from Chinese which could be very difficult for western users or non-architectural people to recognize, judge, or remember. It may be beneficial to display them clearly as texts somewhere. Menu selection provides a solution that these terminologies are shown as menu items simultaneously, which is helpful for users’ decision-making (Shneiderman & Plaisant, 2004). It can be the cognitive-aids that people with poor short-term memory or novices can easily retrieve the terminologies through the menu items. Moreover, since this thesis project will demonstrate the building constructional steps, the order of the menu items from top to bottom can match with the constructional sequences very well.

In addition to the above three styles, other unique interaction techniques have been created in VR, such as augmented reality (AR) and virtual avatar. AR has received
Table 1. Interaction styles for different users (based on Shneiderman & Plaisant’s conclusions)

<table>
<thead>
<tr>
<th>Interaction Styles</th>
<th>Novices</th>
<th>Intermittent Users</th>
<th>Frequent Users</th>
</tr>
</thead>
<tbody>
<tr>
<td>Menu Selection</td>
<td>Appropriate</td>
<td>Appropriate</td>
<td>Appealing (with rapid display and selection mechanism)</td>
</tr>
<tr>
<td>Direct Manipulation</td>
<td>Appealing</td>
<td>Easy</td>
<td>Rapid (with careful design)</td>
</tr>
<tr>
<td>Form Fillin</td>
<td>Can be Hard</td>
<td>Appropriate (for knowledgeable Users)</td>
<td>Appropriate (for knowledgeable Users)</td>
</tr>
</tbody>
</table>

significant research attention recently. The interfaces “fuse the real and virtual worlds together by accurately overlaying virtual content on a view of the real world” (Looser, Billinghurst, & Cockburn, 2004, p. 204), and “offer a natural view of real scenes enriched with virtual objects” (Wojciechowski, Walczak, White, & Cellary, 2004, p. 135). A system to create virtual and augmented museum exhibitions was explored by Wojciechowski, Walczak, White, and Cellary (2004). It allows visitors to touch the virtual artifacts. The feedback from users proved it to be an effective supplement to virtual reality techniques. Lin, Abi-Rached, and Lahav’s (2004) study showed that the employment of virtual avatar could effectively reduce the sickness and increase the participants’ sense of presence and enjoyment. Garau, Slater, Vinayagamoorthy, Brogni, Steed, and Sasse’s (2003) research proved that the inferred eye animation of avatar has a significant positive influence on users’ response in an immersive environment.

**Needs of Incorporating VR in Architecture**

As stated in chapter one, all current major visualization methods in architecture, including physical model, digital still imaging, animation and hand drawing, have their
limitations. These media either cannot present buildings with their real dimensions, or do not allow interactions that users can navigate or manipulate them at real-time. VR, emerging as a new competitor, overcomes these issues. Some full-immersive VR facilities, such as the C6, can provide an enclosed space in which the users are entirely surrounded by simulations. Such an advantage of VR has never been achieved by other visualization methods.

**Architectural VR Requirements**

Usability is often used to evaluate computing products, concerned with how easily the product is accessed and used. The term, usability, was defined as “the extent to which an end-user is able to carry out required tasks successfully, and without difficulty, using the computer application system” (Ravden & Johnson, 1989, preface). There are criteria used to evaluate the usability for different devices or applications. Zhai (1998) discussed six aspects of usability for six DOF input devices, including speed, accuracy, ease of learning, fatigue, coordination, and device persistence and acquisition. As general guidelines, Shneiderman and Plaisant (2004) summarized five criteria to measure the usability in practical evaluations (p. 16):

1. *Time to learn.* How long does it take for typical members of the user community to learn how to use the actions relevant to a set of tasks?
2. *Speed of performance.* How long does it take to carry out the benchmark tasks?
3. *Rate of errors by users.* How many and what kind of errors do people make in carrying out the benchmark tasks? Although time to make and correct errors might be incorporated into the speed of performance, error handling is such a critical component of interface usage that it deserves extensive study.
4. *Retention over time.* How well do users maintain their knowledge after an hour, a day, or a week? Retention may be linked closely to time to learn, and frequency of use plays an important role.

5. *Subjective satisfaction.* How much did users like using various aspects of the interface? The answer can be ascertained by interview or by written surveys that include satisfaction scales and space for free-form comments.

These five criteria can be safely employed in most computing fields, including VR, which can be measured and analyzed statistically.

Architectural VR has its own features and needs. However, no prior study about that has been found so far. In this thesis, three requirements of architectural VR are proposed as follows. They may be hard to be precisely measured, but serve as general guidelines.

1. **Model Realism:** the realism of 3D models usually involves materials, lighting, and geometries. VR still cannot support complex materials and lighting. To achieve a real rendering in VR, texture is a key factor.

2. **Reflection of Architectural Value:** this is the core of architectural VR, which is quite related to the simulation’s topic and contents. What are the architectural knowledge values embedded? It is most likely a task for architectural researchers and should be well prepared before actually implementing in the VR system.

3. **Richness of Interactions:** navigation is a simplest and most frequently used interaction in architectural VR. It could be beneficial to include other dynamic interaction styles. However, the key point is that those interaction styles must make unique contributions, which cannot be replaced by navigation. Otherwise,
they are redundant. To make the simulation interactive, it is better to serve users and present architectural values, not just a demo of techniques.

**Prior Interactive VR Applications in Architecture**

There have been some previous studies of utilizing VR in architecture. The cultural heritage preservation is a field in which the VR has been employed frequently (Zach, Klaus, Bauer, Karner, & Grabner, 2001; Gaitatzes, Christopoulos, & Roussou, 2001). The historical buildings and cities can be reconstructed with vivid details in digital formats and presented to the public in museums or online. Patel, Campion, and Fernando (2002) evaluated the use of VR to brief clients. Their study demonstrated that VR is effective in architectural presentations which can greatly facilitate clients' understanding of the design. Through VR simulations, the spatial dimension, contextual information, and design's realism can be appropriately conveyed. VR had also been explored in the field of architectural design. Frost and Warren (2000) had tried to develop a process on designing laboratory layouts. From their study, VR was confirmed to be beneficial in the collaborative design process. Their results had been incorporated into the building program for the new lab. Anderson, Esser, and Interrante (2003) created a virtual environment for architectural conceptual design, targeted at emulating a typical architect's work area. The basic geometries can be created and manipulated via a kiosk toolbox. Also, this virtual environment can use the imagery and video taken outside.

Most implementations of VR in architecture are concerned with navigation in static space, but only a few studies have explored how to make them interactive. One reason may be that in the physical world, buildings always still objects and remain unchanged. Thus,
navigation is an easy task for people to manipulate. So far, there is no easy-to-use prototyping tool available to implement advanced interactions in VR, especially for the high-end UNIX machines. Technically, it could be very hard for architects to write codes themselves.

Two prior projects related to interactive architectural VR are reviewed as follows. Their strengths and weakness are discussed and compared.

**An Interactive Museum for the Northwest Palace**

A real-time interactive museum was developed by Kim, Kesavadas, and Paley (2003) for the Northwest Palace in Iraq. The purpose of this virtual museum was to preserve damaged and vanishing cultural heritages. It was hoped that users are able to benefit from their research in archaeology, art, and architecture through this immersive real-time environment. The process of their virtual museum project included modeling, model conversion, VR programming, and presentations in VE devices.

As the paper describes, there are four types of interaction features implemented in this project, including navigation, collision detection, information activation and virtual artifacts. The navigation has two types of manual and automatic interactions. For the latter, it has predefined paths, so users do not have to operate it themselves. This is an easy way to go through the scenes effectively, since researchers can make the paths passing all the most valuable spots. Collision detection makes the walls unpenetrable via the techniques of bounding boxes. By clicking the wand or virtual touch, users can trigger the information activations, which include narrations of the building’s historical knowledge, and the King’s voice and motion. Also, users can control the movable virtual artifacts (Figure 30). Their
collision with the virtual hand can be automatically detected. The task is similar to the “click and drag” in the windows desktop system. After an artifact has been selected, it receives the same spatial data in the computing system with the virtual hand. Thus, it can be moved in the virtual space at real-time.

Compared to the first two types of interactions concerned with navigation, the last two are more advanced. The narrations express the cultural information in sound, which may be ineffective to be explained by texts in a virtual environment. As Kim, Kesavadas, and Paley (2003) mentioned, the grabbing of objects make users feel a better connectivity with the virtual environment. Thus, they might be more immersed in the simulation.

Hands-Free Image-Based VR System - Virtual Museum

Hii (1996) developed a multi-user, unencumbered VR system for the masses that involved the hands-free technique. The greatest feature of this system is that only the feet are needed to control the simulation via a pressure sensitive mat, which detects the feet position and contact with the ground. This technique may be especially appropriate for the public exhibition, as “a relief for a user who is lugging museum pamphlets or a mother herding several children” (Hii, 1996, p. 184).
As pointed out by Hii (1996), the passive stereo projection was used to generate the immersive images instead of HMD for three reasons. Firstly, a projector is less cumbersome than HMD; secondly, a projector allows multi-user viewing at the same time; thirdly, with convincing stereo images provided to users, a projector offers a higher error tolerance. Hii (1996) also mentioned that because this virtual museum was for public display, the expected high volume of visitors requires that the VR system be robust, accessible by groups of users, simple to use, and easy to maintain.

Different from the other architectural VR simulations mentioned in this chapter, this one used the pre-generated graphics, which indicated that the real-time navigation is not supported. Two reasons were given in the paper concerning this. First, the quality of non real-time graphics is better than real-time renderings. This is a significant issue of current VR renderings. Second, the limited interactivity may be better for naive users, which "prevents them from getting lost and guarantees that the user will see those 'nice camera angles'" (Hii, 1996, p. 184). Therefore, the interactions in this hands-free project are to select, pause, and resume videos.

The video is paused when both feet are down, and resumed when a foot is raised. If the user keeps walking, the video will be played continuously. When a museum artifact is encountered, the video stops. Then, the user needs to decide to turn left or right by stepping on left turn or right turn foot icons on the sensitive mat. Selecting a direction actually starts another new video file. In summary, the body movements involved are walking (play video), standing (pause video), and stepping on foot icons (select video).
According to the paper, a limitation of this hands-free system is that it only allows one user to drive the simulation, although a group of people can view it simultaneously. Hii (1996) proposed a networked version as a possible solution.

Comparing these two VR applications, the interactive museum for the Northwest Palace reflects richer architectural values such as the building’s historical knowledge via narrations. It has some concerns for users. As its researchers mentioned, the grabbing of objects can offer users a better connection with virtual environments and let them become more immersed in the simulation (Kim, Kesavadas, & Paley, 2003). But, the consideration for users was not sufficient nor was not discussed in detail in the paper.

The hands-free museum did not mention its architectural contents in the paper. Thus, it is hard to judge its model realism or architectural values. Its greatest advantage is the convenient design for museum visitors holding brochures in hand. Actually, in the physical world, people do navigate by feet, but not by handheld devices. Thus, its hands-free interaction technique may be a very natural method. A weakness is that it did not use the interactive graphics. Although it may not be as advanced as another simulation technically, its design concept for users is unique.

Summary

This chapter first discusses the five key components of a VR system: VR engine, input/output devices, software and databases, user, and task. The 3D input devices are reviewed in detail, since they are the equipment by which users directly interact with VR simulations. The conclusion is that currently still no input devices or techniques which can fully fulfill the usability requirements of 3D operations. The two key features of VR,
immersion and interaction, are discussed. Although users of immersive equipment showed a higher performance overall in precedent studies, the more systematic study of human factors in immersion is still needed. The interaction styles, including direct manipulation, menu selection, and form fillin, are reviewed and concluded in terms of their appropriateness for new, intermittent, and experienced users. Three requirements for constructing an appropriate architectural virtual environment are proposed as model realism, reflection of architectural value, and richness of interaction. Some prior interactive architectural VR applications are reviewed and their features are compared.
CHAPTER 4
INTERACTING WITH COURTYARD HOUSE IN VR

To effectively apply interactions in architectural VR, the efforts from multiple fields are always needed. This chapter discusses the methodological steps employed in this project to develop an interactive VR simulation. Based on research of courtyard housing, the first step is VR modeling, followed by interaction planning and C6 implementation (Figure 31).

Site Selection

The prototype of the courtyard house digitalized in this study locates at the XiSiBeiLiuTiao (the 6th Northern Hutong of W. 4th St.) in the northwest of Beijing Inner City. The northwestern and northeastern parts of the Inner City had the top-level courtyard houses in Beijing (Wang & Lu, 1996). As one of the best well-preserved districts in Beijing, there still exhibits traditional building styles. The hutongs in this district are almost east-western orientated, which is a typical layout. Summarized by Wang and Lu (1996), the courtyard houses located in the east-western hutongs were of better quality than the north-south or irregular ones. From a perspective of urban context, this district is an ideal site to study courtyard housing.

This courtyard house is a typical middle-size housing complex with four inner yards. Currently it
is used as a kindergarten. The house has been carefully preserved. Its structures, decorations, materials, etc. are still in good shape. Typical components of Beijing's courtyard houses, such as shadow walls, stones to step on and off horses, are also found to be intact. To accommodate more residents, many additional temporary buildings were added in the inner yards of Beijing's courtyard houses during the last century. They were usually not professionally designed and had created considerable harm to the original architecture. Fortunately, they are not seen in this courtyard house. Its good conditions make it an excellent prototype of the courtyard house for this study.

**VR Modeling**

Digital 3D models have been used extensively in architectural research and design. They can be built precisely and applied with materials, lighting, and environments to produce photo-realistic images and animations. Depending upon the model's complexity, the renderings can be generated immediately or within a short time.

Compared to the modeling for high quality renderings, VR modeling has its particular features, which are mainly caused by the limitations of current VR technologies. Since VR simulations usually need to be refreshed at real-time, heavy calculation tasks require that the file size be controlled below a reasonable level in order to get a smooth running in VR facilities. This indicates a balance between the model's details and simplicity must be properly established.

In any VR system, the ease of model building is very significant (Liu & Huang, 2000). However, the 3D modeling for interactive VR is "an expensive and tedious process" (Sormann, Bauer, Zach, Klaus, & Karner, 2004, p. 148). Han and Medioni (1997) analyzed
the problem from three aspects. First, 2D input devices are inconvenient for 3D tasks; second, 2D output devices lack enough spatial information and visual assistance for 3D objects; and third, only limited developers may have enough artistic and computer abilities in model building.

There are roughly two major modeling methods, manual and automatic, applied in the field. Currently, the manual modeling is more frequently used, which usually needs input of dimensions, textures, and other information manually in modeling packages. To simplify the modeling tasks, some automatic or semi-automatic methods have been developed, which can extract models directly from raster images. The VR Modeler, an interactive modeling system from Sormann, Bauer, Zach, Klaus, and Karner (2004), is capable of generating models from image sequences. Similar modeling methods have been explored by other researchers (Pollefeys & Van Gool, 2002; Lyness, Marte, Wong, & Marais, 2001; Liu & Huang, 2000). Although automatic or semi-automatic methods may be effective under certain circumstances, they were not employed in this thesis project; since they are still not sufficiently reliable to generate models with complex 3D forms, particularly the roof forms in Chinese architecture. Moreover, the quality of available courtyard house photos is not good enough to support an accurate 3D information extraction.

Chan, Tong, Dang, and Qian (2003) explored methods of VR modeling for traditional Chinese architecture on the Temple of Heaven in Beijing. Basically, their method is totally manual. Their process included developing a PC digital model, assigning materials, and converting them into VRML format for VR display and implementation in C6. The modeling packages they used are AutoCAD and 3DS Max. In this thesis project, a similar procedure was adopted because of the similar topic and VR equipment.
In general, the modeling process is linear, but not ultimately a one-way task. There were many revisions among these modeling steps (Figure 32). For example, after the model was exported to 3DS Max for material assigning, some errors including missing faces were found on some of the components. Then, the problems were fixed in the previous step and the corrected parts were exported individually and plugged into the scene. Also, during the file conversion step, it was found that the number of nodes was too large. Thus, the model in 3DS Max was revised to reduce this.

**Geometrical Model Building**

In architecture, drawings of plans, elevations, and sections are often used to build an accurate model. In this project, the modeling was mainly based on two resources—the survey drawings provided by the Beijing University of Technology, and photos taken at the site (Figure 33). The overall dimensions were based on the survey drawings, such as the inner yards’ sizes, the buildings heights, and the distances between columns. For some details, such as the roof’s ridges, the photos were cropped to get their textures, which are used in the next step of material assigning. To match the model exactly with the textures, the images

Figure 32. VR modeling process
were imported as backgrounds in AutoCAD and the lines were traced on them to build 3D models.

The AutoCAD was selected as the modeling package in this step, because it is easy to input data and capture points precisely. Moreover, the survey drawings from the Beijing University of Technology were generated in AutoCAD format. It is much easier to retrieve the measurements and other information from the same package. The AutoCAD model was exported as 3DS format and then imported into 3DS Max. The reason for choosing 3DS format is that when exported from AutoCAD, it can automatically filter out the 2D objects, which are unnecessary parts in the model for 3DS Max. Some minor modifications such as

Figure 33. Photos of courtyard house prototype (provided by Chiu-Shui Chan, Iowa State University)
increasing the height of objects were finished in 3DS Max because of its convenient sub-component operations. At the end, the entire model was checked piece by piece manually to assure that there is no extra polygon in the scene.

A geometrical model was then prepared for material assigning. Since the model is quite large with more than six hundred objects, managing it became an issue. In this project, a naming algorithm was used to name the objects as an approach to manage the model efficiently.

**Naming Algorithm**

Similar to computer programming, a proper naming method can benefit other developers to understand the author’s work. This thesis is part of the Beijing Inner City project that other models may be added later. Therefore, it is crucial to create a proper guideline that other researchers can easily understand this model.

The algorithm employed has a tree structure, which is similar to the method developed by Chan, Tong, Dang, and Qian (2003). The entire name of an object has three parts indicating three different levels. The first level represents the yards, such as the first yard, second yard, etc. It takes one character, such as “a” for the first yard (Figure 34). The second level represents the buildings in that yard, such as the main hall (ZhengFang) and side buildings (XiangFang). It also takes one character. For example, the “DaoZuoFang” is “d”, and “XiangFang” is “x”. The third level represents the building’s components, such as roofs,
walls, and columns (Table 2). In 3DS Max, objects are usually listed alphabetically, so it is very easy to select all the objects with the same initial characters, and operate them together as a group. For example, if the side building in the second yard needs to be moved, then users need to select all the objects starting with “bx”, and group them together.

Table 2. The naming algorithm

<table>
<thead>
<tr>
<th>Objects (expressed as yard, building, object)</th>
<th>1st level</th>
<th>2nd level</th>
<th>3rd level</th>
<th>Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>The first yard, DaoZuoFang, Wall</td>
<td>a</td>
<td>d</td>
<td>wall</td>
<td>adwall</td>
</tr>
<tr>
<td>The second yard, Side Wing (Xiang Fang), Roof</td>
<td>b</td>
<td>x</td>
<td>roof</td>
<td>bxroof</td>
</tr>
<tr>
<td>The second yard, Side Wing (Xiang Fang), Column</td>
<td>b</td>
<td>x</td>
<td>clmn</td>
<td>bxclmn</td>
</tr>
<tr>
<td>The third yard, Main Hall (ZhengFang), Column</td>
<td>c</td>
<td>z</td>
<td>clmn</td>
<td>czclmn</td>
</tr>
</tbody>
</table>

This naming algorithm is used for this model only, which may not be applied efficiently in other projects. If another courtyard house in the Beijing Inner City is modeled in the same way, then there may be a problem when these two models are merged together, because some of their parts will have the same names. To solve this problem, a possible method is to assign a unique city block ID number to each courtyard house, and add that number at the beginning of the naming algorithm. For example, if the block ID is 7057, which represents the city block that the courtyard house is located, then the wall of the DaoZuoFang will be “7057adwall”.

Model Complexity Controlling

During the modeling step, several factors were found influencing the run-time speed of VR systems, including the number of polygons and the size of textures. The feeling of
realism may be harmed if the system delay is obvious. But, if the number of polygons or the dimension of texture is too small, the information embed in the model may not be fully exhibited. This is often an ambiguity for architectural VR modeling.

To control the number of polygons, the objects were modeled, based on their chances to be seen by users. The objects which will be seen very frequently, such as the buildings' front elevations, were modeled with more details. The surfaces which are never seen were not modeled at all, such as the column's bottom sides. All the circles were drawn as eight-sided polygons to control their complexity.

While modeling in AutoCAD, the 3D face was used extensively for two reasons. First, solid modeling will occupy more memory and disk space, which can significantly slow down the computer's speed. Second, the 3D face modeling handles directly with polygons in AutoCAD. While using the 3D face, modelers know exactly which polygon they are working on. However, in solid modeling, 3D objects must be exploded before accessing to the polygon level, which makes the task complex.

**Materials Assigning**

Material assigning for VR is very different from the typical method for high quality renderings. For the latter one, some advanced techniques are often set up such as bump, blend, reflection, and refraction to create photo-realistic graphics. It is the computer's job to automatically generate the textures' details such as shadows. These advanced settings may take hours or even longer to render a single image. However, in VR, these techniques for materials or lighting are usually not supported. Otherwise, the graphics in VR cannot be
refreshed at real-time. Consequently, the textures’ details must be made manually in VR. If they are used effectively, the simulation’s realism will be improved dramatically.

In this project, some textures were cropped from the photos. Since most photos were taken from angles, they were modified to make the textures into the correct shapes and scales (Figure 35). In addition, some textures had to be illustrated manually from 2D graphics (Figure 36), because the number and quality of photos were limited. An advantage of this method is that the textures can be precisely dimensioned. However, a problem was found. These illustrations did not show the sense of history, such as scratches. A method to solve this issue is to draw the scratches manually through image editing tools.

**Tiled vs. Baked Texture**

There are two major methods to assign materials. The first is tiled texture, which means that the texture is repeated on objects. It can use a small texture on a large-sized object, which is beneficial to save computer memory. In high-quality renderings, computer can generate shadows or other details on tiled textures. However, VR does not support these advanced techniques.
Without shadows, transitions of colors, or other subtle details, the objects may look dull. To solve this problem, a method is the baked texture. It can automatically combine original textures and computer-generated details into a new image. Then, this image is assigned to the object to replace the old texture. As shown in Figure 37, although the shadows are pre-generated instead of real-time, they still strengthen the model’s visual appearance.
Obviously, a disadvantage of baked texture is that its dimension is usually large. Using it frequently may negatively affect computer performance. In this project, only a few areas use this technique, such as the main gate. To get the best result, a key is to balance these two types of texture properly.

**File Converting**

In this step, the 3D model with textures applied was converted from 3DS Max into VRML format. Basically, the conversion was completed by 3DS Max automatically.

When the VRML model was shown in C6 for the first time, there were very obvious lags lasting for five or six seconds. Obviously, such a longtime delay harmed the simulation. If users must wait a long time after clicking the button, they will not perceive any interaction.
It took a long time to optimize the model for the C6 display. So far there is no example of a large-scale architectural model which can run smoothly in C6. There is no standard or guideline for how models should be built for C6. For example, what is the limitation of textures or polygons in the model?

Based on prior experience of VR modeling for PC simulation, the lags may be caused by texture dimensions, and the number of polygons or nodes. To find out how to optimize the model, six versions of the model with the same polygons (34565 vertices, 33490 faces) were tested in C6. As Table 3 shows, the number of nodes at 585 is obviously too large. The simulation speed is even slow with only one texture. Therefore, the number of nodes must be a key reason to slow down the simulation. Also, large size textures can also slow the running time speed. Since there is no large texture used in the original VRML model, the number of nodes should be the major problem. In summary, the number of nodes, and the dimension of textures are two critical factors influencing simulation speed in C6. To test this conclusion,

Table 3. Test of courtyard house models in C6

<table>
<thead>
<tr>
<th>Test</th>
<th>Number of Nodes</th>
<th>Textures</th>
<th>Responses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test 1</td>
<td>5 nodes</td>
<td>No texture</td>
<td>Very quick</td>
</tr>
<tr>
<td>Test 2</td>
<td>5 nodes</td>
<td>1 texture (32x32 pixel)</td>
<td>Very quick</td>
</tr>
<tr>
<td>Test 3</td>
<td>5 nodes</td>
<td>5 textures (32x32 pixel)</td>
<td>Very quick</td>
</tr>
<tr>
<td>Test 4</td>
<td>5 nodes</td>
<td>5 textures (512x512 pixel)</td>
<td>Very slow</td>
</tr>
<tr>
<td>Test 5</td>
<td>585 nodes</td>
<td>No texture</td>
<td>Noticeable lag</td>
</tr>
<tr>
<td>Test 6</td>
<td>585 nodes</td>
<td>1 texture (32x32 pixel)</td>
<td>Extreme slow</td>
</tr>
</tbody>
</table>
five other architectural models were tested in C6. Each has several versions of different
nodes and textures. It was confirmed that the conclusion is true without any exception.

When converting from 3DS Max into VRML, one object will have one node of
coding representation. In consequence, the number of objects must be controlled in 3DS Max
in order to decrease the number of nodes in VRML. In 3DS Max, all objects with the same
material can be safely attached into one object, in which the same material could apply to
different mapping coordinates. For example, the doors of different buildings can be applied
the same textures separately, and then attached together. Objects with different materials can
also be attached together with a multi-object material. However, such type of material is not
supported in VRML. Therefore, the number of nodes is entirely dependent upon the number
of textures. That is, the number of nodes is material-driven in 3DS Max. By reducing the
number of node to sixty-nine, the simulation turned out to be much smoother. An attempt
was made to decrease the dimension of texture from 256x256 into 64x64 to improve speed,
but the contribution was not obvious. Also, the small-sized texture may harm the visual
fidelity of historical architecture too much.

**Level of Detail Model 1**

Although the C6 simulation turned out to be much smoother after reducing the
number of nodes, there were still noticeable lags. Then, the level of detail (LOD) method was
attempted to improve the speed further.

To use LOD, developers should define a point as the center of LOD range. The
mechanism of LOD is distance-dependent, which uses simpler models to replace original
ones according to the distance from the camera to the point of measurement. For example,
developers can define the model's center as the center of LOD range and twenty feet as the value of distance. When the camera is more than twenty feet away from the model, the scene will load a simpler model; when the camera moves closer, the simpler model will switch into a complex model. Therefore, the simulation speed can be improved, while the visual fidelity is not significantly harmed. Obviously, a drawback is that developers must generate multiple versions for the same model.

The LOD model was divided into five parts—first, second, third, fourth yards, and the neighborhood (Figure 38). The first, second, third, and fourth yards were converted as regular nodes. An empty node was written in VRML which actually has no polygons. In the VRML file, each yard and an empty node were incorporated into a LOD node. Each LOD node has its own center and range. While navigating in one yard, a regular node is loaded, and the remaining yards load the empty nodes, so that they are actually hided. Because the LOD range is circular, some LOD ranges overlap. Compared to the non-LOD model, this LOD model has a quicker speed in C6.

Figure 38. LOD model

Level of Detail Model 2

After the previous LOD model was generated, an attempt was made to further increase the speed. For this LOD model, the number of nodes was increased to one hundred and thirty-six. For example, originally the roof of the entire housing complex is only one
object (node). But in this LOD model, it becomes four objects (nodes). As previously stated, the number of nodes influences the simulation speed. Thus, a new idea is to use the LOD concept, but still minimize the number of nodes at the same time.

In developing this new LOD model, a rule was generated. The objects used in multiple yards are not divided to control the number of nodes, such as wall, roof, and column; the objects only used in one yard can be applied with LOD, including Chuihua Gate, main gate, and shadow wall. In such a way, the number of nodes can be decreased to a minimum. For example, while navigating in the second yard, the main gate and shadow wall are hidden, and all other objects, such as the wall, are shown as one node each. Consequently, the number of nodes drawn in the scene is forty-two. However, in the previous LOD model, this number is six-nine, when the camera overlaps the yard 2 and yard 3. Comparing this LOD model with the previous LOD model and the non-LOD model, it has the fastest speed. Therefore, this LOD model was used for the final version in the C6 simulation.

**Interaction Planning**

The purpose of interaction planning is to determine what kind of interactions should be implemented in C6. Before initializing the planning of specific interactions, the purpose of implementing interactions was considered. Can these interactions be simply replaced by static simulations? In this study, one of the key purposes is to decompose the “Tailiang” style structure interactively. Such an operation should contain a set of scenes in sequence, which may be easier to accomplish dynamically than statically.
Demonstrating Timber Frame Structure

In this simulation, the main hall’s structure was planned to be demonstrated interactively. To better present it to users, two questions were considered:

(1) Who are the potential users of this simulation?

(2) What characteristics do they have?

Potential users of this simulation are people who are interested in architecture, no matter what are their backgrounds. Although there is no statistic data about previous C6 users, it is safe to assume that most of them would not have much knowledge of the “Tailiang” structure. Actually, even the Chinese would not be familiar with this if they are not professionals in the area.

To plan specific interactions, an initial issue was how to decompose the structure. Because potential users may have very little knowledge of Chinese architecture, it was considered that the demonstration of structure should be easy. Consequently, the main hall’s structure was determined to be decomposed according to its constructional process. Even for people who are not familiar with Chinese architecture, they still can understand the constructional process without recognizing or remembering the components. Besides, the constructional process logically explains how the building is actually built, which is an easy way for users to understand the structure.

The constructional process of Beijing’s courtyard house contains platform, wood structure, wall, roof, door and window. The wood structure’s constructional process is from bottom to top (Ma, 1999). Therefore, a hypothetical process with seven major steps was generated including platform, column, five-purline beam, ridge purline, wall, roof, door and
window. Each menu item represents one major constructional step. By clicking on menu item, the corresponding step is shown in the simulation.

Navigation

As mentioned before, the courtyard houses in Beijing often have multiple yards along the axis. The word “deep” in Chinese is often used to describe a large-scale housing complex. From the outermost yard to the innermost yard, the yards have different sizes, privacies, and dwellers. Walking yard-by-yard would be helpful to understand their unique plan arrangement and spatial transition.

To further facilitate navigation, there are six camera views pre-defined—main gate, main hall, first, second, third, and fourth yards. The “main gate” enters the house or walks through the hutong, which is the default camera when the simulation is launched. The “main hall” is selected for displaying the constructional process. The cameras of four yards are to quickly switch to the corresponding yard. In C6, the walking speed is controlled by users via the wand.

C6 Implementing

In this step, the courtyard house model and planned interactions were implemented in C6 (Figure 39). The simulation runs on Lego, a SGI Onyx2 machine with 400 MHz R12K processors and InfiniteReality 2 graphics boards. To create immersive graphics in C6, OpenSG (OpenSG Home, 2004) was used as the graphic scene generator controlled by VRJuggler (VR Juggler Homepage, 2004).
As the OpenSG’s website describes, OpenSG is a portable scenegraph system which can run on IRIX, Windows and Linux (OpenSG Home, 2004), with multiple model formats directly including VRML. VR Juggler provides an easy method for connection to C6 facilities, which “may be run with any combination of immersive technologies and computational hardware” (VR Juggler Homepage, 2004).

The C6 implementation in this project was based on the VR Juggler Template Applications Collection (TemplateApps), a collection of VR Juggler example applications developed at Iowa State University (VR Juggler Base/Projects/TemplateApps, 2004). It has settings for menus, camera views, or other functions that developers can easily use. Most
settings in the TemplateApps can be modified via an editable configuration file in XML format. This is very convenient that some recompilation can be avoided.

The TemplateApps can import multiple models into one simulation. During the model conversion from 3DS Max to VRML, the user can choose the level of model precision from three to six. The higher precision will bring better model detail, but also a slower simulation speed. In this project, it was found that most objects could be successfully converted at level four without any problem. However, some complex objects such as the wall always failed at this precision level. They had lost or incorrect polygons. Then the higher precision levels were attempted. These complex objects could be successfully converted at level five. Therefore, some model parts were converted at level four, and others, which could not be converted successfully at level four, were converted at level five. As long as they keep the same coordinates in 3DS Max, their relative positions in the C6 simulation will not be changed.

The courtyard house model was roughly divided into two sets, master model and main hall. The master model does not contain any interaction in the simulation and the main hall shows the constructional process. Table 4 shows all models loaded and organized through the TemplateApps. The demonstration of the constructional process was implemented via the “cyclegroups” in the TemplateApps. This function can switch among different models. For each constructional step, there is a corresponding model of the main hall’s structure. When the user selects a constructional step, the scene will load its model to replace the original one. This is very convenient for architectural researchers. If one model has problems, they can simply replace that specific model without touching the others.
Based on the TemplateApps, the menu system of this simulation has a tree structure with three levels (Figure 40). For the first level, there are items of “Camera Views”, “Interactions”, “Enable Flight”, “Reset Nav”, “Reset Model”, “Save View”, and “Hide” from top to bottom respectively. The “Enable Flight” is to turn on the “flight mode” where users can change the height of camera. If users get lost in the navigation, they can click the “Reset Nav” to return to the starting position of the simulation. Since the models in the TemplateApps can be set to movable, the “Reset Model” returns models to their initial positions. The “Save View” shows the current camera position in the 3D space. To hide the menu from simulation, users need to click the “Hide”.

The “Camera Views” has a set of pre-defined camera views that users can quickly switch, which has a sub-menu with eight items. The top one, “Back”, returns to the main

<table>
<thead>
<tr>
<th>Master Model (no interaction)</th>
<th>LOD</th>
<th>Precision Level</th>
<th>Main Hall (interaction)</th>
<th>LOD</th>
<th>Precision Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Environment (sky, street, ground)</td>
<td>No</td>
<td>4</td>
<td>Platform</td>
<td>Yes</td>
<td>5</td>
</tr>
<tr>
<td>House-simple (simple components of house)</td>
<td>No</td>
<td>4</td>
<td>Column</td>
<td>Yes</td>
<td>5</td>
</tr>
<tr>
<td>House-complex (complex components of house)</td>
<td>No</td>
<td>5</td>
<td>5-Purline Beam</td>
<td>Yes</td>
<td>5</td>
</tr>
<tr>
<td>Shadow Wall</td>
<td>Yes</td>
<td>5</td>
<td>Ridge Purline</td>
<td>Yes</td>
<td>5</td>
</tr>
<tr>
<td>Main Gate</td>
<td>Yes</td>
<td>5</td>
<td>Wall</td>
<td>Yes</td>
<td>5</td>
</tr>
<tr>
<td>Chuihua Gate</td>
<td>Yes</td>
<td>5</td>
<td>Roof</td>
<td>Yes</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Door &amp; Window</td>
<td>Yes</td>
<td>5</td>
</tr>
</tbody>
</table>
menu; the bottom one, “Hide”, hides the entire menu. Users can easily go to the pre-set positions through the other six items.

The “Interactions” is to launch the interactive demonstrations. Its sub-menu has two items, “Constructional Process” and “Gate Styles”. The “Completed Structure” under the “Constructional Process” shows the entire structure of the main hall, which is the default setting of the simulation. The other seven items, from “Platform” to “Door & Window”, demonstrate the major constructional steps. The “Gate Styles” is for future work where different gate styles can be displayed on the main gate. This is not implemented in this project.

The modifications of “cyclegroups” and menu items are associated in the TemplateApps. To add a sub-menu such as “constructional process”, developers can establish a new “cyclegroup” called “constructional process” in the configuration file. To add an item “roof” under the “constructional process”, developers can name a model as “roof” within that “cyclegroup”.

**User Feedback**

There were five viewers who saw this simulation and provided feedback. Two viewers (V1, V2) did not have an architectural background and saw the non-LOD simulation.
The other three viewers (V3, V4, and V5) are architectural professionals, who saw the final version of simulation two months later than the first two viewers. The final simulation has a quicker speed than the non-LOD simulation. Their interactions are very similar. The final simulation has revised terminologies and fewer constructional steps in its menu system.

Users commented that the full-immersion was very effective to show the inner yards without exception. So far, all feedbacks were very positive that C6 is very strong at simulating the courtyard house. As one viewer (V1) described, C6 gave him a feeling of standing in the yard, but PC animation only told him that he is somewhere outside. Another viewer (V3) mentioned that she could feel as though she was in the yards physically, which is difficult to achieve by image sequences.

The timber frame structure had good results in C6. Its dimension, volume, and relationship between components were clearly shown with stereoscopic graphics. In the demonstration of the constructional process, one viewer (V2) commented the interactivity to be not too helpful. It was concerned that showing the process interactively in C6 does not contribute significantly to the users' understanding. Also, it was concerned that the full-immersive environment may distract users, since everything surrounds them. To better demonstrate the constructional process, one viewer (V4) mentioned how the structural components are moved, lifted, and conjoined at the site can be added in the simulation.

Overall, the feedbacks are positive on full-immersion and interactivity. A major concern is the amount of information embedded in the simulation. All three viewers (V3, V4, and V5) who saw the final model mentioned that more details could be added. For example, children playing in the yards, servants cooking in the kitchen, and people studying in the reading rooms, which illustrate daily life and the buildings' functions in courtyard housing.
Also, chairs or stools can be placed in the yards to indicate a building's dimensions. The gardens can have more plants. Another limitation of the simulation was commented (V1, and V3) to be the speed. If the simulation is very smooth without any lag, a better realism can be perceived by users.

The first two viewers (V1, and V2) also saw an animation of the same courtyard house as C6 on a PC monitor (Appendix). The animation was commented to be not effective in showing the inner yards for both of them. One viewer (V2) thought the animation to be equally effective as C6 in showing the constructional process. An advantage mentioned (V2) of animation was its better graphics in terms of resolution, color, and lighting.

**Summary**

This chapter discusses the methods to model the courtyard house, plan interactions, and implement the model in C6. The VR modeling took the longest time in this project. Many trials were tested to determine how to optimize the model for C6 display. It was found that the number of nodes and the dimension of textures are significant factors influencing simulation speed. In the interaction planning step, the main hall's structure was demonstrated based on its constructional process. This simulation was implemented in C6 through the TemplateApps.
CHAPTER 5
CONCLUSIONS AND RECOMMENDATIONS

The previous four chapters have outlined the history of courtyard housing; reviewed VR technologies, HCI techniques, architectural VR applications; and introduced methods of VR modeling, model converting, and C6 implementation. It was found that the exploration of involving interactions in architectural VR is still in the initial stages. The issue of HCI has been ignored in VR and it is still more technology-pull rather than user-pull. There is no universal platform in VR on which the interaction can be easily standardized and developed. Although many input methods had been invented in research labs or commercial companies for 3D manipulation, none of them is dominant in VR applications.

In this thesis project, an interactive VR simulation of Beijing’s courtyard house was developed in C6. The user can navigate and interact with the simulation in this full-immersive VR environment.

Findings

The interactive architectural VR simulation is a highly interdisciplinary field, which combines architectural research, digital 3D modeling, interaction design, computer graphics programming, and other academic aspects. It was noticed that it is crucial to build a user-centered design team for similar HCI projects. To develop an interactive product within an expected time, a cooperation of experts with various backgrounds can dramatically increase both quality and efficiency. In fact, HCI is essentially a multi-disciplinary field where no one person can take charge of everything.
As Barnum (2000) described, there are at least six benefits to build a user-center design team. Four of them are: (1) speed: team members can work on different aspects at the same time, but not in sequence, (2) complexity: the diversity of team members improves the organization’s capability of problem solving, (3) customer focus: teamwork helps meet the needs of users, and (4) creativity: the diversity of team members inspires more creative ideas. In regard to the architectural VR teamwork involving 3D modelers, interaction designers, usability engineers, hardware engineers, and programmers, all these benefits can be successfully applied.

Another finding is the demand of VR scripting tools with graphic user interface (GUI). Currently, there is hardly any such tool available for high-end UNIX machines. To some extent, VR is only a tool. Its value depends on how customers apply it to different industries. The success of almost all popular applications, such as Microsoft Windows, firmly proves that the adoption of GUI is the key to making a product usable and acceptable by regular users.

In general, developing a VR model must become a simple task for users without programming knowledge. Otherwise, VR will still remain a subject in research labs that only few professionals know how to manipulate. In this project, several architects complained about VR during the discussions. Obviously, they care more about how easy it is to use, rather than how strong it is. How to simplify the development and manipulation of applications is sure to be a goal of current VR technologies.

The model conversion was found to be very confusing and time consuming. There is still no effective method to easily convert models from modeling packages to a VR platform. In this thesis study, there were two issues concerned with the modeling process. First, to run
the simulation smoothly in C6, which aspect is the key—texture dimension, number of nodes or polygons? Second, by which method could users pre-calculate the system’s running speed? If this is possible, then many revisions of the model would be avoided.

Compared to the modeling for high quality rendering, a big challenge of VR modeling is the realism. It is found that the baked texture is not very useful for Chinese architecture, which usually has complex textures. Since the baked texture usually combines several textures, the new texture must be large enough to maintain high visual fidelity. However, this will greatly slow down the speed in C6. If the texture is too small, then it will be too blurry to deliver the original visual information. Different from the baked texture, tiled texture repeats itself, so the image quality can be sharp even when the texture is small. Therefore, this is why the tiled texture was used more frequently in this project. Currently, this C6 simulation runs on Lego. With an update of the VR engine and related facilities in the future, the baked texture can be employed more frequently as an effective means to enhance visual fidelity.

Limitations

As mentioned in the previous chapter, there are very few precedent studies exploring how to implement interactions in architectural VR. This could be a negative factor affecting the methods generated. Not only are studies on human computer interaction in architecture extremely limited, but also some basic questions, such as the VR model optimization in C6 still do not have a mature method or guideline.

Another limitation is the lack of involving users in the development process. Assumptions were made based on the researcher’s previous user research experience and
personal perception of architecture. Although there were several informal discussions during the interaction planning step, the formal usability testing must strengthen the results.

Furthermore, another limitation arises from the availability of related resources, including the pictorial and textual materials of courtyard housing. In addition to the photos taken on-site, some textures were scanned from books. The book resolutions were not always of a high quality. On-site survey drawings covered all of the main facades, but not every side facade. The number of books or papers of courtyard housing available in the school library was limited as well. Since there was no on-site visit by the thesis researcher, the simulation’s realism could be influenced.

**Recommendations for Future Study**

Upon the completion of this thesis project, some experience was gained and some lessons were learned. The following recommendations are suggested in regard to potential fields for further research.

**Adding sound in interactions**

To strengthen interactions, sound can be added to the simulation. For instance, clicking a button would trigger a sound file to notify users that the operation is completed successfully. This method has been extensively used in desktop applications. Also, sounds can help simulate the real world. For example, users could hear some noises while walking in a hutong or opening the door. Furthermore, sound can indicate the building’s functions. For instance, while navigating in the reading room, users can hear that children are reciting poems.
Launching the simulation online

Currently, there is a VRML version of the simulation ready to be launched online. However, it does not contain any interactions except selecting camera views. Another version with advanced interactions, such as demonstrating construction process, could be launched for both online and PC use. File size is often an issue of online simulation. But for this project, potential users would most likely to have a good education and more opportunities to get access to high-speed Internet. Also, since users who download this simulation may play it at multiple times, it is worthwhile to take some time to download it online. Therefore, the file size may not be too crucial for the online simulation through high speed Internet connections.

Adding characters into the simulation

The implementation of characters may be beneficial to enhance the simulation’s realism. Characters can present more cultural information including costumes and gestures, indicate the building’s functions such as walking routes, or even participate in the advanced interactions as virtual characters, who are capable of communicate with users intelligently. Because some potential users may not have an architectural background, characters could help them perceive the houses more efficiently. For instance, they can determine a building’s height by comparing it to the height of a virtual character in the simulation.

Presenting more features of courtyard housing

In addition to the timber frame structure and gate styles, there are other unique features of courtyard housing which are valuable and can be implemented further, such as the
utilization of Fengshui, the walking routes for different dwellers in the same housing complex, the residents’ daily lives, and the places for public activities in hutong.

The interior of the main building has been modeled in this project, but not implemented in C6 because the simulation speed was concerned. There is a large amount of information contained in the interior, such as Chinese traditional painting, calligraphy, and musical instruments. The elegant furniture styles prevailing in Ming and Qing dynasties are especially famous in China. With the update of computing systems, these could be added in the future.
APPENDIX

ACCOMPANYING CD-ROM AND OPERATING INSTRUCTIONS

CD-ROM contains an animation of Beijing courtyard house developed in this project. The animation’s format is avi with music, which can be played by Window Media Player or other media players.

System requirements: IBM PC or 100% compatibles; Windows 95 or higher; 32 MB free RAM or higher; sound capability; CD-drive; Windows Media Player.
REFERENCES


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