VIRTUAL REALITY
-IMPROVING THE FIDELITY OF ARCHITECTUREAL VISUALIZATION

by
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# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>ACKNOWLEDGEMENTS</th>
<th>ii</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSTRACT</td>
<td>v</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>vi</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>vii</td>
</tr>
</tbody>
</table>

## CHAPTER

I. INTRODUCTION 1

II. THE SEARCH FOR FIDELITY IN MODERN ARCHITECTURAL VISUALIZATION 6

2.1 Hand-drawn Image 7

2.2 Computers and architectural visualization 18

2.2.1 Geometry 19

2.2.2 Material 27

2.2.3 Lighting and Rendering: ‘Shading the Material’ 32

2.3 Computer Animation 38

2.4 Summary 43

III. VIRTUAL REALITY 44

3.1 Key Components of Virtual Reality 47

3.1.1 Virtual World 47

3.1.2 Immersion 49

3.1.3 Interactivity 51

3.1.4 Sensory Feedback 57

3.2 The Hindrance to the application of Virtual Reality 59

3.2.1 Computing Hardware 62

3.2.2 Virtual Reality Software Development 64

3.2.3 Virtual Reality Projection System 69

3.3 Summary 74
IV. ARCHITECTURAL VISUALIZATION CASE STUDIES OF VIRTUAL REALITY

4.1 Software Information 75
4.2 Virtual Reality with SketchUp 77
  4.2.1 Project Introduction 77
  4.2.2 Computer Software, Hardware and Projection System 78
  4.2.3 Virtual World 79
  4.2.4 Immersion and Interactivity 83
4.3 Virtual Reality with EON Studio 85
  4.3.1 Project Introduction 85
  4.3.2 Computer Software, Hardware and Projection System 87
  4.3.3 Virtual World 89
  4.3.4 Immersion and Interactivity 94
4.4 Summary 97

V. CONCLUSIONS AND FUTURE 100

REFERENCES 105
ABSTRACT

With the rise of Computer Aided Design (CAD) software, digital media have been applied ubiquitously to architectural design. CAD not only works as a visualization technology but also as a way to transform the process of architectural design. It revolutionizes architectural design radically. During CAD’s development, computer image, computer animation, and virtual reality were introduced as the main media of architectural visualization. As the ultimate computer-generated visualization, today virtual reality is gaining more and more attention from architects and clients. It improves the fidelity of architectural communication in architectural design. Unlike other visualization mediums, with virtual reality, the audience is not passive but is a player in a virtual environment. In fact, virtual reality is not only a communication medium. With virtual reality, the audience can interact in the virtual world just as it does in the physical world, so virtual reality will become the final product of architectural design as the virtual world versus the physical world one day.

The primary purpose of this thesis is to explore how virtual reality can improve the fidelity of architectural visualization as a communication medium.
LIST OF TABLES

4.1: The Comparison between SketchUp and EON Studio Case Studies 98
LIST OF FIGURES

1.1 A computer rendering image of an office Tower 2

2.1 Giotto’s painting in the Arena Chapel 8

2.2 Perspective as a graphic construction: An interpretation of Leon Battista Alberti’s “costruzione legittima”. 11

2.3 Albrecht Durer’s interpretation of the veil and grid. 12

2.4 The Perspective of olio su pannello by Piero della Francesca 12

2.5 Capitoline Hill/Campidoglio, Rome, Italy 14

2.6 Raphael: La Scuola di Atene, Rome 15

2.7 Palazzo Farnese: Sala di Giove 16

2.8 The Hand Perspective of East Wing of National Gallery before Construction 16

2.9 The photo for East Wing of National Gallery after Construction 17

2.10 The photo of DAC-1 computer graphics system 20

2.11 The photo of Sketchpad computer graphics system 21

2.12 The photo of Sketchpad computer graphics system 21

2.13 The image of the typical hidden-surface model 22

2.14 The Boolean operations in constructive surface geometry 23

2.15 The polygonal modeling in architectural visualization 24

2.16 The NURBS modeling in Maya 25

2.17 The subdivision surface model 26

2.18 Flat Shading 28
2.19 Gouraud Shading
2.20 Phong Shading
2.21 Blinn Shading
2.22 Metal Shading
2.23 The texture map to simulate the material and light effect on the wall
2.24 The effect of bump map
2.25 One object has different effect with different bump maps
2.26 The computer image by raytracing rendering
2.27 A computer image of a steel mill with radiosity rendering
2.28 Top: A scene rendered without radiosity. Bottom: The same scene rendered with radiosity
2.29 The computer image for Philadelphia's City Hall
2.30 A shaded courtyard view of an unbuilt church designed by rendered with Lightscape
2.31 A computer image for Notre Dame in Paris
2.32 The computer animation for the construction process of George Pompidou Center in Paris
2.33 The computer animation for an unbuilt Castle
2.34 The frames of a computer animation for architectural visualization
3.1 The scene of Tomb Raider
3.2 A simplified model for a sofa in virtual reality
3.3 The texture map for sofa in virtual reality
3.4 The effect of texture map for a sofa in virtual reality

3.5 Manipulations such as “Move table a little to the right” can be accomplished using any of the four forms of manipulation demonstrated here

3.6 Physical control mechanisms can be integrated as part of the user interface to control various aspects of a VR experience. Here, the participant controls the virtual vehicle using a physical steering wheel and foot pedals

3.7 In this example of a virtual slider, the handheld wand is used to point at the virtual handle (the sphere) and move the slider (Application courtesy of Dan Sandin / EVL)

3.8 Navigation is the combination of wayfinding (knowing where you are and how to get where you want to go) and travel (the act of moving through a space)

3.9 Many devices have been developed to enable travel through a virtual world. These photos show a participant using a “surfboard” device to control a virtual surfboard in the virtual world. The participant moves in a manner that imitates an actual surfboard ride. The device was constructed by attaching pressure sensors to three corners of a reduced surfboard

3.10 Here, two participants interact in a CAVE application to examine and discuss weather data presented through a variety of representations

3.11 The graphics shows virtual reality system

3.12 Graphics performance comparison between PCs and high-end SGI workstations. Speed is given in Polygons per second

3.13 The Space effects without the Render to Texture in EON Studio

3.14 The Space effects with the Render to Texture in EON Studio
3.15 The Space effects with the Render to Texture in EON Raptor

3.16 Fishtank VR (monitor-based) provides a display paradigm that is similar to peering into a fishtank. The participant is able to see and look about a 3D world that appears to exist within the confines of the monitor.

3.17 VR Projections

3.18 CAVE Projections

3.19 Head-based VR

3.20 LCD HMD image resolution evolution in the 1990s. XGA, Extended graphics array; VGA, video graphics array; NTSC, National Television System Committee; CGA, color graphics adaptor.

4.1 Virtual reality of an architectural museum

4.2 View along Calle Rosario: existing building on site, church and entry to plaza Corralillo Santo Tomas

4.3 View of existing building on site

4.4 The model of SketchUp

4.5 The Model of SketchUp

4.6 The material of SketchUp

4.7 The material effect in SketchUp

4.8 The sunlight changes from the morning to night in SketchUp

4.9 The sunlight effect in SketchUp

4.10 The real-time movement in SketchUp

4.11 The viewpoint change in SketchUp
4.12 The Church of Light

4.13 The floor plan of Church of Light

4.14 The Passive Projection display

4.15 The Passive Projection display

4.16 The model in 3D Studio Max

4.17 The model in 3D Studio Max

4.18 “Render to Texture” in 3D Studio Max

4.19 Use texture Map to simulated the details in architecture

4.20 The photometric light in 3D Studio Max

4.21 Virtual reality of Church of Light

4.22 Virtual reality of Church of Light. In virtual reality, the omni light can be turned off and the background image can be changed

4.23 Virtual reality of Church of Light. Click the door in the scene will open and close it

4.24 Virtual reality of Church of Light
CHAPTER I
INTRODUCTION

“The realization of architecture from initial project identification to occupation by owners involves a complex system of communication among a diverse group of persons concerned with a wide variety of subjects.”¹ In order to become a successful architect, the designer needs a creative talent for understanding form and space and excellent communication skills to help him exchange ideas with his design partners, consulting engineers, clients, and users. Through communications, architects can test alternative design concepts and make successful design decisions. Communications help architects find a reasonable way to develop a design and ensure that the design process is moving in the proper direction. The exchange of ideas is significant for the successful progress of architectural design. After all, architecture is the combination of art, engineering, and economics. A poorly designed architectural product will have a severe social and economic impact and is very difficult to correct.²

People depend on the senses to communicate. They understand by listening, touching, smelling, tasting and seeing. While meetings, discussions, and texts can help architectural communication, architecture is fundamentally a visual art. So visual communication during the design process is the predominant medium for

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understanding. Architectural visualization is just an important type of visual communication.

Figure 1.1 A computer rendering image of an office tower. 
Source: Peddle Thorp Architects.

Architectural visualization is the act or process of interpreting space in visual terms. Through architectural visualization, architects show their concept and design to communicate and test alternative ideas. Architectural visualization is also a method of predicting the visual effect of the final design product before it is constructed (Figure 1.1). Especially for non-architectural participants in architectural design, like clients and users, architectural visualization can be very helpful in communicating the
function and form of the architectural design. Due to the difficulty of understanding professional drawings such as floor plans, sections, and elevations, architects use architectural visualization to communicate with clients, users and each other. Without this ability, most architects would agree that the design process would be impossible.

The history of architectural visualization is a gradual step-by-step development in improving fidelity, starting with the hand-drawn image and arriving, most recently, at virtual reality. Creating more and more fidelity is the goal of the architectural visualization. The higher the fidelity of architectural visualization the greater the mutual communication between designers and clients, helping them make more informed design decisions. Thus, the fidelity of architectural visualization is important to the efficiency and effectiveness of architectural communication.

The dictionary definition of fidelity is “accuracy in details; exactness”\(^3\). There are three key components to the fidelity of architectural visualization: the realistic representation of a virtual world, the level of immersion and interactivity. The virtual world consists of three components: geometry, material, and light. The virtual world is a basic component of architectural visualization. Without this virtual world, architectural design would be impossible. Creating a virtual world gives architects “an imaginary space often manifested through a medium” and “a description of a collection of objects in a space and the rules and relationships governing those

objects”. Besides the virtual world, interactivity and immersion are also crucial components of architectural visualization. Interactivity can be defined as the observer’s ability to affect the visualization, such as changing one’s viewpoint within a virtual world. Although interactivity is not an indispensable element in architectural visualization, it significantly enhances the fidelity of architectural visualization and makes the experience of architectural visualization closer to the experience of the physical world.

In visualization terms, immersion means the “sensation of being in an environment that can be a purely mental state or can be accomplished through physical means”; mental immersion is “the state of being deeply engaged, suspension of disbelief and involvement”; physical immersion is “bodily entering into a medium, synthetic stimulus of the body’s senses via the use of technology, this does not imply all senses or that the entire body is immersed/engulfed”. To obtain a complete sense of presence, one must be both physically and mentally immersed in a virtual world. In general, immersion is the feeling of being in a virtual environment. With immersion and interactivity, the visual experience in a physical world can be realized through architectural visualization.

Today, the hand-drawn image, computer image, computer animation, and virtual reality are the main approaches to architectural visualization. Although the

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hand-drawn image, computer image, and computer animation can create a realistic virtual world, only virtual reality offers interactivity and physical immersion in the virtual world.

Time and cost factors limit the ability of virtual reality to create a realistic representation of geometry, material and light compared to the hand-drawn image, computer image, or computer animation. Fortunately, this situation is improving quickly with the development of computer hardware, virtual reality software, and virtual reality projection systems. High speed computer software is crucial to decreasing rendering time and supporting complicated projects. Virtual reality software can make the execution process of virtual reality easier and improve the rendering quality. Virtual reality projection systems work to help achieve a more realistic visual experience.

Virtual reality can offer a more realistic virtual experience and improve the fidelity of communications in architectural design. In the following pages, I will present evidences for this claim through logical argument and case studies.
CHAPTER II
THE SEARCH FOR FIDELITY IN MODERN ARCHITECTURAL VISUALIZATION

The history of modern architectural visualization is a gradual step-by-step development in improving fidelity, starting with the hand-drawn image and arriving, most recently, at virtual reality. The history of modern architectural visualization offers us a vivid clue to its transformation and increased fidelity. In spite of using different media, the quest for the highest fidelity in architectural visualization continues, and the development of each visualization medium brings a new milestone of fidelity to the discipline.

Virtual reality is the inevitable result of efforts to increase the fidelity of architectural visualization. During the history of architectural visualization, virtual world, interactivity, and immersion have gradually helped to create a more realistic visualization of design moving from one breakthrough to the next to boost architectural visualization to a higher level of fidelity. Thus, virtual reality is not a gift that falls from the sky but the fruit of a process that constantly needs a higher level of fidelity. It is certain that the history of modern architectural visualization will give us a deeper understanding of why virtual reality will become the next logical step in the development of architectural visualization.

2.1 Hand-Drawn Image

The first written discussion of perspective dates back to 1435 AD. Although it took place many centuries ago, the quest for fidelity in perspective was similar to today’s visualization efforts. In order to create a realistic image, artists, architects, scientists, and mathematicians incorporated their various discipline into the study of perspective, using the technologies available to them.⁸

Before the invention of perspective, the main subjects of drawing were human figures and animals that could be expressed well with the height and width of the canvas but need not be accurate in depth. Although a century before the invention of perspective there were already some attempts to express architecture in drawings, such as Giotto’s paintings (Figure 2.1) in the Arena Chapel and frescos at Assisi, lack of accurate geometric rules of perspective limited their fidelity.⁹ From figure 2.1 we can see that a hand-drawn image of that time did not have appropriate proportions and perspective geometry, so the perspective rule was developed to achieve more realistic visualization.

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Our perception of the physical world can be simplified down to geometric entities such as points and lines on paper. These geometric entities try to achieve correspondence with images of the physical world. This two-dimensional medium on paper became the perspective principle. The invention of the perspective principle gave artists, for the first time, the chance to represent accurately the three-dimensional world in a two-dimensional medium. It was a crucial milestone in achieving higher fidelity in visualization. From this point on, architects and artists were able to present the physical world in a two-dimensional medium with correct proportion, scale, and perspective. Making an accurate geometrical representation of the virtual world for

10 http://www.kfki.hu/~arthp/tours/giotto/virgin.html
architectural visualization is the most important achievement of the perspective invention.\footnote{The first theory in perspective by Alberti brought forward the scientific principle to create two-dimensional perspective that represents the three-dimensional world. Alberti’s first theory boosted the development of the hand-drawn perspective in the next several centuries. Then in 17th century, another great milestone took place in perspective theory: the French philosopher and mathematician Rene Descartes, put forward an idea that the point, line, or surface in perspective can be coincident to numbers. This idea became the base of today’s computer visualization technology. The representation of the three-dimensional world scientifically through two-dimensional medium is the question that the first theory in perspective tried to solve. How does the two-dimensional scene to represent the three-dimensional world make up of? “The human vision can be described as follows: when we perceive an object with both eyes, we obtain two different views, one for each retina. The distance between the viewpoints and focal points is the distance between the two eyes, which is about 6.5 cm. these views converge in a final image.”\footnote{Binocular vision through our eyes creates the perception of depth on the retina. In this vision process, the perceived size of the object on the retina is decided by the distance between the object and the observer. The perceived size will change smaller with the increasing of distance. On the other hand, the clarity of the perceived object will decrease. “Several common phenomena occur in our most basic visual perceptions: The size of an object decreases with the distance from the observer, rectangles are perceived as trapezoid, angles change amplitude, parallel lines meet in a point called the vanishing point, and parallel planes meet in a line – the horizon – which we know from our everyday experience as the place where the sky meets the earth. Only the relations of objects parallel to the picture plane – the plane in which the two-dimensional representation is formed – are conserved.” Daniela Bertol, 1997, “Designing Digital Space: An Architect’s Guide to Virtual Reality”; John Wiley & Sons, INC. U.S, pp. 3-4.}

In the fifteenth century, perspective was considered the window to observing the world, like the eye’s retina. So vision principles were utilized for perspective. To simulate the three-dimensional world, big sizes and strong colors were utilized for near objects, and small sizes and light colors were utilized for distant objects. Meanwhile the vanishing point is also an effective approach to achieve the three-dimensional effect. In the several centuries of perspective development, these principles always worked as the basis for pursuing fidelity in hand-drawn perspective. Even today, although the computer has revolutionized architectural visualization radically, perspective rules are still the foundation of the virtual world.

From the systematic rule of perspective written by Leon Battista Alberti in 1435 AD, perspective was considered not only a kind of art but also a science. Systematic geometric rules started to be applied to achieve more accuracy in
Alberti defined perspective as “to treat the two-dimensional picture plane (the wall, or panel, or canvas) as if it were a window in which a three-dimensional scene appears”\textsuperscript{12}. He used “pyramid of light”, “centric point”, and “plane of the picture” as the basic terms and principles for perspective\textsuperscript{13}. In his article, Alberti thought that the object in the physical world was the combination of planar polygons and that the eye worked as the “pyramid of light”. Connecting visual rays joined each point on planar polygons to the eye. These connecting visual rays projected to the “plane of the picture” to compose the perspective. The procedure to create perspective was to use geometric rules to help imitate this projection process on the canvas.

Another geometric rule discussed in Alberti’s article was “legitimate construction”. (Figure 2.2) With this rule, the measurable relations between the eye, the picture plane, and the physical object were found to help develop perspective. Figure 2.2 shows how to draw a perspective of a checkerboard floor under a certain height of viewpoint and distance between the observer and object. At that time, the veil and square frame were also applied to improve the accuracy of perspective. Figure 2.3 shows how these instruments worked to assist painters to progress in their work.\textsuperscript{14} Undoubtedly, Alberti’s article is the first milestone in the history of perspective development. It is with Alberti that we start our quest for higher fidelity in

architectural rendering and hand-drawn perspective, the first medium of modern architectural visualization. With Alberti’s theory, Piero della Francesca (Figure 2.4), Masaccio, Francesco di Giorgio Martini, Paolo Uccelo and Donatello created many wonderful examples of perspectives.15

![Perspective as a graphic construction](source: Daniela Bertol)

Figure 2.2 Perspective as a graphic construction: An interpretation of Leon Battista Alberti’s “costruzione legittima”.
Source: Daniela Bertol.

From the beginning of perspective development, in addition to geometric rules, color was considered to be applied to achieve realistic light and material effects. The skillful application of color with pigment helped to improve the fidelity of volume.

[Figure 2.4. The Perspective of olio su pannello by Piero della Francesca. Source: Gallery Nazionale.]

http://utenti.romascuola.net/bramarte/400/img/pie7.jpg
and space. In the Renaissance, painters had already begun to learn about the influence of light on material and color representation in perspective. The geometric rules made accurate polygons, and color simulated the realistic light and material effect in perspectives. All these techniques used together created a hand-drawn image to imitate the physical world. However, in the hand-drawn image, architects and artists used color according to what they saw experientially. There were no scientific rules for using color in perspective. Nevertheless, through their long-time observations and exercises, architect and artists were able to apply color on hand-drawn images to create realistic material and light effects.

All these discoveries lead to the wide application of the hand-drawn perspective in architectural visualization. Before the invention of perspective, from the time of Vitruvius, plan and elevation drawings were already used in architectural design for communication. However, these elements could not offer the three-dimensional perception of volume and space. Especially to unprofessional participants in architectural design, plan and elevation drawings were difficult to understand. So perspective emerged. With it, architects and clients had the chance to observe three-dimensional form and spatial effects before construction. Due to its high efficiency for architectural communication, the hand-drawn perspective was quickly emulated and started to be widely applied to architectural design. Perspective had as significant an influence on architecture as it did on art. It was used by almost all the major

architects of the time, such as Michelangelo (Figure 2.5), to express their ideas and help develop designs.

At the same time, the fresco represented another trend in visualization that developed with the rise of the hand-drawn image. The fresco became a new way to explore architectural space. Through it, virtual architecture and physical architecture joined together to create a new spatial effect. At that time, the fresco was used prevalently for interiors and Raphael’s School of Athens (Figure 2.6) is one of the best examples of this kind of effect.18

Figure 2.5 Capitoline Hill/Campidoglio, Rome, Italy. Drawn and designed by Michelangelo Buonarroti. 1538-64. Source: Tigertail Associates19

From the first emergence of perspective theory, this approach to architectural visualization dominated the field until the twentieth century.

The twentieth century brought extensive improvements to fidelity through the technology of geometric rules and the representation of light and material effects. The fidelity of hand-drawn perspective has increased throughout the ages, from Palazzo Farnese (Figure 2.7) in the late sixteenth century to Paul Stevenson Oles in the late twentieth century. Indeed Paul Stevenson Oles’s perspective for the East Building of the National Gallery is one of the best examples available of hand-drawn perspective that achieves high fidelity. His hand-drawn perspective (Figure 2.8) before construction is very close to the photo of the famous building and the building photo after construction (Figure 2.9). This achievement in high fidelity overcame the
gap between the virtual world and the physical world. It raised the efficiency of architectural communication to a new level.

Figure 2.7 Palazzo Farnese: Sala di Giove. Source: Bonechi, Edizioni “Il Turismo”.

Figure 2.8. The Hand Perspective of East Wing of National Gallery before Construction. Designed by I.M.Pei. Source: Paul Stevenson Oles.
Throughout the history of hand-drawn image, the primary purpose of architectural visualization was to represent the physical world. Each improvement in fidelity was accomplished through a refinement of geometric rules, color, and value. The quest for higher fidelity to improve the effectiveness of architectural communication continued to be recognized and developed in the next generation of visualization media. The geometric rules and color principles of hand-drawn perspective still work today as the basis for creating the next level of the virtual world. The rise of hand-drawn perspective established geometric rules scientifically and experiential tradition for the use of color to represent material and light realistically. However, it did not establish scientific rules for how material and light influence each other in the physical world. With hand-drawn images, this effect is very difficult to be realized and takes an artist a long time to achieve.
2.2 Computers and Architectural Visualization

The next fundamental innovation in architectural visualization was the application of the computer. In the second half of the twentieth century, the rise of computer technology transformed the world radically in many disciplines. With this innovation, human society entered into the information age. In the area of architectural visualization, the influence of computer technology is significant due to the application of Computer Aided Design (CAD). Before the computer, representation made with ink and paper was the basic tool for architectural visualization. Although geometric rules and color principles are still the basis of computer visualization, CAD programs use an array of color pixels generated by the computer to visualize an architectural design.²⁰ The strong algorithmic power of the computer has made possible more accurate geometric, material, and light representations. Meanwhile, the computer database has changed the computer visualization from a two-dimensional medium to a three-dimensional medium. Today, the audience can observe a three-dimensional model in computer visualization with different angles of views and locations. This initial interactivity made computer animation and virtual reality possible for the future. Nevertheless, computer graphics was also a step by step development process, from imperfect technology and rough effects, at the beginning, to today’s high fidelity in computer visualization. These

current developments have been achieved through advances made in geometry, material, and light technology for computer graphic systems.

2.2.1 Geometry

In 1959, General Motors and IBM made the first computer graphic system, DAC-1 (Design Augmented by Computers). This system imported the three-dimensional data of an automobile so that viewers could observe a three-dimensional model on the computer screen (Figure 2.10). At that time, there was no material and light for the 3D model. The audiences could only observe the line 3D model. The results of this computer graphic system were rough even compared with the hand-drawn perspective of the same time. However, it started the quest for higher fidelity in computer visualization. Meanwhile, the computer model was no longer only a two-dimensional medium. With the three-dimensional data in the computer system, audiences had the chance to observe the computer model from different viewpoints on demand. This was a crucial advantage of the computer medium compared to a hand-drawn image.

In 1961, an MIT student named Ivan Sutherland, developed another computer graphic program called Sketchpad (Figure 2.11 and 2.12). The program gave users the ability to draw simple geometric models without material and light on the computer screen with a light pen. Models in the computer database could be saved and reopened. Sutherland’s Sketchpad was an important step in the modeling technology of computer graphics. Even today, some Sketchpad standards on modeling are still used in computer graphic systems. For example, the Sketchpad method of drawing rectangular shapes and its modeling approach to divide a whole model into different parts are still graphic system standards.\(^{22}\)

Most early computer graphic systems were all vector graphics composed of lines. At that time, color with pixels on the screen was not considered in computer graphics for two reasons. The first reason is the limited speed of computer hardware

in the 1960s. The second is the immaturity of computer graphic software. Then in the late 1960s, the hidden-surface algorithm was developed by the University of Utah. With it, the computer could find the back face of a surface and hide it from the viewer’s perspective (Figure 2.13).\(^{23}\) This technology made the appearance of a solid object in computer graphics possible. It also saved significant time in the rendering process.

Figure 2.11 The photo of Sketchpad computer graphics system. Source: Ivan Sutherland, MIT.

Figure 2.12 The photo of Sketchpad computer graphics system. Source: Ivan Sutherland, MIT.

Figure 2.13 The image of the typical hidden-surface model.
Source: Hao Wu.

All of these were important early modeling technologies in computer graphics. From this point, unceasingly improvements in computer modeling technology offered more and more freedom to create complicated models. Today, polygonal meshes, constructive polygonal solid geometry, NURBS, and subdivided patches are among the different geometric modeling technologies applied in computer graphics.

Hence the rise of computer graphics, most computer models are composed of surface geometry, created with one of the most popular modeling technologies, polygonal meshes. Some early computer graphic systems, such as DAC-1 and Sketchpad, already made use of this kind of modeling technology, although it was not perfect at that time.

With the continued development of computer graphic systems, complicated models with more details and volume have gradually been obtained by a new modeling technology, constructive solid geometry. With this modeling technology, some operations based on polygonal modeling were developed to help make a
complex figure on a primitive volume, like the Boolean process. With Boolean, two or more solid geometric primitives can form a new geometry from the union, intersection, and difference of the two or more geometric shapes (Figure 2.14). Besides Boolean, there are many other constructive operations, like loft and terrain, which improve the modeling capability for achieving different types of shapes.

Today, polygonal meshes and constructive solid geometry can create not only simple shapes but also very complex shapes. Most architectural masses are surface geometries, so polygonal meshes and constructive solid geometry are the most common modeling technologies in architectural visualization (Figure 2.15).

<table>
<thead>
<tr>
<th>Boolean union (the merger of two objects into one)</th>
<th>Boolean difference (the subtraction of one object from another)</th>
<th>Boolean intersection (the portion common to both objects)</th>
</tr>
</thead>
</table>

Figure 2.14 The Boolean operations in constructive surface geometry.

24 “Constructive solid geometry”, http://www.arthistoryclub.com/art_history/Constructive_solid_geometry
In the early of 1990s, the famous computer graphic company, Alias Systems Corporation (formerly Alias Wavefront), for the first time, applied NURBS (short for nonuniform rational B-spline) as the main commercial modeling technology in its computer graphic software. NURBS modeling (Figure 2.16) can easily construct complex curved shapes. Compared with polygonal modeling, NURBS is far superior at creating curvilinear surfaces. However, NURBS is more algorithmically intensive and requires more computer power. With the continued development of computer graphic systems, this problem has been solved and NURBS is applied prevalently in computer image and computer animation, due to its strong modeling ability. Nevertheless, because most architectural models are composed of simple polygonal surface geometries, this modeling technology is not very popular for architectural

visualization. Only to some architects, such as Frank Gerry, who always designs curvilinear forms, is this modeling technology very helpful.

In 1978, Edwin Catmull and Jim Clark, as well as Daniel Doo and Malcom Sabin created a new modeling technology, subdivided surface patches at the same time. However, it developed very slowly. It was not until 1995 that Ulrich Reif solved a critical problem for its application, subdivided surfaces behavior near extraordinary vertices. After that, it became popular in computer graphics. Similar to NURBS, subdivided surface is applied to create smooth surfaces out of arbitrary meshes (Figure 2.17). Compared to NURBS, subdivided surface is easier for making arbitrary topology and implementation. This modeling technology enhanced polygonal meshes so they could represent curves more effectively and easily with low computing costs. This kind of model is also more stable to run on a computer graphic system than
NURBS. Still, due to the same reason as NURBS, this technology is not popular in architectural visualization.

Figure 2.17 The subdivision surface model. Source: Teresa Lang.

These four modeling technologies are the main geometric modeling technologies in the development of computer graphics. Today, we can see very realistic geometric models in movies and computer games. However, in architectural visualization, models are relatively simple compared with other computer media. The main modeling technologies applied in architectural visualization are polygonal meshes and constructive solid geometry. This technology can realize most architectural volumes and spaces. Today, we can create more complicated architectural models, with the development of CPU, memory, and video adaptors but these kinds of models were very difficult to run on the early computer graphic system.

26 “Subdivision surface”, http://www.arthistoryclub.com/art_history/Subdivision_surface
Meanwhile, more and more operations, like Boolean and loft, are helpful in making more complex forms in architectural visualization.

2.2.2. Material

The representation of material is done by the computer graphics process called shading. In general, material representation works with lighting technology to achieve high fidelity computer image. As discussed in the last section, in the early stages of computer graphics, we could only observe line models on computer graphic systems. In order to achieve a realistic visualization, the material and lighting technology had to be imported into the computer graphics.

At the beginning of the 1970s, flat shading (Figure 2.18) was already applied in computer graphics so that the geometric shape could be observed on the computer screen. However, without advanced shading technology, this kind of computer graphics was only composed of solid color. Meanwhile the sharp edge of the polygon modeling impaired the realism of the image. So it was not effective in representing a curved shape.

In order to solve this problem in 1971, Henri Gouraud invented Gouraud Shading (Figure 2.19) to improve the realistic quality of a curved face through interpolating the color across the polygons. Then in 1974, Bui-Toung developed Phong Shading with better specular highlight (Figure 2.20). It improved Gouraud shading technologies, which can not hide the back face making incorrect reflections.
and disappearance of polygons take place when very close to the curved face. However, the computation speed of Phong Shading was significantly slower than Gouraud Shading. The rise of Blinn Shading (Figure 2.21) continued the improvement to shading technology. It realized softer and rounder highlights and improved the algorithm for shading. Then, the development of other shading technologies, such as metal shading (Figure 2.22), made computer graphics able to represent more types of materials.

Figure 2.18 Flat Shading.
Source: Autodesk, Inc

Figure 2.19 Gouraud Shading.
Source: Autodesk, Inc

Besides shading technology, mapping technology is also very important to the representation of material representation. It is a kind of technology that improves the
appearance and fidelity of the material. In 1974, Ed Catmull studied texture mapping in his PhD thesis. Texture mapping is “a method of varying the surface properties from point to point (on a polygon) in order to give the appearance of surface detail that is not actually present in the geometry of the surface” (Peachey 1994). Properties that can be mapped onto a surface include color, transparency, and light reflectivity (bump-maps). Texture mapping (Figure 2.23) simplified material and light effects in the virtual world with different texture maps so that computer renderings could be quicker and the final effect very realistic. Today, the software of virtual reality also uses this mapping method to obtain high fidelity and decrease the rendering time. With texture mapping, the geometric model size can be reduced without impairing the final effect. Today, Texture mapping is still an efficient method in computer graphics to save rendering time.

![Figure 2.23 The texture map to simulate the material and light effect on the wall. Source: Hao Wu.](image)

In the late 1970s, bump mapping (figure 2.24) also started being applied in computer graphics. In 1978, James Blinn discussed this technology in his article, “Simulation of Wrinkled Surfaces”. This mapping technology achieved richer and more detailed effects in surface representation. Figure 2.24 shows that bump mapping adds detail and a bumpy effect to the surface of the model. With it, a common sphere looks like an orange. Bump mapping is a very efficient technology to simulate some materials from the physical world, like stone, concrete, and water. This mapping technology is applied prevalently in architectural visualization to obtain surface high fidelity (Figure 2.25).

Figure 2.24 The effect of bump map.

29 “Bump mapping”, http://www.arthistoryclub.com/art_history/Bump_mapping
Like the geometric modeling, shading technology is also a gradual development process but the good news is that the development of shading technology never stops. With the continued advance in shading technology, more material effects in the physical world will be imported into computer graphics.

2.2.3. Lighting and rendering: ‘Shading the polygon’

Shading technology is related to lighting technology because it calculates the influence of the light to the object and material. The advancement in shading technology has also been a breakthrough to lighting technology. On the other hand, several rendering technologies such as raytrace and radiosity have also been developed to create advanced lighting effect in the development of computer graphics.
“Ray tracing is one of the most popular methods used in 3D computer graphics to render an image. It works by tracing the path taken by a ray of light through the scene, and calculating reflection, refraction, or absorption of the ray whenever it intersects an object in the world — hence the name.” The first application of raytrace rendering was started by scientists at Mathematical Applications Group, Inc., (MAGI) in 1966. Raytrace (Figure 2.26) can create more realistic effects such as shadow, refraction, and reflection due to its more accurate simulation of the light in the physical world. Its simplicity to achieve this high fidelity of computer image is another reason for its popular application. Nevertheless, compared to other advanced rendering technologies, raytrace needs more rendering time and a more powerful computer graphic system. Its limit as a light representing technology is that it does not simulate indirect light only direct light.

Figure 2.26 The computer image by raytracing rendering. Source: Lutz Essers.

Radiosity is the rendering technology that adds the indirect light simulation to the rendering process. “The inclusion of radiosity calculations in the rendering process often lends an added element of realism to the finished scene, because of the way it mimics real-world phenomena.”31 In 1984, C. Goral, K. E. Torrance, D. P. Greenberg and B. Battaile at Cornell University brought forward radiosity as a rendering technology in their paper, “Modeling the interaction of light between diffuse surfaces”. In 1989, radiosity was applied at Cornell University to improve the light effect in computer renderings of architecture (Figure 2.27). The crucial achievement in the lighting algorithm, radiosity, simulates lighting in the physical world with a different method than raytrace. But its effects are also as realistic as raytrace. In figure 2.28, the effects are shown with and without a radiosity rendering. Raytrace and radiosity simulate two different lighting conditions and are the most efficient when used together.

Figure 2.27 A computer image of a steel mill with radiosity rendering.
Source: Cornell University.

31 “Radiosity”, http://www.arthistoryclub.com/art_history/Radiosity
In computer graphics, lighting and rendering technologies always work together to simulate the lighting effect in the physical world. Their advancements have improved simulations to lighting activity in the physical world and have achieved higher fidelity in computer graphics.

From studying the history of modeling, material, and lighting technology in computer graphics, we can see that most theories were developed and introduced at the early stages of computer graphics. However, at that time, the immature computer
graphic hardware and software hindered their application to create high fidelity computer image.

High fidelity computer image have been realized gradually with the development of high performance computer software and hardware. Today, CPUs, memory, and video adaptors improve very quickly. Meanwhile, the main software of computer graphics, such as 3D Studio Max, 3D Studio VIZ, Maya, Lightscape, revolutionize the application of these modeling, material, and lighting technologies. If we make use of these computer graphic systems and software properly, high fidelity is no longer a problem in computer image.

There are some examples of high fidelity of computer graphics in architectural design. In 1997, Bentley made a computer graphic system for Philadelphia's City Hall (Figure 2.29) in a real city model with Bentley Systems' MicroStation 95 and MasterPiece software. In 1998, Andrzej Zarzycki utilized the AutoCAD R12 and Lightscape 3 together to render a computer image for a courtyard of an unbuilt church designed by Alvar Aalto (Figure 2.30). In 2005, Luciano Neves created a computer image for Notre Dame in Paris. (Figure 2.31) All these figures show the development on the fidelity of computer image.
Figure 2.29 The computer image for Philadelphia's City Hall.
Source: Bentley.

Figure 2.30 A shaded courtyard view of an unbuilt church designed by rendered with Lightscape 3.
Source: Andrzej Zarzycki.
2.3 Computer Animation

Animation is “a motion picture made by photographing successive positions of inanimate objects”. Computer animation is animation using a computer graphic system to accomplish this task. It developed along with the advancement in computer image.

Computer animation uses the same modeling, mapping, and lighting technologies as all from computer image, so basically, computer animation does not

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improve the virtual world, but enhances its experience. Some of the most popular software of architectural visualization, such as 3D Studio Max, can create computer image and animation. One digital three-dimensional model allows architects to render many computer images with different view points. It offers the chance for architects to create computer animation quicker than the hand-drawn medium.

Our experience of the physical world is an animated process. So with time and motion, computer animation increases the fidelity of the visualization and improves mental immersion in architectural visualization. With proper tools, the computer animation also can enhance physical immersion. However, because computer animation is a predetermined virtual experience and the audience seldom has a chance to choose the route and viewpoint, there is no basic advance in interactivity with computer animation.

With a computer graphic system, architects can set a certain amount of key frames with the different positions of the camera or object so that the computer graphic software can automatically render all the “in-between” frames to create the animation. Nevertheless, in the hand-drawn image, if architects hope to create an animation, they need to draw the animation frame by frame and every frame is a completely new work. There is so much time and cost in a hand-drawn animation in that the hand-drawn animation did not develop as an architectural visualization medium. However, with computer animation, time and cost also increases because a single computer image is only one frame of the computer animation. If we want 30
frames for a one-second animation, a one-minute animation needs 1,800 frames. This requires significant computing time. On the other hand, with a computer animation, we can observe more details and angles of the architectural plan and more sophisticated three-dimensional representation can be created, even as it adds time and cost to the architectural visualization process.

At the beginning of the development of computer graphic systems, due to the limited speed of computer hardware, rendering even one computer image was very slow, so the time and cost was not practical for the popular application of computer animation. However, there were some pioneering experiments during this developmental stage. In 1987, with Spring’s Iko-Light AEC software, Spring architects made a computer animation of the construction process of the George Pompidou Center in Paris (Figure 2.32), and several years ago, the increase in the speed of computer hardware made computer animation easier to realize. The time and cost of computer animation continues to decrease with more and more architects learning about its value as an approach to architectural visualization. In 1999, the BB-Digital company created a 3.5 minutes, 5000 frames computer animation for an unbuilt castle of Ludwig II of Bavaria with Kinetix's 3D Studio Max (Figure 2.33).
Today, computer animation has joined the mainstream as an architectural visualization medium (Figure 2.34). Architects make use of it to achieve more efficient communication in the architectural design process. By using the same modeling, mapping, and lighting technologies as computer image, computer animation can achieve the same high level of virtual world as computer image. However, it adds time and motion to the visualization experience. Time and motion improve the immersion level of experience in architectural visualization. With the help of the proper projection system, computer animation gives the audience the
feeling of being personally on the scene. This improvement in the fidelity of visualization has established computer animation as a new medium in architectural visualization that has revolutionized the static perspective image of the past. With improvement in computing hardware and software, the time and cost of computer animation is dropping significantly, giving architects a higher fidelity of communication.

Figure 2.34 The frames of a computer animation for architectural visualization. Source: Shanghai Jingyuan Digital Ltd.
2.4 Summary

Through the history of the hand-drawn image, computer image, and computer animation, the quest for higher fidelity architectural visualization has driven the development of visualization technology. Over several centuries, the realistic quality of the virtual world represented with the hand-drawn image of geometry, material, and light, achieved a high level of fidelity, as seen in the works of Steven Oles. The use of computer technology on architectural visualization has exceeded the fidelity of even the best hand-drawn images, as seen in the works of Andrzej Zarzycki.

In the search for higher fidelity in architectural visualization, computer graphics has added animation as another dimension in the search for fidelity. Computer animation has brought time and motion to architectural visualization improving mental immersion to in the architectural design experience. Although interactivity of architectural visualization cannot be realized in the hand-drawn image, computer image, and computer animation, they have given a firm base to the next step in higher fidelity architectural visualization. With the continued development of fast and inexpensive computer hardware and software, the time is right for the application of virtual reality.
CHAPTER III
VIRTUAL REALITY

With the proper projection system, computer animation offers a high level of architectural fidelity, but is this the limit of our quest? As we discussed in chapter one, the five key components of fidelity in architectural visualization are determined by the realistic representation of geometry, material, and light, and an increased level of immersion and interactivity. The representation of geometry, material, and light make up what is commonly referred to as a “virtual world”. From the first written discussion of perspective in 1435, to today’s prevalent application of computer animation, the goal has been to improve the fidelity of the virtual world to increase our mental immersion. These developments in visualization theory and technology have given architects the capability to create very realistic virtual worlds.

The next question is whether or not we can improve on the photorealistic representation of computer image and immersion based on time and motion. It is obvious that the continued advancements in modeling, mapping, and lighting in computer graphic systems provide for improving photorealism. Meanwhile, increasing computer speeds allow the programmer an opportunity to now include the fifth key component, interactivity. So where will we go next?

The answer is virtual reality. “Virtual reality is a computer-generated world involving one or more human senses and generated in real-time by the participant’s
actions.” In virtual reality, the audience is not only a passive viewer, but also a player in real-time interaction.

“Real-Time is a level of computer responsiveness that a user senses as sufficiently immediate or that enables the computer to keep up with some external process (for example, to present visualizations of the weather as it constantly changes). Real-time is an adjective pertaining to computers or processes that operate in real time. Real time describes a human rather than a machine sense of time.”

Will we improve animation and go to real-time and virtual reality as a primary visualization method? In this chapter, virtual reality will be introduced, detailing its key components and technologies. Through this discussion, we can learn how virtual reality improves the fidelity of architectural visualization and why this new visualization medium will become the key method in architectural visualization in the future. Currently, there are still some problems which hinder its application in architectural visualization. In this chapter, we will also discuss how to solve these problems.

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35 http://whatis.techtarget.com/definition/0, sid9_gci214344,00.html
Today, most people get their understanding of virtual reality through 3D computer games. In fact, 3D computer games are a type of virtual reality. Players interact with a set of characters in a computer environment. Compared with old two-dimensional computer games, the realistic virtual world of three-dimensional computer games appeals to more and more people. Every one that ever played “Tomb Raider 4” (Figure 3.1) has been deeply impressed by its realistic virtual world of an Egyptian Pyramid. Of course, virtual worlds applied in architectural visualization are a little different than 3D computer games, but the essence of their computer technology is the same.
3.1. Key Components of Virtual Reality

Virtual reality has four key elements for creating a real-time experience: virtual world, immersion, interactivity, and sensory feedback.37

3.1.1 Virtual World

In the hand-drawn image, computer image, and computer animation, the quest for a compelling representation of virtual world has already been realized. Virtual reality also uses similar modeling, mapping, and lighting technology to create its virtual world.

In real-time architectural visualization, the geometric method (Figure 3.2) is similar to computer image and animation. However, in order to decrease rendering time to obtain a smooth movement through the virtual world, geometry is minimized as much as possible. Complex geometric models are difficult to run in virtual reality systems.

![Figure 3.2 A simplified model for a sofa in virtual reality. Source: Hao Wu.](image)

In contrast to computer image and animation, in order to simplify the model and guarantee the high frame-rate animation in virtual reality, texture mapping is popularly applied in this real-time visualization. A texture map can simulate most effects of common material like shadow and texture. Figure 3.3 and 3.4 show texture mapping is applied to represent the lighting effect and concrete texture in a church interior.

Today, in virtual reality, the sophisticated lighting technologies, such as radiosity and raytracing used in computer image and animation, cannot currently be utilized. A texture map is often used to simulate lighting effects. The reason is that it is very difficult to obtain smooth movement in virtual reality with sophisticated lighting technologies on the current computer graphic systems.

Figure 3.3 The texture map for a sofa in virtual reality. Source: Hao Wu.
Today, compared with computer image and animation, the virtual world created by virtual reality is often simplified to guarantee its smooth movement on computer graphic systems. However, this technique often impairs the visual fidelity of the virtual world.

3.1.2 Immersion

There are two types of immersion we have previously discussed, mental and physical immersion. Mental immersion is what is obtained with fixed image visualization media. Computer animation, with its ability to create a sense of time and
motion, improves the level of mental immersion, but only virtual reality achieves physical immersion.

Mental immersion means “a sense of presence” within an environment.\textsuperscript{38} For some virtual worlds, such as those described in novels, mental immersion is crucial for the success of the whole virtual experience.

For a successful architectural visualization, it is also important to make sure the audience obtains a proper sense of presence. Although the hand-drawn image, computer image, and animation achieve a certain level of mental immersion, virtual reality improves it to a higher level. The interface of real-time visualization offers the audience the perception of being personally on the scene. Meanwhile, the time and motion in virtual reality is not predetermined as in computer animation. It provides more chances to audiences to act as if they are in the physical world, keeping the audience acquire more accurate mental sense of visualized space.

“Physical immersion is accomplished by presenting a virtual world to users based on their location and orientation and providing synthetic stimuli to one or more of their senses in response to their position and actions. The VR system presents perspective-dependent images to each eye, synchronized audio to the ears, and haptic information to the body. When the user moves, the visual, auditory, haptic, and other qualities that establish physical immersion in the scene change in response.”\textsuperscript{39}


Today’s interface of virtual reality can accomplish good fidelity of physical immersion. The head-mounted displays, BOOM, CAVE and projection systems can all help the audience of virtual reality achieve impressive physical immersion. Today, the haptic, olfactory, and gustatory immersions are not popular in architectural visualization due to technology and cost issues. However, a three-dimensional sound source can easily be created within virtual reality easily, and other sound effects, like the sound for opening a door, are often utilized in architectural visualization to create physical immersion. In fact, with other traditional visualization media, such as the hand-drawn image, computer image, and computer animation, there is no physical immersion. Virtual Reality is the only visualization medium available to significantly increase the realistic effect of architectural visualization, transforming architectural visualization into an immersion experience.

As a key component of architectural visualization, the level of immersion is crucial for the fidelity of architectural communication. In this area, virtual reality performs much better than other traditional visualization media. It can help architects, clients, and other participants in architectural design understand the design idea more accurately and make a more informed decision.

3.1.3. Interactivity

“According to Webster’s dictionary(1989), interaction is “reciprocal action or influence.” Thus, interacting with a computer-generated environment occurs when
user inputs are responded to by corresponding actions of the computer.” 40 This interaction takes place through the user interface. The relation between people and the physical world is a kind of interactive connection. People walk and act in the physical world and get feedback from it. This interactivity makes up an important part of the experiencing in the physical world. With the development of computer graphic systems, more and more designers and engineers in computer visualization started trying to include interactivity into computer representation. Virtual reality is the fruit of this effort.

Unlike earlier media of architectural visualization, interactivity is a significant characteristic of virtual reality. In the experience of virtual reality, the audience can walk through the space, rotate the viewpoint, open the door, move objects, play videos, turn off the lights, and many other interactions. In other words, the goal of virtual reality is to create a virtual world like the physical world, or like the story in the movie “Matrix”.

The interactivity of virtual reality includes manipulation, navigation, and communication. Manipulation means the ability “to treat or operate with the hands or by mechanical means especially”. 41 In virtual reality, we have more choices for manipulating the virtual world. In general, there are three methods to perform the manipulation: direct user control, physical control, and virtual control. Direct user

control (Figure 3.5) uses “interface gestures that mimic real world interaction”. 42 This control works only when the participant is in the virtual world. Physical control (Figure 3.6) refers to “devices that user can physically touch”. 43 Devices exist in the physical world and the participant controls the virtual world by them. Many computer games use this kind of manipulation. For example, the joystick under the control of the player is the operating resource in many computer games. Virtual control (Figure 3.7) refers to “devices the user can virtually touch”. 44 Unlike physical control, virtual control devices only exist in the virtual world. In most cases, virtual control is the simulation of physical control in the virtual world. 45

Figure 3.5 Manipulations such as “Move table a little to the right” can be accomplished using any of the four forms of manipulation demonstrated here. Source: William R. Sherman & Alan B. Craig.

Figure 3.6 Physical control mechanisms can be integrated as part of the user interface to control various aspects of a VR experience. Here, the participant controls the virtual vehicle using a physical steering wheel and foot pedals. Source: William R. Sherman.

Figure 3.7 In this example of a virtual slider, the handheld wand is used to point at the virtual handle (the sphere) and move the slider (Application courtesy of Dan Sandin / EVL. Source: William R. Sherman.
Navigation is the ability to walk through virtual reality. It consists of two parts: wayfinding and travel (Figure 3.8). Wayfinding refers to methods that help the audience in virtual reality certainly its position and find the place to go next. In real-time architectural visualization, the door, window, lobby, corridor, stair, and signage in the real architectural environment is simulated, so the audience can find its way using common sense about the architecture to get to the designed destination. Everything takes place as if in the physical world. Travel refers to the audience ability to move in the virtual world with the help of devices (Figure 3.9).  

In the architectural virtual reality created by EON Studio, we can use the mouse to control Travel easily, for example, we can go forward and backward, change the elevation, and rotate the viewpoint.

Figure 3.8 Navigation is the combination of wayfinding (knowing where you are and how to get where you want to go) and travel (the act of moving through a space). Source: William R. Sherman & Alan B. Craig.

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47 Eon Studio is the interactive 3D and virtual reality software from EON Reality, Inc., the world's leading interactive visual content management software provider.
Communication refers to the interaction with other audiences or agents in virtual reality (Figure 3.10).\textsuperscript{48} This is popular in computer games today, and many games support double or multiple player communication. In architecture, virtual reality interaction with other audiences is not yet a popular area. While it offers the chance for architects to expand the virtual design environment, its requirements for computer hardware, software, and the interface of real-time visualization are not readily acceptable.

As was discussed, interactivity is a crucial part of the virtual reality. It is considered one of the key components of fidelity in virtual reality and is unique to the medium. With continual advancement in computer hardware and software, there will be more interactivities from the physical world to be created in the virtual world, bringing even more realistic experiences to virtual reality.

3.1.4. Sensory Feedback

Better than other traditional visualization media, virtual reality also offers sensory feedback to the audience. In most cases, visual feedback is the main sensory feedback in architectural virtual reality. However, aural feedback is also useful to architects in keeping the audience obtain a more realistic virtual experience. The proper sound can be simulated for opening the door or playing a video. Haptic, olfactory, and gustatory feedback need high-speed computers and an advanced
interface. Today, they are seldom utilized in architectural visualization as their time and cost are often not practical for architectural communication. Due to the current condition of sensory feedback applications in architectural visualization, they are not the emphasis of this thesis. Nevertheless, in the future, with the continuing development of computer technology, this kind of sensory feedback will be applied to architectural visualization at reasonable cost and efficient speed and improve the fidelity of virtual experience.

Through the introduction to four key components of virtual reality, it is obvious that this new medium has unmatched advantages over other visualization media. All these advantages ensure that it will improve the fidelity of architectural visualization to a higher level than before.

With virtual reality, architects can develop an architectural design in a virtual environment. This is an immersive design. Let’s imagine the architectural construction process. The worker creates the architectural space through piling up construction elements, such as brick, wood, concrete, steel, and tile, in a 1:1 scale with the physical space. The relationship of the worker to the architectural space is real without the misunderstanding that often takes place in two-dimensional drawings and three-dimensional representations. The design process for architects was different before the rise of virtual reality. Before construction, architects could only use two-dimensional and three-dimensional visualization media to get feedback for design ideas and then transform them step by step. A physical model is another approach to
architectural communication, but it is difficult to realize a 1:1 scale of representation with physical models. The rise of virtual reality changes everything, offering architects a virtual design environment. “Within this immersive design environment the creation of form in space becomes possible for the first time, without any intermediation. Like a magician, the architect’s gesture can raise walls, cut openings, and adjust the slope of roofs. Floors and stairs can be added and subtracted according to the reaction and judgment provoked by the perceptual impact. If the design is based on volumes, Boolean operations of addition or subtraction can be utilized, allowing the molding of virtual space similar to the creation of a sculpture by a molding and carving motion.”  

All these things take place in a 1:1 scale of virtual space to guarantee architects get the most realistic and accurate perception for the whole design space. Now, architects do not need two-dimensional and three dimensional images or models to aid their work. They can create the virtual space in virtual reality, just as the construction worker creates the physical space.

3.2 The Hindrance to the Application of Virtual Reality

Virtual reality improves the immersion to a new level of physical immersion and introduces interactivity to architectural visualization. In order to achieve a realistic representation of geometry, material, and light in the virtual world, virtual reality uses a similar modeling, mapping, and lighting technology as computer image...
and animation but achieves more fidelity in architectural visualization. Nevertheless, today virtual reality is not yet popularly applied to architectural visualization. Time and cost are still obstacles to its wide application.

In virtual reality, the audience has the opportunity to observe more elements of the virtual world. In contrast, computer image and animation need only create the geometries to be shown to the audience. The three-dimensional model of virtual reality has to have more polygons than computer image and animation. This decreases the running speed and increase the time and cost of production. This complicated modeling process increases the amount of texture mapping in order to realize high map quality. A high resolution of texture mapping is necessary to achieve good fidelity that also decreases the running speed. In virtual reality, real-time feedback is necessary for audience interaction. Unlike computer image and animation that can be rendered in advance and just shown to the audience, virtual reality needs high speed computer hardware to achieve smooth motion with real-time feedback. A complicated polygonal model, high-resolution texture map, and real-time interactivity are all necessary to the successful realization of virtual reality. Unfortunately, today to achieve all these requirements in reasonable time and at reasonable cost is very difficult with the current speed of computer hardware, virtual reality software, and virtual reality projection systems. In order to create virtual reality efficiently, some compromise have been accepted, such as simplifying the geometric model or using
low resolution mapping, but they will influence the fidelity of virtual reality. This is the reason why today virtual reality is not widely applied in architectural visualization.

The establishment of virtual reality as the future architectural visualization medium is dependent on the advancement of three key factors: computing hardware, virtual reality software, and virtual reality projection systems. Figure 3.11 shows how a virtual reality system works. In this chart, the realization of VR-Render depends on the computer hardware and software. The projection systems decide the VR-display. These three elements are crucial to the virtual experience because they are related to the speed and quality of virtual reality.

Figure 3.11 The graphics shows virtual reality system.
Source: William R. Sherman & Alan B. Craig,
3.2.1 Computing Hardware

The ability to provide real-time graphic rendering is critical to virtual reality. Rendering is the process of creating the images that are projected on a screen or monitor. In creating a computer image or animation, a significant computing time is spent rendering a single image or frame of animation, but, in a virtual reality, this is unrealistic. So virtual reality has high demands on computer hardware capacity and speed.

The CPU, RAM, and video adapter are crucial computer hardware for an effective rendering of virtual reality. CPU (Central Processing Unit) is the brain of the computer where most calculations take place. During the rendering process, algorithmic conditions are calculated in the CPU. In terms of computing power, the CPU is extremely important hardware for a computer system.\(^{51}\) RAM (random access memory) is the memory module for all PC computers. In the rendering process, much temporary data is stored in RAM and its rendering speed is directly related to the amount of RAM.\(^ {52}\) The video adapter is a board that plugs into the computer to give it display capabilities. The display capabilities of a computer, however, depend on both the logical circuitry (provided in the video adaptor) and the display projector.\(^ {53}\) The video adaptor determines the color of each pixel projected. These components, CPU,

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RAM and video adaptor work together as an integrated system, each component playing a related and vital task in the rendering process.

The exciting information is that the speed and capacity of computer hardware have developed rapidly in the last decade. These advancements in hardware performance are providing designers and engineers a chance to create more sophisticated models and textures for virtual reality.

“One of the most important changes was the tremendous improvement in PC hardware. Not only did the central processing unit (CPU) speed get faster, but so did the speed of PC-based graphics accelerators. According to the well-known Moore’s law, CPU performance doubles every 18 months. The same law could be applied to PC graphics accelerators. In the early 1990s the speed of PC graphics boards was very poor, at 7000-35,000 polygons rendered in a second. Based on that, Moore’s law predicted a speed of 20 million polygons rendered every second by 2003. Rapid technological advances in 3D rendering chipsets made this happen much earlier. By 2001 the performance of PC graphics matched or exceeded that of high-end SGI graphics supercomputers (Figure 3.12).”

The same thing has happened with RAM. In the last several years, it has developed from an asynchronous to synchronous technology, and new technologies emerge in endless form, from PC100 SDRAM, PC133 SDRAM, HSDRAM, VC SDRAM, DDR SDRAM, ENHANCED DDR_II, to DRDRAM. All of these

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improvements have increased RAM speed and integration with the CPU creating faster systems for computer image.55

The cost of hardware is another important element in virtual reality application. In 1993, the price of the fastest graphic workstation from Silicon Graphics Inc was over $100,000, but today a significant reduction in price makes the typical hardware equipment for virtual reality technology available to almost everyone.56

![Figure 3.12](image.png)

**Figure 3.12** Graphics performance comparison between PCs and high-end SGI workstations. Speed is given in Polygons per second. Source: Burdea (2000).

### 3.2.2 Virtual Reality Software Development

In order to achieve high fidelity and wide application of virtual reality, we need not only high speed hardware but also advanced software. There are three software components needed to create a VR simulation, the content generator, real-time editor, and real-time viewer. The basic virtual world is produced with the content

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generator, and interactivity is added with a real-time editor. Finally, the real-time viewer works as the interface for virtual reality to achieve physical immersion. There are two crucial elements, for the development and application of virtual reality software: easier execution and more fidelity. Easy execution means that virtual world can be created quickly, the interactivity can be added conveniently, and virtual experience can be viewed easily. Meanwhile, high fidelity for the virtual world, as well as high level interactivity and immersion are also crucial to the application of virtual reality software.

A good example of this content generator, real-time editor and real-time viewer relationship is the use of 3D Studio Max by Autodesk and EON Studio by Eon Reality. 3D Studio Max is a popular software for creating geometric models, texture maps and lighting for architectural image and animation. It is also used by a number of real-time computer game developers. In 3D Studio Max one can develop virtual world that can be used in VR.

A virtual world created in 3D Studio Max can be imported into a real-time editor such as EON Studio. In EON Studio interactivity may be added to the Max model. Geometry can be made to move and animate. Sound and video may be added. Interactivity and physical immersion can be made possible with sample object oriented programming.

EON Studio also works as a real-time engine and viewer that allow one to display and run the VR simulation on the internet or on stereo projection systems.
One can also attach haptic devices that allow one to virtual “touch” objects in the virtual world. The EON Studio is a complete VR software system that allows for easy development of architectural visualization.

However, with the old version of EON Studio, the execution of the virtual world is complicated in virtual reality. The old version of EON Studio cannot directly import 3D model from the 3D Studio Max. So the Max file must be converted to 3DS file then imported to EON Studio. In this process, many settings of the Max file are missed, especially texture. Nevertheless, the advancement in this area is significant. In order to solve this problem, recently EON Reality has developed a new plug-in software for 3D Studio Max, EON Raptor. So now we can open a virtual reality window in 3D Studio Max and save it as an EON Studio file directly. This development is a very important breakthrough for easy execution of virtual reality.

Fidelity is another crucial factor in the software application of virtual reality. It is related to the virtual world, interactivity, and immersion. In the virtual world, geometry used by virtual reality is no different than other visualization media. The material and light effects of the virtual world are simulated by texture mapping in virtual reality. As was discussed before, this technique usually stores information in a two-dimensional domain, which is used during rendering to simulate texture\(^{57}\). Texture mapping is an excellent technique to speed up Real-Time rendering. With the

old version of EON Studio, in order to export the texture setting from 3D Studio Max through 3DS file, we can only use the shell map for the textures. With it, it is very difficult to realize the photorealistic effect, like radiosity and raytrace renderings of 3D Studio Max, even though the color, brightness and contrast of the texture map can be adjusted by hand. Now with the new plug-in software, EON Raptor, EON Studio solves this problem with the 3D Studio Max function, Render to Texture. Render to Texture is a method that can save the result of radiosity or raytrace renderings as a texture map to every object in the 3D model. So we can export the material to EON Studio and realize the photorealistic effect in virtual reality. Meanwhile the development of EON studio offers more interactivity in virtual experience. This advancement improves the immersion of virtual reality.

Using some examples of virtual reality with different mapping techniques, we find that EON Studio is always improving fidelity and the development has been more rapid (Figure 3.13, 3.14 and 3.115). The first was the virtual reality without Render to Texture. The second was Render to Texture in EON Studio but the execution process was very complicated. The third was created with EON Raptor. Its execution process is simple and the photorealistic effect is similar to computer image and animation.
Figure 3.13 The Space effects without the Render to Texture in EON Studio.
Source: Arthi Amaran and Tania Pramanik.

Figure 3.14 The Space effects with the Render to Texture in EON Studio.
Source: Hao Wu and Dake Zhang.

Figure 3.15 The Space effects with the Render to Texture in EON Raptor.
Source: Hao Wu.
However, currently, the development of virtual reality software is not enough for its wide application. Compared with radiosity and raytrace rendering, high-resolution mapping is difficult to run in virtual reality even with EON Raptor and the reflection effect in virtual reality is not so perfect. All these drawbacks influence the execution and fidelity in virtual reality. Nevertheless, with the continuing development of virtual reality software, we have reasons to believe that these problems will be solved in the near future.

3.2.3 Virtual Reality Projection System

Another key factor of virtual reality is how the audience perceives the environment. One perception of the virtual world is based entirely on what the computer displays and how it responds to the activity.\textsuperscript{58} The visual properties of a display device are a significant factor in the overall quality of virtual reality.\textsuperscript{59} Undoubtedly, an excellent projection system will increase the fidelity of visualization and a bad one can impair it.

Today, two types of projection systems are mainly applied in architectural virtual reality. They are stationary and head-based.

<table>
<thead>
<tr>
<th>Stationary Projection System</th>
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</thead>
<tbody>
<tr>
<td>Monitor-based or Fishtank:</td>
</tr>
<tr>
<td>The simplest form of virtual reality display</td>
</tr>
</tbody>
</table>


utilizes a standard computer monitor and is called monitor-based VR, or more often fishtank VR. The name fishtank comes from the similarity of looking through an aquarium glass to observe the 3D world inside (Figure 3.16). Viewers can move their heads from side to side and up and down to see around, over, and under objects, but they cannot actually become physical immersed.60

Figure 3.16 Fishtank VR (monitor-based) provides a display paradigm that is similar to peering into a fishtank. The participant is able to see and look about a 3D world that appears to exist within the confines of the monitor. Source: William Sherman.

Projection-based: Projection-based visual displays are systems where the computer graphics are projected onto a screen. The screen is much larger than the typical monitor display, thereby filling more of the participants’ fields of view and allowing them to roam more freely and to become more physically immersed (Figure 3.17). The size of the display influences the level of immersion into the virtual world. Most projection VR systems are rear-

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projected to avoid the participants casting shadows on the screen. Some projection systems physically immerse the participant by surrounding the participant with projection screens such as the popular CAVE (Figure 3.18).

![Figure 3.17. VR Projections. Source: Calibre Institute.](image)

![Figure 3.18. CAVE Projections. Source: ETH Zentrum.](image)

- **Head-based:**

  “Unlike fishtank and projection visual display paradigms, the screens in head-based displays are not stationary; rather, as their name suggests, they move in conjunction with the user’s head (figure 3.19). Ultimately, this type of display will

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shift to hardware that is more appropriately referred to as head-worn rather than head-mounted-approaching something on the order of a device similar to a pair of glasses in weight and size, yet conveying high resolution and wide field of view.”

Fortunately, rapid technological developments are taking place in this area. The computer monitor has advanced from CRT, LCD to LED in the last decade. The rise of new display technology from VGA, XGA, SVGA to UXGA keeps the computer monitor support higher and higher resolution and more colors. With a head-based projection system, the situation is similar. “Early LCD-based color HUDs were very heavy and had poor resolution. A breakthrough in HMD ergonomics occurred in 1998 when Sony introduced a much slimmer Glasstron with a weight of only 310 grams. Shortly thereafter Kaiser Electro-Optics Launched the first LCD-based HMD with extended graphics array (XGA) resolution (1024 x 768 pixels). Such

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resolution was previously available only on much more expensive and heavier CRT-based HMDs or on desktop color monitors. The steady increase in HMD resolution during the 1990s meant much sharper images without the unwanted jagger pixilation effect of earlier models. "64 (Figure 3.20)

![Figure 3.20 LCD HMD image resolution evolution in the 1990s. XGA, Extended graphics array; VGA, video graphics array; NTSC, National Television System Committee; CGA, color graphics adaptor. Source: Kaiser Electro-Optics Co.]

Another bonus is that the price of projection systems is always dropping although their performance is steadily improving. Five years ago, you needed to spend about $300 on a 15’ flat CRT. Today, you can buy a 19’ LCD for the same price.

Due to the importance of projection systems to virtual reality, their development will increase visualization fidelity and make their application more popular. Some other interfaces in virtual reality, such as aural and haptic, are also helpful in improving the fidelity of virtual experience. However, today they are not usually applied in architectural visualization.

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3.3 Summary

The rise of virtual reality is the direct result of the development of computer graphic systems. It is the fruit for pursuing high fidelity in architectural visualization. Undoubtedly, the key components of virtual reality, like immersion, interactivity, and sensory feedback, take the fidelity of architectural visualization to a new level. However, in the early stages of computer development, due to the low speed of CPU and the low resolution of display systems, the value of virtual reality was not recognized. By the end of the twentieth century, computer technology had advanced enough to create a high fidelity virtual world and other accessories for virtual reality. It is time for virtual reality to begin to govern the area of architectural visualization, and more advancements in this area promise to take place in the near future.
CHAPTER IV
ARCHITECTURAL VISUALIZATION
CASE STUDIES OF VIRTUAL REALITY

Two case studies will be discussed in this chapter to show the range of fidelity of virtual reality that can be achieved today in architectural visualization. One case study is an atelier project in an old city and it is created with SketchUp. Because SketchUp can offer an immersive design environment, it works as the design tool in this case study. Another case study is visualization of a church designed by Tadao Ando. In this case study, EON Studio works as the visualization tool to offer the audience a virtual experience to this project.

4.1 Software information

As a user of virtual reality, I had already learned to create virtual reality for architectural visualization one year before I produced the case studies of virtual reality in this chapter. So I am familiar with the main software used to create virtual reality, like EON Studio, VRML, and virtual reality technologies such as modeling, lighting, and mapping. As discussed before, there are three kinds of software used to produce virtual reality. They are content generator, real-time editor, and real-time viewer. Choosing the proper visualization software is an important factor in producing virtual
reality. In the case studies of this chapter, three software programs, SketchUp, 3D Studio Max, and EON Studio, will be applied to create and experience virtual reality.

- **SketchUp** is now widely used in architectural schematic design. Its functions of quick 3D modeling and virtual reality help architects to develop projects in immersive and interactive design environments. Although SketchUp does not have accurate and advanced modeling, mapping, lighting, and rendering functions as does 3D Studio Max, it offers designers the ability to create models, with texture and light quickly. In virtual reality, it can work as a content generator, real-time editor, and real-time viewer.

- **3D Studio Max** is one of the most popular 3D modeling and rendering softwares applied in architectural design. Its polygonal modeling makes it more appropriate for creating architectural models than Maya with NURBS modeling because there are not many curved faces in architectural model. For virtual reality, the task of 3D Studio Max is to create the model and texture. So it works as a content generator. Another reason to choose 3D Studio Max is that EON Studio depends on its model and texture to create the virtual world. The “render to texture” technology helps EON Studio achieve high fidelity material and lighting effects conveniently.

- **EON Studio** can create high fidelity of virtual reality (Figure 4.1) compared with other virtual reality software, such as Director and VRML. With the assistance of 3D Studio Max, it can create accurate and advanced geometry,
material and light effects. So it is a good tool for producing virtual reality for final design review. Its compatibility with 3D Studio Max is also an important reason why it is usually applied in architectural visualization. EON Studio works as a real-time editor and viewer in virtual reality. Another tool in EON software, EON Web Viewer, offers audience an easy way to experience virtual reality.

Figure 4.1 Virtual reality of an architectural museum. Source: Hao Wu.

4.2 Virtual Reality with SketchUp

4.2.1 Project introduction

In the Spring of 2004, I chose a project in a third-year architectural design studio to be visualized with virtual reality. The project was an atelier for university
students located in an old city in Spain (Figure 4.2 and 4.3). The atelier consisted of work and living space for 10 students. Workspace consisted of an appropriately sized day-lighted studio, a classroom/discussion/review space, and a small office for a professor. Living space consisted of shared dorm style rooms, a common lounge/dining area, a communal kitchen and shared bathrooms/toilets. This was not a big project but still a challenge to architects. The challenge was to create a new building in a complicated environment.

4.2.2 Computer Software, Hardware and Projection System

SketchUp was chosen as a basic tool to aid the design process because it offers architects a virtual design environment. SketchUp is an easy and quick software for architectural design application. If one has previous CAD experience, it only takes one or two hours to be familiar with its fundamental functions. Another advantage of SketchUp is that it does not need high-end computer hardware.

The computer hardware I used to produce a SketchUp virtual reality was
equipped with an AMD Athlon XP 2400+ (CPU), 256MB memory (RAM), 40GB hard disk, and 17” Envision flat CRT monitor. In June of 2003, the computer was bought for the price of $450. Today, you can buy the computer with a similar configuration for even a much lower price. This hardware configuration is enough to run SketchUp.

In order to lower the cost, I did not use an advanced projection system for this virtual reality. The 17” Envision flat CRT worked as the interface for this virtual experience.

4.2.3 Virtual World

The modeling method in SketchUp is similar to 3D Studio Max. Drawing a 2D object first then giving it height through the “Pull/Push” function is the main modeling method in SketchUp. Every 3D object in SketchUp is an editable mesh as in 3D Studio Max. Moving a vertex or face is convenient. Many architectural components like a door, window, and furniture make its modeling quick and easy for architects. (Figure 4.4 and Figure 4.5) Although its model is not that usually accurate, I used the inch as the unit to make this model and the precision was 1/2”. The model took me 20 hours to finish and the polygon count was about 150,000. In my experience, the speed of SketchUp modeling is not much faster than 3D Studio Max, but architects can always observe a quick rendering effect in SketchUp. While in 3D Studio Max, you need to work a long time to achieve the rendering effect.
Figure 4.4 The model of SketchUp.
Source: Hao Wu.

Figure 4.5 The Model of SketchUp.
Source: Hao Wu.
For materials, SketchUp also uses a texture map (Figure 4.6). So we can place the images of brick, stone, shingle, and stucco on the model to visualize the realistic effect. However, in SketchUp, material is only a map, and we cannot adjust material attributes such as shine, bump, reflection, and raytrace. In order to achieve high fidelity materials, these configurations are very important. Materials in the physical world present their special effects and influence each other. Nevertheless, the color and opacity of materials can be adjusted in SketchUp. The result of SketchUp material technology is that it can save time in the rendering process by not including algorithmically intensive material configurations, but its effect is not the highest in fidelity. (Figure 4.7) In SketchUp, there are already many architectural materials in the library, if you do not need to create special materials for your model, the time it takes to show material in the model is very quick in SketchUp. In my model, I only spent one hour placing all materials.

Figure 4.6 The material of SketchUp.
Source: Last Software, Inc.
In SkechUp, the light effect is also created simply. Sun light can be chosen according to the location, time, and date. Every configuration of light, such as intensity and angle, is preset with the location, time, and date. There is no light that can be added manually. The best advantage of the light effect in SketchUp is that you can observe the real-time light effect when you change the light settings. However, there are no radiosity and raytrace rendering procedures in SketchUp. No advanced lighting effects are available. In SketchUp, the 3D object is only divided into bright face, gray face, and dark face with no change in brightness and color. In the physical world, indirect light (radiosity) is very important to deciding an object’s brightness and color. Without this function, it is difficult to achieve high fidelity in the SketchUp virtual world. The shadow in SketchUp can be calculated with the light angle and
object shape and the shadow brightness can be preset. The shape of the shadow in SketchUp is accurate, but its effect is flat without advanced rendering. (Figure 4.8 and 4.9)

Figure 4.8 The sunlight changes from the morning to night in SketchUp. Source: Hao Wu.

Figure 4.9 The sunlight effect in SketchUp. Source: Hao Wu.

4.2.4 Immersion and Interactivity

In SketchUp, virtual experience can be observed during the architectural design process. Although SketchUp does not have high fidelity of the virtual world, it
takes mental immersion to a new level because its motion is not predetermined but interactive. Using the computer system mouse the audiences can move in the virtual world freely and choose any viewpoint they want. (Figure 4.10 and 4.11) It is not possible to achieve physical immersion because SketchUp does not support any of the visual, audio, haptic displays usually available for VR systems.

Figure 4.10 The real-time movement in SketchUp. Source: Hao Wu.

Figure 4.11 The viewpoint change in SketchUp. Source: Hao Wu.

Today, there are not many choices for interactivity in the SketchUp virtual experience, because SketchUp is not a real-time editor software. General interactivities in virtual reality, such as opening the door, moving the object, turning off the light, and playing a video, cannot be realized in SketchUp. With it, only real-time movement and light changes can be obtained. In the images shown in the last several sections, these interactivities of SketchUp are known already. Because there
are not many interactivities in SketchUp virtual reality, no time need be spent trying to produce it.

The first case study of virtual reality was produced completely with SketchUp. Through this study, we can see that the fidelity of SketchUp virtual reality is not perfect. However, with its speed of execution and low cost, it is a valuable tool for architectural schematic design. Perhaps SketchUp is not the best program for a final presentation but it does help architects develop their design concepts in a virtual design environment quickly with limited resources.

4.3 Virtual Reality with EON Studio

4.3.1 Project information

In the spring of 2004, I chose a famous building; the Church of the light (Figure 4.12), designed by Tadao Ando, to be visualized with EON Studio. The building was designed and built in 1989 as an addition to an existing wood structure and located in the suburb of Ibaraki, Osaka, Japan. The architectural form and space are composed of a box and a wall that is inserted into the box at 15 degree (Figure 4.13). As a low-cost concrete structure, it is a small and simple modern building without much adornment, but its sacred light, space, and material effects are impressive. The purpose of this case study was to study VR tools that have the capability of creating higher fidelity VR experience.
Figure 4.12 The Church of Light.
Source: Tadao Ando.

Figure 4.13 The Church of Light.
Source: Tadao Ando.
4.3.2 Computer Software, Hardware and Projection System

EON Studio is a professional software for virtual reality, demanding more time and cost than SketchUp, EON Studio realizes high fidelity in the virtual world, immersion, and interactivity. It also has a higher requirement for computer hardware than SketchUp.

For this case study, I used a computer with Pentium 4 3.0 GB, 1G Memory and a Gforce 4000 64MB video adaptor. In the spring of 2004, the cost for this computer was about $1200, and even with this computer hardware configuration, it was difficult to run a complex model of virtual reality, so I simplified the model under 100,000 polygons for this virtual experience.

For high fidelity of EON virtual reality, an advanced projection system could be applied to improve physical immersion. In this case study, I use a passive stereo projection display. This Projection system includes Linear Polarized 4x4 projector Lenses, Cyviz Xpo.2, active to passive stereo converter, two 1500 lumens Viewsonic Pj551, and Da-lite 'Silver Matte' Tripod Screen (Figure 4.14 and 4.15). “The xpo.2 accepts the frame sequential stereo signal that is supported by existing active stereo viewing devices (e.g. StereoGraphics CrystalEyes or similar products) and converts it to separate display signals for the left and right eyes to allow polarized passive stereo display. These separate signals are fed to two projectors. The dual images of which are precisely aligned (using adjustable stacking racks provided by CyViz) and superimposed onto a single polarization preserving screen. Polarized filters are placed
in the projection path (immediately in front of the projectors) and inexpensive polarized glasses are worn by viewers to maintain the separation of left and right eye images that is required for stereopsis.\textsuperscript{65}

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\textsuperscript{65} Visualization Group, Penn State University, “VR Desktop Initiative”, http://gearsaset.psu.edu/viz/facilities/initiative/
4.3.3 Virtual World

EON Studio is not a content generator for virtual reality but it can import a 3D Studio Max model as its fundamental content generator. Therefore I used 3D Studio Max to create the model for this project (Figure 4.16 and 4.17). The unit of this model is millimeters and I spent 20 hours creating it. Creating this simple model did not take 20 hours, but in the working process, the polygons of the model needed to be decreased to fit the requirements of virtual reality without impairing the final effect. So I spent much time simplifying details like doors, windows, lamps, chairs, and tables. This model has 50,000 polygons and was created with simple 3D geometries and editable mesh.

Figure 4.16 The model in 3D Studio Max.
Source: Hao Wu.
Figure 4.17 The model in 3D Studio Max. 
Source: Hao Wu.

The material technology applied in EON Studio is texture map, like the model, it can be created in 3D Studio Max. Although the material can be created in EON Studio too, EON Studio has many limitations in creating realistic materials as does 3D Studio Max. Today, only limited material configurations of 3D Studio Max can be exported to EON Studio and they include diffuse channel, specular channel and Blind and Phong shades. However, some other important material configurations, for example, some advanced material shades (Raytrace, etc.), reflection channel and refraction channel can not be directly used in EON Studio. It impairs the material effects in EON Studio. In order to save more material and lighting effects, I use the
3D Studio Max Function “Render to Texture” (Figure 4.18) to export the material from 3D Studio Max to EON Studio in this case study. The principle of this kind of material is similar to SketchUp and places a texture map on the face of the model. It can reserve most of the effects of normal material, like shine, bump, and refraction, on the texture map, but loses the reflection channel. In order to decrease the size of the model for some unimportant face, texture map was applied to simulate details like doors and windows (Figure 4.19). So the material work in 3D Studio Max is not as quick and easy as in SketchUp. Fifteen hours were spent on the material.

Figure 4.18 “Render to Texture” in 3D Studio Max.
Source: Hao Wu.
In EON Studio, there is no advanced light rendering procedures such as radiosity and raytrace. To achieve high fidelity lighting in this virtual world, the texture map is applied to simulate these advanced light effects. In figure 4.18 and 4.19, you can see the light and shadow effects on the texture map such as the shadows of the tree leaves on the wall. To achieve it, a good rendering effect needs to be created in 3D Studio Max. So, for this model, the photometric light (Figure 4.20) that
accurately simulates light in the physical world was used in 3D Studio Max. This kind of light makes the algorithm of radiosity possible in 3D Studio Max so that higher fidelity can be achieved in the final rendering. Second, “Render to Texture” can save the high fidelity of the light effect in texture map. In this phase, I spent four hours setting all lights and adjusting their intensity, color, and location to obtain the ideal effect.

Figure 4.20 The photometric light in 3D Studio Max. Source: Hao Wu.
4.3.4 Immersion and Interactivity

With higher fidelity to the virtual world, EON Studio improves mental immersion in its virtual experience. Meanwhile, with many interactivities, EON Studio can achieve high fidelity of physical immersion with the help of an advanced projection system. In this case study, I use a passive stereo projection displays. As I introduced before, it improves the fidelity of the virtual experience very much. Although I do not import the haptic virtual experience into this case study due to the low cost, today it can also be realized in virtual reality. It would be a great improvement to physical immersion. With it, the audience can get the direct feeling to the material and space through touching them.

After importing the virtual world from 3D Studio Max, EON Studio can edit many interactivities for the virtual experience. These interactivities includes opening a door, playing the video, moving the object, changing properties of objects, starting the preset animation, turning on or off the lights, and changing a background image. All of these interactivities offer the audience higher fidelity in the virtual experience. I spent 6 hours adding interactivities (Figure 4.21, 4.22 and 4.23).
Figure 4.21 Virtual reality of Church of Light. Click the red button will start the preset animation.
Source: Hao Wu.

Figure 4.22 Virtual reality of Church of Light. In virtual reality, the omni light can be turned off and the background image can be changed.
Source: Hao Wu.
Compared with SketchUp, EON Studio (Figure 4.24) creates a higher fidelity virtual reality. However, its strict requirements for computer hardware, expense, and time may limit its use for a quick design process. I often apply it for the final representation.

Figure 4.23 Virtual reality of Church of Light. Click the door in the scene will open and close it. Source: Hao Wu.

Figure 4.24 Virtual reality of Church of Light. Source: Hao Wu.
4.3 Summary

In this chapter, two case studies show virtual reality applied to architectural design and visualization. I found that SketchUp is an effective tool for architectural schematic design because it offers architects an immersive design environment. In the schematic design process, architects can observe and modify their designs in a three-dimensional virtual environment easily with SketchUp. This process is interactive and mentally immersive. Meanwhile, this software does not need high-end computer hardware capabilities and display systems. All these advantages make it a valuable tool for architectural schematic design. It does not have high fidelity in virtual world, interactivity, and immersion but these are often not important qualities for architectural schematic design.

Compared with SketchUp, EON Studio can achieve higher fidelity in the virtual world with the help of 3D Studio Max. As a real-time editor, EON Studio realizes many interactivities in virtual experience and may add physical immersion of virtual reality with the help of advanced display systems such as stereo projection and haptic technologies. However, it does not offer an immersive design environment to architects. The audience may observe virtual architecture in virtual reality but cannot modify it easily. This software also has higher computer hardware requirement and takes more time and expense to operate. So, in general, it is a good tool to create a final architectural visualization with high fidelity.
Sensory feedback is also a key element to virtual reality. However, with the limited time and expense involved, sensory feedbacks, such as haptic, olfactory, and gustatory, are not included in these two case studies. Only visual and a limited aural feedback were applied in these case studies. Maybe in the future, sensory feedback can be expanded in architectural virtual reality. Today, it is not efficient for architectural virtual reality.

In my experience, these two software have their own advantages and disadvantages compared to each other. According to the phase of architectural design, architects can choose the proper tool. The level of virtual world, interactivity, and immersion that they can achieve are already discussed. In order to help readers understand these two softwares, Table 4.1 compares the hardware, cost and time of the two systems.

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<thead>
<tr>
<th>Table 4.1 The comparison between SketchUp and EON Studio case studies</th>
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<tr>
<td><strong>SketchUp (The atelier in Spain)</strong></td>
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<tr>
<td>Geometry</td>
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<tr>
<td>Precision: 1/2”</td>
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<tr>
<td>Material</td>
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<td>Light</td>
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<tr>
<td>Immersion</td>
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<td>Interactivity</td>
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Through this table, virtual reality created by EON Studio takes a longer time and achieves higher fidelity in the level of virtual world, immersion and interactivity than SketchUp. As the professional content generator, EON Studio also spends time to add interactivities into virtual experience but SketchUp does not have this function. They are two kinds of software that can be applied in the different phases of architectural design.
The development of architectural visualization is a gradual process in pursuing the higher fidelity. The fidelity of architectural visualization is decided by five key elements: geometry, material, light, immersion, and interactivity. Geometry, material and light compose the virtual world of architectural visualization. In order to achieve higher fidelity in architectural visualization, various kinds of visualization media have been used to simulate these five elements.

Historically, the hand-drawn image developed a high fidelity virtual world through the development of the perspective rule and the use of color. Then, the rise of computer aided design made computer image popular in architectural visualization. With the development of computer image, more accurate representations of light and material in architectural visualization were achieved. This increased the case of creating high fidelity computer images over hand-drawn images. The development of 3D computer image in addition made computer animation possible. Computer animation introduced “time” and “motion” to architectural visualization and raised mental immersion to a new level. This historical development of the hand-drawn image, computer image, and computer animation, has raised the fidelity of the virtual world and mental immersion of architectural visualization to a photorealistic level.
However, these media have reached their limit fidelity and do not offer physical immersion or interactivity.

Virtual reality is capable of raising the fidelity of architectural visualization to this next level fidelity through introducing physical immersion and interactivity, and increasing the effectiveness of the communication process. The application of virtual reality in architectural visualization is limited by current hardware and software development. It is obvious that the situation is changing rapidly and improvements in hardware and software are solving these problems. Indeed, the high fidelity of the virtual worlds in 3D real-time computer games shows us the potential of VR technologies. Unfortunately, because of the time and cost of development, this level of fidelity is difficult to achieve in architectural visualization. All these instances indicate that virtual reality has a bright future, but architects and computer engineers need to work together to achieve this promise.

In order to study the application of virtual reality in architectural design and visualization, two case studies were discussed. Compared with other visualization media, the fidelity of the virtual world in virtual reality is not yet perfect. However, virtual reality raises immersion and interactivity to a new level, and the technological development of the virtual world in virtual reality continues rapidly.

Undoubtedly, virtual reality improves the fidelity of architectural visualization compared to hand-drawn images, computer image, and computer animation. With the development of virtual reality technology, more and more architects and clients must
seek to understand and acquaint it themselves, so the wide application of virtual reality in architectural visualization will be more than a dream in the near future. Nevertheless, virtual reality is not an end but a beginning in pursuing high fidelity in architectural visualization. Architects still have challenges for achieving higher fidelity visualization and transforming the design process. Areas for continuing to develop higher fidelity architectural visualization include:

**Improve sensory feedback in architectural visualization.** Sensory feedback is a key element of virtual reality. It includes not only visual but also aural, haptic, olfactory and gustatory feedback. As discussed before, sensory feedback has only begun to be realized in architectural visualization, with only visual and some aural simulations. Today, the time and cost to high fidelity sensory feedback is not affordable for architectural design and visualization.

However, sensory feedback is important to people’s perceptions in physical world and its development should be very helpful to achieving higher fidelity in virtual reality. As the cost in hardware, software and time decreases to allow importing sensory feedback into architectural virtual reality, audiences would have the chance to enjoy higher fidelity architectural visualization.

**Create communication interaction in virtual reality.** Another possibility for future virtual reality is to use the internet to help long-distance design collaboration. Today’s virtual reality that offers an immersive design environment to architects accommodates the operation system of only a single player due to the high cost for
multiple players. Like computer three-dimensional games, if a multiple-player system can be imported into architectural virtual reality, it will become than a visualization medium to communicate with someone else. A design team can engage among one another to develop a design in a multiple-player virtual reality system.

At that time, the need for meeting space will disappear. Architects will not need to come together physically to discuss and integrate the design. With the internet, everyone can work anywhere. Each designer can enter into the immersive design environment with his own identification. In the immersive design environment each designer can work with his own viewpoint interactively. Any modification of the virtual building will be known by the other architects in this system. They can work together to modify the design in order to obtain a satisfactory result.

**Virtual reality becomes the final product of architectural design.** Every one that watched the movie “Matrix” has a deep impression of its perfect virtual reality. This virtual world simulates everything in the physical world so people can live in it as in the physical world. In it, virtual reality is no longer a visualization medium. It makes up another world in our life parallel for the physical world. With the further development of virtual reality, maybe in the future, virtual reality will become the final product of architectural design as meaningful as the building itself.

The dream that people can live in the virtual world with the help of a computer system would not be impossible. With this kind of virtual building and world, architects have more freedom to create the form and space they want. Like other
artists, architects’ creativity would not be limited by building technology. They could develop whatever inspired them.

Of course, all these possibilities are only suppositions. How virtual reality will develop depends on technology and social requirements. However, today we can not deny the fact that virtual reality has higher fidelity than other visualization media. Although there are still some implementation issues, its application in architectural visualization is irresistible. Here I hope every architect and client can accept this new technology to help us design better architecture.


Michael Morrison, 1994, “Becoming a Computer Animator”,
http://hem.passagen.se/des/hocg_intro.htm

“3D Computer Graphics”,
http://www.arthistoryclub.com/art_history/3D_computer_graphics