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APPLICATIONS OF AUGMENTED REALITY DURING CONSTRUCTION STAGE

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**Applications of Augmented Reality
during Construction Stage**

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**A thesis submitted in partial fulfillment of the requirements
for the degree of Master of Philosophy**

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CERTIFICATE OF ORIGINALITY

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ABSTRACT

With the rapid development of virtual reality (VR) technologies during past two decades, building information modeling (BIM) tools have been improved quickly and applied extensively in architecture, engineering and construction (AEC) industries. In the basis of BIM, technologies of four-dimension (4D), five-dimension (5D) or incorporation of all possible dimensions have been developed in recent years. These technologies have been utilized for architecture design, construction planning, facility management, and building demolition. Project managers could share and exchange virtual data of BIM, 4D or 5D, send feedback to each other, and improve the original data.

According to the literature review, in the respect of real-time share and exchange of virtual data, the practical construction phase has not fully benefited from VR technologies. Namely, a break of continuous utilization of digital data in the building life cycle has been existed. This problem may be caused by the complexity and dynamics of the construction site. Even though the construction planning could be tested and improved by related software tools before practical building, the implemented scenarios have been probably different on site. In other words, virtual data created by BIM and multidimensional tools have not released the full potentials during construction stage.

This research attempts to fill this gap with an emerging technology called augmented reality (AR). AR can display virtual data in physical real-world environment in real time. ARToolKit software library was used for creating AR applications. In order to achieve

high-performance rendering effect of virtual data, a rendering engine of 3D scene graph was introduced, which is called OpenSceneGraph (OSG). An integrated library framework of ARToolKit and OSG termed OSGART was also used, in which more flexible and free AR technologies can be supported. In this research, augmented reality-aided construction system (ARAC) was built with ARToolKit, OSG and OSGART. By using computer with a camera, ARAC was implemented with virtual data of SHUI CHUEN O project in Shatin Area, Hong Kong.

The study found that, ARAC users on site could intuitively checked the digital data of geometry, spatial relationship, quantities and properties of building components. The virtual operation guides shown in real environment would assist users in finishing tasks more quickly and accurately. Users also could refer the virtual construction simulation and other dynamical operation. Moreover, actual finished building components could be compared with designed virtual 3D models in real time. If there were differences between finished components and designed BIM models, it could be identified directly by AR technology. Users on site could feedback these differences to the designers and planners, then get updated construction scheme which improved by BIM or multidimensional software tools. This feedback loop could improve the construction process, enhance operation efficiency, and update original virtual data which could be utilized after construction stage. In terms of continuous utilization and improvement of virtual data, ARAC bridged the break between construction implementation phase and other phases in the building life cycle.

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ACRONYMS

2D	Two-dimensional
3D	Three-dimensional
4D	Four-dimensional
AEC	Architecture Engineering and Construction
AR	Augmented Reality
AV	Augmented Virtuality
BIM	Building Information Modelling
BVH	Bounding Volume Hierarchy
CAD	Computer Aided Design
CVP	Construction Virtual Prototyping
DLL	Dynamic Link Library
HMD	Head Mounted Display
IVE	Immersive Virtual Environment
MR	Mixed Reality
OSG	OpenSceneGraph
SDK	Software Development Kit
VE	Virtual Environment
VR	Virtual Reality

CHAPTER 1 INTRODUCTION

The innovative technologies of Virtual reality (VR) and augmented reality (VR) have affected the architecture, engineering and construction (AEC) industries. In this thesis, the research background, problem, objective and methodology are first introduced. Then the applications of augmented reality (AR) in construction stage and the core technologies of AR are reviewed. On the basis of literature review, a hybrid system called augmented reality-aided construction system (ARAC) is presented, which was developed with the libraries of ARToolKit, OSG and OSGART. ARAC contains following functions: displaying virtual models and operation guides in real environment, realizing interaction between users and virtual objects, and creating virtual simulation of the construction process. Then ARAC was implemented with the BIM data of SHUI CHUEN O project in Shatin Area, Hong Kong. The future works are proposed based on the analysis and evaluation of the ARAC implementation results.

1.1 Research Background

Visualization technology has been developed and applied in various industries for decades. In the manufacturing industry, digitalization of productions is universal, and simulation of manufacturing process is also popular. Before practical production, objects are created as 3D digital models and producing course is simulated for further observation, analysis and modification. In past decades, with the rapid development of visualization technology which is known of virtual reality (VR), building information modeling (BIM) tools have improved and been applied extensively in AEC industries. On

the basis of BIM, technologies of four-dimension (4D), five-dimension (5D), or incorporation of all possible dimensions have been advanced. 4D technology introduces the factor of time on the basis of 3D, and 5D technology introduces the factor of cost on the basis of 4D. These technologies have been applied in the stages of architecture design, construction planning, facility management and building demolition.

A review of the literature and previous research shows that, during the construction stage, there are little direct applications of virtual information which are built by BIM or multi-dimension tools. In other words, from construction planning stage to facility management stage, there is a break of continuous utilization of virtual information. This research attempts to fill this gap by an emerging technology called augmented reality (AR). AR technology can display digital information in physical 3D world. When the user wear the optical-through glasses or take video-through devices, the physical objects can be tracked in real time and displayed on the display device together with virtual objects. The relationship of position and orientation between real and virtual objects can be updated in real time when the user is moving. There are various kinds of AR applications in the fields of entertainment (digital games), military (combat simulation), surgery (operation guide and body models display), and culture (digital recovery for ruins of famous cultural relics). According to the AR application in other industries, AR technology could be introduced to the construction field. Literature of AR applications during construction phase was reviewed. Because most of AR researches focus on the particular AR technologies especially outdoor registration and tracking, it is necessary to explore more extensive research on AR applications and further utilization of AR technology.

Because of the complex and dynamic natures of construction site, the 2D drawings and 3D models maybe not enough for the project teams on site. The direct and intuitive display method of virtual information on site is needed for workers and managers. In other words, it is necessary not only to build virtual models before practical building, but also display digital information in real construction environment. In addition to static 3D virtual models, construction processes are also needed to be simulated and shown on site. Moreover, it is expected that virtual information can be analyzed together with real object in physical 3D world. Then based on the analysis results, architecture design and construction planning could be improved in real time along with the actual construction process. Based on this research idea, the thesis introduces the development process of ARAC and evaluates its implementation results. This AR visualization framework dynamically provides virtual information for users on site, such as clients, contractors, managers and workers. It also realizes the function of direct interaction between user and 3D virtual models, and construction simulation on site.

In this research, ARAC was developed with following development libraries. ARToolKit (HiroKazu Kato, 1999) is used for creating the basic AR framework. In order to get high-performance rendering effect of scene graph, OpenSceneGraph (OSG) was introduced. As an integration development library of ARToolKit and OSG, OSGART was also used in this research.

1.2 Research Problem

The problem addressed in this research is:

How can AR be developed and applied during construction stage by using technologies of ARToolKit, OSG and OSGART?

In order to answer this question, three major tasks have been finished. The first one is exploring difficulties and limitations faced by project teams during construction phase, especially in the aspect of utilizing virtual information. The second task is designing an AR application software framework. The third one is implementing all ARAC applications with virtual information of Shui Chuen O project. Then the implementation results are analyzed. Based on analysis, the improved ideas and measures are proposed.

1.2.1 Status of Digital Information Utilization on Site

In general, before real construction on site, project planning is carried out. The strategies, schedule, construction path, and assembly sequences are arranged. 3D models are built by relevant computer aided software such as REVIT and CATIA. Construction simulation is created by software such as DELMIA, Virtools and NavisWorks for 4D visualization. All these virtual information which are created before real construction could be saved in database in computer and shared by different project teams. Users would find that it is more convenient and effective when check 3D models and 4D simulations, comparing with traditional 2D drawings. Another important advantage of

VR technology is the powerful ability of structure analysis and collision detection of models and operations. However, the connectivity between construction planning and real construction phase is worth rethinking. The variables on site are complex and changing irregularly. Virtual information built on construction planning phase cannot be utilized fully and is updated with the construction process in real time.

This research was stimulated by the gap of continuous usage of BIM information and advances of AR technologies which augmenting real construction site with virtual information. An AR application software application called ARAC was designed and developed for the visualization on the construction phase.

1.2.2 AR System Design

There are researches of AR applications during construction stage, such as crane displaying and simulation, operation guide for workers. But the functions of AR are only limited in displaying digital models. It is one kind of static assistance, although users can move around anytime and anywhere. The layout of construction site is changing all the time. Locations of project team members, resource and machines are dynamic, as well as the status of building. It is obvious that the static displaying of digital information is not enough for the complex and fast-changing construction site.

Moreover, as Section 1.2.1 mentioned, there is a break of digital information utilization between construction planning and real construction. The Information of virtual models

and analysis results could not be delivered to project teams on site quickly and effectively. The people who are making plans of construction process and creating digital information may not collaborate sufficiently and efficiently with site project teams. The managers who are supervising construction process may not understand the digital information sufficiently. And workers on site who are mastering operation skills are often kept apart from this virtual information. It is necessary to improve more clear and efficient communications among these groups.

In this research, ARAC have been developed. It provides functions including static model displaying, operation guide, geometry information assistance, and dynamical construction simulation, interaction with keyboard, mouse and hand gesture. All these AR applications were tested indoor with building models which are scaled down. Three critical libraries which were linked into these applications were ARToolKit, OSG and OSGART. ARToolKit library provides methods of calibration, registration and tracking. OSG provides the powerful graphic rendering ability and node linking method. OSGART provides useful libraries of combination of ARToolKit and OSG. The ARAC framework designed with these libraries will be introduced in detail in Chapter 3. Then the development and implementation of loading 3D models and testing all AR functions will be presented in Chapter 4 and Chapter 5.

1.2.3 Development, Implementation and Evaluation of AR System

Building industry is different from other industries such as surgery and entertainment. Because of the natures of outdoor construction, the real environment becomes more complex than other industries. For example, the light situation of the virtual models would be changed when models are displayed on site; because the models are not only illuminated by lights which are added from the software, but also the real sun lights. Moreover, when the marker is small-size, the distance between marker and camera is short, and the sun light is too bright, the accuracy rates of marker identification and tracking would be reduced. This problem would be alleviated through adopting AR technologies.

In this study, several AR software applications were developed and implemented. Firstly, preparation works was done to set up programming environment. The OSG and OSGART resources are configured and their solutions are generated in CMake. Related libraries and DLLs were built in Visual Studio environment. Before creating AR applications, models were created in REVIT Architecture and exported as FBX format, then imported to 3DS Max, finally exported as 3DS, IVE or OSG format files. When format conversion of digital modes was finished, a basic AR application was built. After that, a hybrid system called ARAC was designed and developed. With the virtual information of Shui Chuen O project, ARAC was tested indoor and implemented in outdoor environment. The implementation results were analyzed and evaluated for future improvement.

1.3 Research Methodology

Generally, two issues are required to be taken into account in terms of research methodology: the method of information collection and generation; the method of information analysis. As Table 1 shows, Ellis and Levy (2009) presented nine kinds of research approaches. These approaches are distinguished by three factors: information type, problem stage and theory categories. The focuses of these nine approaches are summarized in Table 1.

Table1: Key categories of research (Ellis and Levy, 2009)

Approach	Most common type of information	Stage of problem	Categories of Theory
Experimental	Quantitative	Evaluation	Testing or revising
Causal-comparative	Quantitative	Evaluation	Testing or revising
Historical	Quantitative or Qualitative	Description	Testing or revising
Developmental	Quantitative and Qualitative	Description	Building or revising
Correlational	Quantitative	Description	Testing
Case study	Qualitative	Exploration	Building or revising
Grounded theory	Qualitative	Exploration	Building
Ethnography	Qualitative	Description	Building
Action research	Quantitative and Qualitative	Applied exploration	Building or revising

With regard to the developmental methodology, there are three crucial steps: establishing and validating criteria the product must meet, following a formalized, accepted process

for developing the product, and subjecting the product to a formalized, accepted process to determine if it satisfies the criteria (Ellis and Levy, 2009). This methodology was adopted in this research and these three elements were embodied in the specific cases.

O'Brien (1998) presented an overview of action research methodology and devised its definition. Action research aims to contribute both to the practical concerns of people in an immediate problematic situation and to further the goals of social science simultaneously. Thus, there is a dual commitment in action research to study a system and concurrently to collaborate with members of the system in changing it in what is together regarded as a desirable direction. Accomplishing these twin goals requires the active collaboration of researcher and client, and thus it stresses the importance of co-learning as a primary aspect of the research process. Because this methodology involves collaborative teams and clients, it becomes much more complex. In this research, developmental methodology was the main approach for creating a hybrid AR system to address limitations of virtual information utilization on construction stage. Then in future work, in addition to construction team, teams who supervised other phases in building life cycle will be invited to evaluate this hybrid system and help to improve it in further. So the action research methodology maybe adopted in future works, together with the developmental methodology used in this research.

A case study is an empirical inquiry that investigates a contemporary phenomenon within its real life context using multiple sources of evidence (Noor, 2008). This methodology is focusing on empirical inquiry, in other words, it is qualitative rather than quantitative. In

the construction industry, site environment is complex and dynamic. The empirical inquiry is necessary for investigating some problems or phenomenon. So, methodology of case study will be adopted in future work which involves project teams and clients. In sum, this research chose developmental methodology.

Table 2: Summary of popular research methodologies (Ellis and Levy, 2009)

Methodology	Focus / Essence	Adopted in this research?
Experimental	If a cause-effect relationship exists between a factor and second factor, or a set of factors and second set of factors. (factor(s): dependent variable(s))	No
Causal-comparative	Same with Experimental methodology. While not control factor(s), but rather observe, measure and compare factor(s).	No
Historical	Explain the causes of change through time.	No
Developmental	Method to build a 'thing' to address the problem	Yes
Correlational	Presence and degree of a relationship between two factors.	No
Case study	Explore, describe, or explain phenomena by an exhaustive study within its natural setting.	No
Grounded theory	Generate theory that explains, at a broad conceptual level, a process, an action, or interaction about substantive topic.	No
Ethnography	In-depth qualitative investigation of a group that share a common culture.	No
Action research	finding a solution to a local problem in a local setting	No

1.4 Significance of the Research

The application procedure of VR is: BIM team builds and analyzes digital 3D model, construction planning team creates construction procedure and improves it through the collaboration with modeling team and constructors. This course could be extended to the outdoor construction site by adopting an emerging technology: augmented reality (AR).

A hybrid system based on AR technology, termed ARAC, was developed for the construction phase in this research. The problem of the break of virtual information continuous utilization was alleviated. The utilization of digital information which was created before real construction was extended to the construction stage.

1.5 Thesis Outline

Chapter 1 presents the research background, main research problems, methodology, significance and outline of this chapter. The research problem is discussed in three parts: status of the digital information assisting on construction site; the design flow of AR software applications; development, implementation AR applications indoor and outdoor, and evaluation for improvement.

Chapter 2 reviews AR research works, especially the AR applications in AEC industry. Firstly, the definition of AR, comparison among reality, AR, AV and virtual reality are reviewed. Then core technologies of AR are presented mainly in four parts: calibration and registration, tracking, display, and interaction. Last section reviews the AR application in various industries which including the AEC industries. Then the applicability of AR technology during construction phase is analyzed.

Chapter 3 presents the logical flow of ARAC design course. The tools for creating ARAC are introduced. ARToolKit, OSG and OSGART are the main development libraries in

this research. Then every integrated component of ARAC and the logical relationships among the components are introduced.

Chapter 4 demonstrates the specific development flows of all sub-applications of ARAC. Before creating AR software applications, preparation works needs to be conducted. After setting up programming environment, building OSGART dynamic libraries and converting file formats of models, a basic AR application was created and tested indoor.

Chapter 5 shows the implementation results of ARAC in both indoor and outdoor environments. The augmenting effects in these two environments are different because there are more variables in the outdoor environment. Reasons for these differences are discussed further and solutions are proposed for the system improvement. The augmenting results of text information assistance, virtual construction simulation, interaction between user and models are analyzed. Then ARAV is evaluated through statistical analysis of the measured variables, and descriptive analysis. Moreover, the relationships among multiple virtual modes in the real environment are discussed. This research also found that the real environment could affect virtual information.

Chapter 6 concludes the study with regards to the objective, contribution and limitation of this research. Moreover, according to the research results, several recommendations are proposed for the future works.

1.6 Summary

The BIM technology has been studied and applied in the AEC industries in recent years. The potential value of virtual reality could be explored in the construction stage in further. Moreover, the problems existing on the construction site, especially in the aspect of the continuous usage of building information, needed a new method to alleviate. The methodology, significance and structure of this thesis were presented. In the next chapter, AR core technologies and application fields will be reviewed and analyzed.

CHAPTER 2 LITERATURE REVIEW ON AUGMENTED REALITY (AR)

2.1 Introduction

According to the research problems and objectives, an AR application system was developed. The concepts of AR and the differences among AR, AV and VR are introduced. Every set of the two concepts and relative technologies are compared and analyzed. The reason of using AR to improve the construction procedure is explained. The core technologies of AR technologies are reviewed. The relevant AR works applied in various kinds of fields are introduced.

2.2 AR Conception

It is known that virtual reality (VR) is the opposite aspect of real environment. As Figure 1 shows, 3D world is divided into four parts: reality, augmented reality, augmented virtuality and virtual reality (Milgram and Kishino, 1994). First of all, the relationships and differences between completely virtuality and completely reality are necessary to discuss. In the research of Dunston et al. (2005), the centricity continuum focused on user's frame of reference (viewpoint), the congruence continuum focused on the mapping between viewpoint and manipulation of elements in view scene.

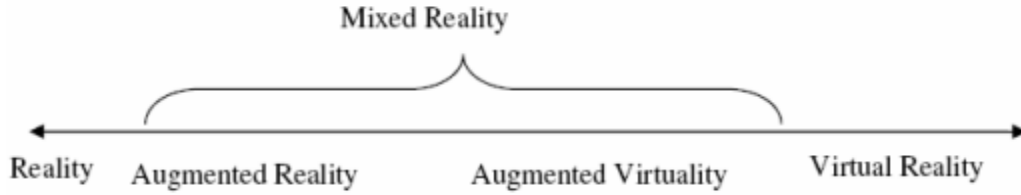


Figure 1: Reality-Virtuality Continuum (Milgram and Kishino, 1994)

In centricity continuum, egocentric pole illustrates nominal viewpoint of the worker in operating cab of equipment. Exocentric pole refers to global 3D view scene which is independent of site operation. With regard to centricity, virtual reality can provide not only global perspective flexibly, but also travel in the building models in the viewport of users egocentrically. But the viewport is limited in the virtual environment which exists in the computer software. Another method used on construction site is setting up camera around site and supervising construction activities, while the viewport is limited in the view scene of the global one. So the augmented reality is a suitable choice in respect of centricity for workers who are not only machine operators and managers on site.

Congruence between users' input demands and corresponding reactions of machines is affected by directness, alignment and order (Dunston et al., 2005). The directness factor inspects the need of manipulating device such as a joystick or a lever to control the operational space. The alignment factor means the position and orientation of device in relation to the operational space. The order factor refers to the order of the transfer function between the input commands to the control device and the resulting system response. According to these factors mentioned above, the most reasonable choice in various systems from reality to virtuality ones is the augmented reality system.

2.2.1 Augmented Reality

Interaction and emergence of real and virtual environments is an expansive realm in RV continuum and it is defined as mixed environments (ME). In ME real objects and digital information or models are intermingled. The ME novel concept and its relevant application allow the AEC industries to share information and collaborate in safe or remote locations. The collection of augmented reality and augmented virtuality is called mixed reality (MR). Mixed Reality refers to the continuum over which computer-generated content may be blended in varying proportion with an individual's view of a real world scene, and it offers new options for project life cycle interactions both with the virtual design information and with project collaborators (Dunston et al., 2005). In the RV continuum, mixed reality occupies the realm of the whole continuum with two poles which are real physical world and virtual reality respectively.

2.2.2 Differences among AR, AV and VR

AR can superimpose dynamical, real-time, and background-professional information on the visual receptive fields of users. AR treats the reality as standard, allows coexist of virtual and real objects, and emphasizes virtual technology service for the real world. By contrast, reality environment cannot provide such additional virtual models. Therefore, there are distinct merits of AR compared to pure reality.

Virtual Environment (VE) is commonly recognized as computer-generated three-dimensional spaces that are populated to depict a particular scenario. The completely real environment and pure virtual environment are two poles, the integration and linkage of them forms various kinds of situation of the mixtures of virtuality and reality.

Researchers developed theories and investigated applications of virtual technology in a wide range of fields including AEC. Entirely computer-simulated environments are used by architects for designing concepts, visualizations and communicating with designed objects. It is quite flexible and free to change scene scale and user viewport in virtual environment. Structure conflict of building can also be analyzed and corrected by building information modeling (BIM). The practical applications of VR in design and construction of buildings have achieved great progress and become mature. But there is inherent and unavoidable limitation of VR which completely immerses a user inside a virtual environment. When users are immersed in a virtual environment, they cannot see the real world around them and a break of linkage between the user and the environment is generated. In contrast, AR allows the user to observe the real world around him/her and make real-time homologous response, with virtual objects superimposed upon or composite with the real world. Therefore, AR supplements reality, rather than completely replaces it. Ideally, it would appear to the user that the virtual and real objects coexisted in the same space. In summary, VR is suitable for creating visual 3D models and construction simulation. MR technology, especially AR, can provide the direct and intuitive sense by displaying virtual information in the real environment.

When real objects are viewed from perspective of virtual reality, the virtual environment is augmented by the real one. This concept and its supporting techniques are termed as augmented virtuality (AV). Tele-immersion realized that users who are in different places communicate and collaborate real-time in a shared virtual environment. The main application field is 3D video conferencing (Regenbrecht et al, 2003). From the AV application, we can understand the concepts of AV and the limitation of its application fields.

In contrast, augmented virtuality expands the absolute virtuality by embedding streaming video of real people or other objects from physical spaces, namely projecting to virtual world. The applications of AV are relatively fewer than VR and AR and mainly focus on gaming development. If users adopt AV in the construction phase on site, it may be necessary to carry the heavy device to display virtual objects modeled in advance and embedded real objects such as workers, materials and equipment into virtual world. This is not practical because it is almost impossible for workers to carry these devices, and it is not effective to assist construction because what the construction panels need is the uncompleted part which could be visualized and analyzed.

With the emergence of various novel concepts and supporting technologies, the classification of reality-virtuality continuum which is presented in the research of Milgram and Kishino in 1999 is not sufficient. Some researchers have classified this continuum in a more adequate measure. As Figure 2 shows, amplified reality, mediated

reality and virtualized reality are added into this continuum as subsets. The poles of continuum are still real reality and virtual reality. Between the two poles there are augmented reality which is closer to the real environment and augmented reality which is closer to true virtual one. There are also some other classification and concepts such as tangible reality that focuses on the interaction method. Researchers who are developing tangible reality found some very simplified and practicable control ways such as color fingertips that is applied in SixthSense developed by MIT Media Lab.

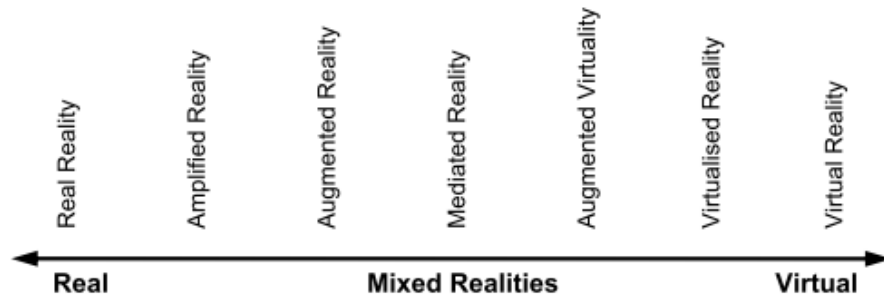


Figure 2: Reality-Virtuality (RV) continuum with sufficient subsets (Schnabel et al., 2007)

(1) Amplified Reality

As shown in Figure 2, amplified reality is between real environment and augmented reality. By using information technology amplified reality enable nature properties of real objects to be more plentiful. Falk et al. (1999) point out that the goal of amplify reality is to enhance the publicly available properties of a physical object by means of embedded computational resources. AR is about how the user perceives reality, while Amplified Reality influences how the perceived reality is made available to the user (Schnabel,

2009). In a word, amplified reality can enrich the expressions of physical elements, while augmented reality can enrich the impressions of real objects. Another important issue of amplified reality is the added information is not only properties of real objects, but is public for all users present. While in augmented reality systems, wearable head mounted devices (HMDs) or special glasses to display virtual information for users privately are needed. The relationship between amplified reality and augmented reality is shown in Table 3. Recently more researchers are focusing the application of ubiquitous computing in augmented reality. GIS, GPS, RFID and some other technologies are applied together with augmented reality in the AEC industries. In the aspect of proprietary issue, these combinations of new technologies integrate advantages of amplified and augmented reality, so the recent research of RV are mainly focused on augmented reality.

Table 3: Comparison of key attributes of amplified reality and augmented reality (Falk et al., 1999)

Amplified reality	Augmented reality
Expression	Impression
Public	Private
Embedded	Superimposed

(2) Mediated Reality

Mediated Reality describes the general concepts of artificial modification of human perception by re-synthesizing the light that reaches the eye of a user (Schnabel, 2009). Mediated reality is also termed as diminished reality; methods of deleting objects from a scene and replacing them with suitable backgrounds were researched (Lepetit & Berger, 2001). In mediated reality systems, sensory input of HMD or other display devices are changed dynamically for altering the appearance of objects in the real world. Applications of mediated reality have been developed for AEC fields such as urban design. When planners are inspecting the real site, situation of removing, reappearing and replacing buildings or public accommodations can be realized and checked on real landscape by mediated reality systems.

(3) Virtualized Reality

In virtualized reality system, events which happened in real environment are captured by several cameras from various angles. Suitable images of selected viewports are reconstructed by stereo technique. So users can view freely in the reconstructed scene even from a new viewport. The concept of virtualized reality was presented and hardware and software were developed to set up a studio to make virtualized reality movies (Kanade et al., 1995). While virtual reality is quite different, models in virtual reality systems can be built in relevant software such as AutoCAD, 3DS Max and Revit. Virtualized reality captures real scene and builds new ones from different direction, rather than build 3D models and display them in the software.

In summary, augmented reality is a new immerging technology which can blend graphics, text annotation and some other virtual information generated by the computer into the real world scene viewed by users. AR systems are composed following three characteristics: combining real and virtual, interactive in real time, and registered in 3-D (Azuma, 1997).

2.3 AR Core Technologies

2.3.1 Calibration and Registration

The methods of calibration and registration are using close-range measurement, building up observation point based stereo pair, and obtaining observation real-time location to track the user's location and space transformation of his/her viewport. The key techniques of these methods are including single pair fast auto-matching and comparative positioning close-range phototypography, high precision information capture and auto-processing, consecutive pair speedy auto absolute positioning referencing location tracking value, auto arrangement of observation point moving path (Guo et al., 2008). In order to avoid operating great quantity of environment images by directly analysis and identification, a prototype which used several colorful symbols of the object that was expected to be registered and a colorful CCD camera was developed. The method adopted is camera projection and getting camera's coordinate location and orientation relative to markers by deduce arithmetic.

2.3.2 Tracking

There are several tracking manners such as optical tracking, video tracking, magnetic tracking and inertial tracking. In this research, video tracking manner is used, rather than the optical tracking technology. Video tracking is the process of poisoning and tracking moving objects in time using a camera. Video frame is analyzed and location of moving targets within the video frame is confirmed. In contrast, when the user is moving, the position and orientation of targets by coordination transformation can be also calculated.

2.3.3 Display

Relationships of coordination transformation among virtual objects, real environment, observer and projection plane (HMD) are analyzed in this section. The coordinates of virtual objects are transformed to absolute real environment coordinates. At the same time, user location and orientation are calculated to real environment coordinates and the matrix between them is confirmed, then through the matrix, coordinates of virtual objects can be transformed to the one of the user. Through three coordinates' transformations, the 3D virtual objects are ultimately displayed in the real 3D world.

2.3.4 Interaction

In AR applications, appropriate interaction techniques enable users to interact with virtual content in an intuitive way. The interaction methods used in AR systems mainly include tangible, collaborative and hybrid AR methods. These three kinds of interaction techniques respectively focus on manipulation tool, relationships among multiple users, and comprehensive application of various interaction techniques.

Tangible user interfaces (TUIs) are interfaces where users can manipulate digital information with physical objects (Ishii & Ullmer, 1997). For users, because the physical objects have familiar properties, physical constraints, and affordances, it is powerful and convenient to manipulate them. The mapping course was intuitive and it is unnecessary for users to take prior AR experience. The intuition could be improved not only by the natural manipulation tools, but also the infiducial markers, such as the universal media book (Gupta & Jaynes, 2006). The combination of physical objects and hand gestures is mostly adopted in tangible AR interaction applications. Besides the usage of keyboard, mouse, joy-stick and pen-input panel, it is natural and easy to manipulate virtual object by hand. Therefore, through identifying hand gesture and converting it to computer command, users can interact with digital content by natural hand gesture.

The collaborative AR applications for multiple users have been started to develop (Schmalstieg et al., 1996). The users could communicate with each other in a collaborative AR platform. In recent AR applications, remote collaboration has been

researched with telecommunication technologies. Users in different contexts could collaborate and interact with the virtual content in remote context.

The visual identification methods have been the main intuitive interaction technique. Integrating with technologies of speech command, multi-touch, digital glove and eye tracking, hybrid AR interaction system could be developed and improved more flexibly. The hybrid AR interface facilitates particular AR application, such as medical and military augmentations.

2.4 AR Applications

AR application, in which 3D virtual objects are integrated into a real environment in real time, has been applied in the various fields such as medicine, manufacturing, simulation, path planning, entertainment, military and AEC.

2.4.1 Applications of AR in Various Fields

(1) Medical

Medical Vision Group of MIT is researching and applying AR theory in image guided surgery such as anisotropic modeling of brain shift, surgical navigation, trans-cranial magnetic stimulation and endoscopic navigation.

(2)Entertainment

In recent decades, VR has been applied in the industry of computer games extensively. AR technology has begun to demonstrate excellent performance such as further immersion of the user and more natural operation and real-time reaction during computer games in the last few years. For example, Japanese electronic gaming company developed the entertainment product named virtual reactive maid ARis for the general public in 2008. AR technologies are also utilized in games: The Eye of Judgment which is the first game to use the camera peripheral, with which it is available in a bundle in different countries. Similarly, AR also has begun to be utilized in various kinds of fields of entertainment such as advertising, simulation of outdoor maximal exercises.

(3) Emergency Assist

When emergency or even the serious disaster happens, rescue teams need to arrive at the scene as soon as possible. Especially when the emergency happens in metropolis, additional and functional service for accelerating the traffic speed of rescue team is needed. Projective displays in front of the driver or personal display glasses showing navigation hints and traffic information with the assistance of GPS can make great favor to quickly reach the scene.

(4) Visualization of Historical Ruins

AR can be applied for representation of virtual resurrection of destroyed historic buildings for historical education and the tourist industry in museums, exhibitions and outdoor ruins. For instance, the royal carriage in Shang Dynasty which was

excavated in 1930 was displayed by AR for relevant complete recovery and disassembling and assembling course for visitors in shows held by Academia Sinica in 2008.

2.4.2 Applications of AR in AEC Industries

There are comprehensive applications of AR technology in the AEC industry. The main applications are introduced as follows (Wang and Dunston, 2005): 1) Work in remote or hazardous environments: such as nuclear reactors, contaminated storage sheds, underground, pipelines, minefields, damaged buildings. 2) Construction and assembly: AR would help to decrease waste which is caused by misinterpretation of plans or imprecision of transmission from plan to real practice. 3) Maintenance and renovation: AR technology may help workers avoid hidden objects, decrease accidental damages and speed up operations. 4) Inspection: AR would allow inspectors to work without reference of printed construction drawings. 5) Safety: AR maybe a candidate technology to prevent accidents usually caused by workers' negligence. 6) Training: The time of training from novices to skilled persons would be shortened by efficient information from AR systems.

2.4.3 Applicability of AR on Construction Site

The tasks in construction field can be categorized as physically and information intensive types. Machine automation finishes tasks physically by operation of construction

materials. This kind of physical task on construction site needs the guide of additional information, while large amounts of documents and information causes challenge of accessing and communicating quickly and effectively. It is time-consuming and imprecise for workers to read and understand the traditional annotated printed drawings. After reading related information, workers carry out tasks by guide of their working memory. Although BIM technology is used in large-scale projects, the information is only viewed and checked on computer; seamless combination of virtual information with worker's real environment view is deficient. It is reasonable and convenient for workers if any virtual information can be displayed in the real environment. This means construction site environment needs to be augmented by information which is traditionally be accessed on printed drawings or on computers.

AR technology can be applied in the all stages in the building lifecycle, which is including initial planning, architecture design, construction planning, facility management and building demolition. AR allows users to visualize and interact with virtual 3D models and simulated construction process during the construction stage.

In recent years, some research has been conducted on the application of AR aiding for the fields of architecture and construction. Integrating the state-of-art technologies which contain 3D computer graphics, computer vision, augmented reality, 4D Simulation, human-computer interaction, computer supported cooperative work, mobile computing and sensory devices are proposed for helping the AEC industries. These technologies can help contractors to finish construction more efficiently, accurately, with lesser costs. An

AR prototype system for inspection, the ARCam, which has been developed in the Advanced Construction Systems Laboratory at Purdue University, focuses on steel column inspection for the experimental evaluation. Construction tasks were assessed from the viewpoint of human to find the rationale of benefitting from AR in construction fields. Based on the assessment of construction tasks, a comprehensive map which reveals eight tasks shows the AR application areas during construction stage. These tasks are chosen from seventeen classified construction tasks, which are layout, excavation, positioning, inspection, and coordination, supervision, commenting, and strategizing (Do H. S., 2008).

Ergonomics features concerning AR systems can be summarized human-AR interaction and hypothetical perceptual and cognitive process in AR system (Wang and Dunston, 2006). When using AR systems, users not only need to interact with virtual information, but also carry out physical tasks. In the four types of hand occupation the authors conceived, extra time and energy is consumed in concurrent physical tasks type. The problem could be addressed because of the integration of virtual entity and real one.

2.5 Summary

This chapter presented the literature review of augmented reality which includes its conception, core technologies and applications. The differences between AR and other fields of reality-virtuality, such as augmented virtuality (AV) and virtual reality (VR), were analyzed, and then the advantages of AR were introduced. The key technologies of

AR were reviewed in aspects of calibration and registration, tracking, display, and interaction. There are various AR applications in fields of military, surgery, entertainment, education, relics, and emergency assistance. The potential advantages of AR could also be explored in the AEC industries. The literature of AR applications in AEC industries, especially for the construction field, was reviewed. The logic flows for designing the AR systems were analyzed and specific methods and devices for calibration, registration, tracking, display and interaction were summarized. The applicability of AR in construction stage was specified for supporting the method adopted in this research, which is using AR to alleviate the problems during the construction phase.

CHAPTER 3 DESIGN OF AR-AIDED CONSTRUCTION SYSTEM (ARAC)

3.1 Introduction

The logical flows of designing AR systems have been reviewed. Three tool libraries were chosen for developing ARAC, which were ARToolKit, OSG and OSGART. Then the whole design flow of the AR software system was created in this research.

3.2 System Design Review

The registration, tracking and display functions are realized by peripherals. For example, laptop, GPS receiver, portable power pack, GPS Antenna, Orientation tracker, helmet, HMD, digital camera, touch pad and wearable keyboard were used and integrated (Behzadan et al., 2008). This kind of system may have limitations which maybe not easy to solve because of the interior nature, though it can be reused and plugged with other devices. Firstly, cost of these kinds of devices is high, such as the HMD. This disadvantage would limit extensive application and further development. Secondly, the system hardware is heavy because of combination of several devices which may cause uncomfortable after long time usage which is against the user friendly principle. So, a system that can overcome these disadvantages mentioned above is needed.

Another kind of system framework is focusing on portable and reusable function. Developments of such kind of systems usually use ARToolKit. The tracking of position and orientation, and the tracking of marker and calibration of camera are supported by this toolkit. In the beginning of AR system, portable power pack, laptop, laptop backpack, helmet, HMD, camera, touch pad and keyboard were used. In recent years, these devices are replaced by lighter and handy devices such as smart mobile phone which can be inserted with AR software applications. Orientation tracker is not needed any more because ARToolKit itself has the library which can be developed to track the markers. So the whole system is integrated by only one kind of hardware such as smart mobile phone and one kind of software which is for AR function realization. The more important advantage is that the software development can be installed in the smart mobile phone or some other smart devices by many users. Functions of AR and purposes of reusability, remote information sharing and collaboration would be achieved by the portable device.

3.3 Tools for ARAC

As the first development library of the AR applications and the basis of ARAC, ARToolKit is introduced and the interior principles are explained in brief. Second section introduces OSG which provides the structural design ideas of ARAC. Then osgART library is reviewed because it provides high performance of 3D model rendering with functions of AR.

3.3.1 ARToolKit

There are almost ten kinds of extensive libraries which have been further developed based on ARToolKit. It was developed by HiroKazu Kato in 1999 and now provides users with commercial licenses. ATOM Authoring Tool is a front end for ARToolKit, while can only create simple applications. FLARToolKit is an ActionScript 3 port of ARToolKit for flash. NyARToolKit is an ARToolKit library which has been released for virtual machines host Java, c# and Android. AndAR is a native port of ARToolKit to Android platform. OSGART is an integration of ARToolKit and OpenSceneGraph which is C++ cross-platform development library.

ARToolkit is a cross-platform software library developed with C and C++ languages originally by Dr. Hirokazu Kato of Nara Institute of Science and Technology in 1999. It was released and supported by HIT Lab at University of Washington and HIT Lab NZ at University of Canterbury. ARToolkit is available freely for non-commercial use under the GNU General Public License. The algorithm principles and realization courses of ARToolKit are introduced in Figure 3.

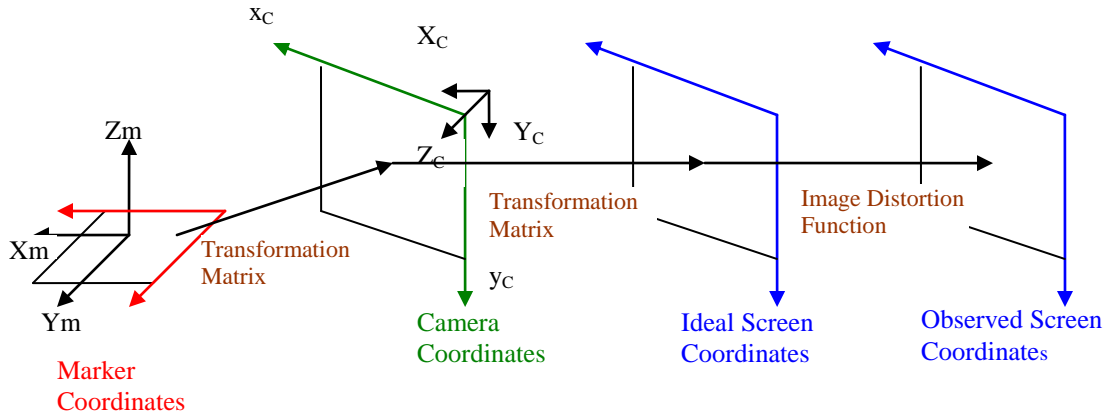


Figure 3: Relationship of coordinates between marker, camera and screen

In terms of algorithm, pose and position estimation and rectangle extraction are briefly presented as follows. Relationships among coordinates of the camera, marker and screen are critical issue and shown in Figure 3. Coordinates of marker can be transformed to camera coordinates by the transformation matrix.

In regards to image processing, marker identification is the key issue which needs to be taken account. There are several default marker patterns which are located in information directory by default. The ARToolKit Marker Generator can be used to create markers. This generator is available for applications of ARToolKit and FLARToolKit. As shown in Figure 4, there are three main function tools. In the mode select dropdown menu, camera mode and load marker image are available. Although there are only two kinds of modes, this tool is useful for different needs of marker generating. Small scale pictures such as printed as 8cm*8cm can be identified from a certain degree and transformed as file with PAT format. This format can be loaded in the programs of AR applications conveniently. Furthermore, pictures of real scenes photographed by digital camera can be loaded as a

marker image and roughly identified by this marker generator. When the gradation of this photo is clear, it could be used for markerless application. A basic experiment was created in this research. A door of the laboratory in the real environment is shot by the camera and this photo was loaded to the marker generator. Then a PAT format file was generated and used in a program built in Visual Studio environment. When running this tested AR application, a virtual 3D cube was shown on the door.

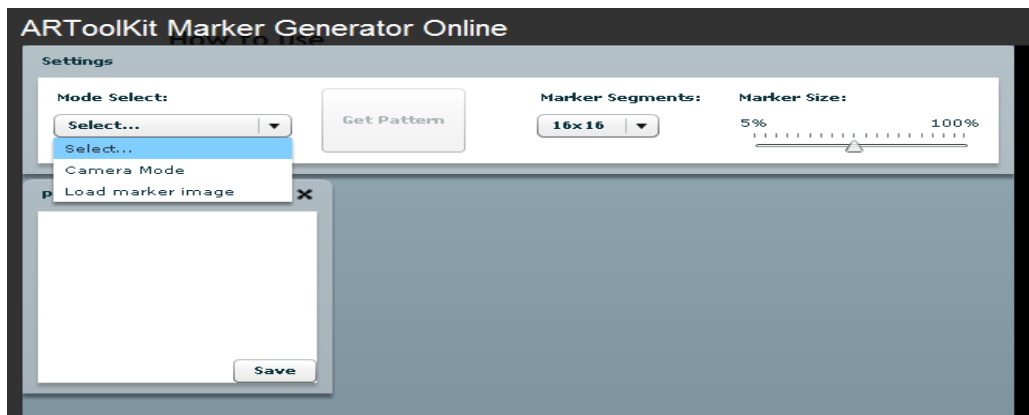


Figure 4: ARToolKit Marker Generator Online for creating markers

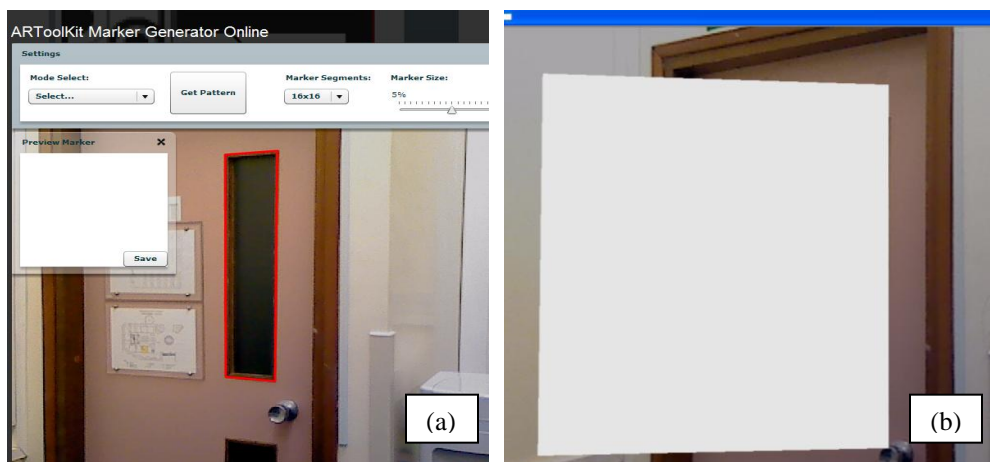


Figure 5: (a) Photograph of the real scene (b) A virtual 3D cube displayed on the door

3.3.2 OpenSceneGraph (OSG)

OpenSceneGraph (OSG) is an open source, cross-platform, and high-performance 3D graphic rendering toolkit for creating application of visual simulation, games, virtual reality, scientific visualization and modeling. OSG applications are all written in Standard C++. OSG provides an object-oriented framework on the top of OpenGL, helps developers to focus high-level graphics calls, and provides additional utilities for rapid development of graphics applications.

There are several reasons for choosing OSG to render 3D digital models. The key strengths of OSG are its performance, scalability, portability and the productivity. OSG is a toolkit with high performance graphics because it supports occlusion culling and accelerates model loading. The main OpenGL functionality which is encapsulated into OSG provides rendering optimizations and rapid development of high-performance graphics. By building relevant plug-ins, more than 30 kinds of 3D models formats can be identified and image, video and font also can be read by plug-ins. The most important and useful feature is that OSG introduces the concept of node. This concept is adopted all through the whole application developed in this research. OSG can be rapidly ported to a wide range of platforms because it has minimal dependency on any special platforms.

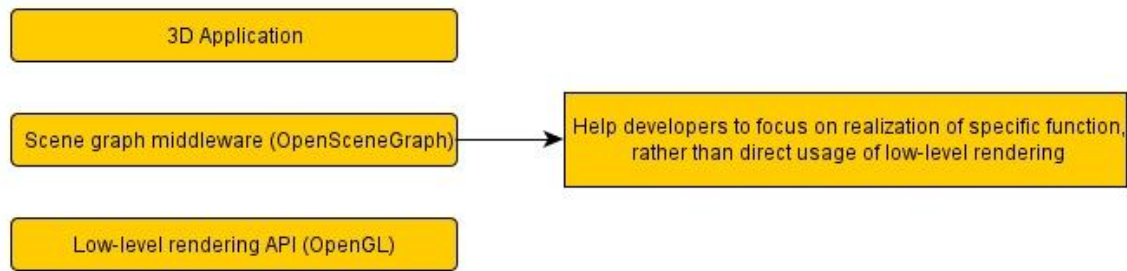


Figure 6: Relationships among 3D application, OSG and OpenGL (Paul Martz, 2007)

The level of OSG is shown in Figure 6. OSG is based on the low-level rendering API and for creation of 3D applications (Wang and Qian, 2009). Scene graph is a method for information structure design in the subjects of computer games and graphics. This concept is adopted in AutoCAD and Java3D. This rendering engine is a set of APIs for realizing structure management and drawing of 3D scene graph. There are more than ten kinds of popular rendering engines, such as PHIGS, Open Inventor, OpenGL performer, Crystal Space, Java3D, Unreal, OpenSG, OGRE 3D, Irrlicht and Vega Prime. Through the comparison among these 3D rendering engines, OSG has been chosen in this study for creating software application with AT toolkit.

The core components of OSG are a series of dynamic link library (DLL), plug-in, libraries, include files, executable applications and code examples. OSG can be divided into five components: 1) OSG core libraries provide basic scene graph and rendering function. The core libraries contain `osg`, `osgDB`, `osgUtil`, `osgGA` and `osgViewer`. 2) NodeKits for node expansion contains `osgAnimation`, `osgFX`, `osgManipulator`, `osgParticle`, `osgShadow`, `osgSim`, `osgTerrain`, `osgText`, `osgVolume`, `osgWidget` and `osgIntrospection`. 3) File reader and writer read exterior model files with more than

twenty kinds of file formats. 4) Demo OSG applications and code examples provide the basic ideas of realizing rendering functions. The libraries mentioned above will be used in the following application development.

Three concepts and principles of OSG which are basic and very important for application development are introduced as follows.

(1) Memory management

For creating a scene graph with extensive objects, it is easy to make mistake in creating and deleting all nodes, allocating space and freeing up space. Memory leak and dangling pointers are likely to happen in this kind of complex and tedious method of memory allocation. Sometimes the program project can be built successfully, but run with expected exceptions. This problem may be caused by memory break. But it is difficult and time-consuming to find out which object space is not deleted. In order to manage memory allocation in OSG, new memory management method is created. It is called garbage collection system which uses the method of reference-counted memory. OSG provides an automated garbage collection system that uses reference-counted memory. Nodes in OSG scene graph are reference counted, when they are not referenced by father node, namely, father node delete itself, reference count of child node or children nodes will be decremented to zero and delete itself or themselves.

There are two components to this garbage collection system (Martz, 2007):

- OSG node and scene graph information classes are all derived from a common base called `osg::Referenced`, which contains an integer reference count and methods for incrementing and decrementing it.

- OSG defines a smart pointer template class called `osg::ref_ptr<>` that is used like a normal C++ pointer. Use `ref_ptr<>` variables to store OSG node and scene graph information addresses allocated on the heap. When a `ref_ptr<>` variable is addressed with a `Referenced` object, the reference count in `Referenced` automatically increments.

The Figure 7(a) demonstrates only memory of root node is released when the application deletes root node. Spaces allocated to node 2 and 3, 4 are not deleted. While as shown in Figure 7(b), when adopting smart pointer, as long as the memory of root node is released, child node 1 of root node will be released. Because node 1 references node 2, node 2 is released correspondingly. Similarly node 3 and 4 are released as node 2 does not reference it.

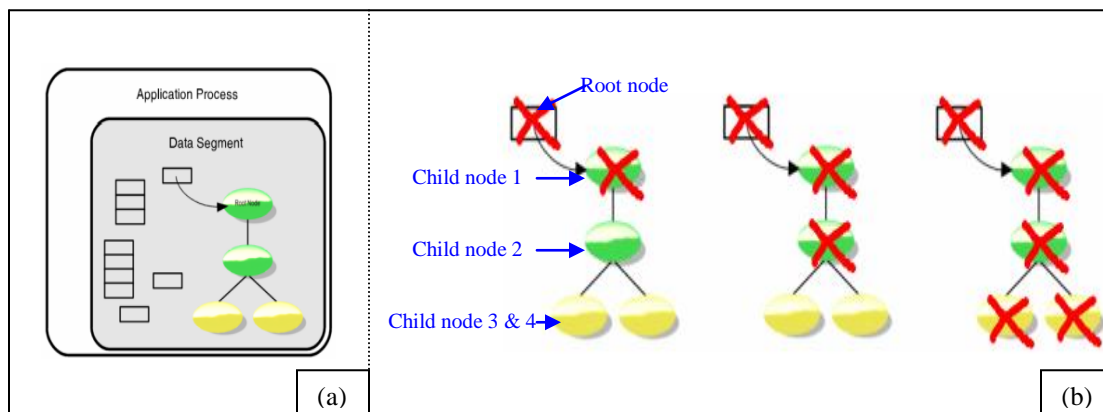


Figure 7: (a) Only memory space of root node is released when root node is deleted (b) Memory of children nodes of root node are deleted one by one when memory of root node is deleted (Martz, 2007)

So in this research, all class objects are derived from referenced class store pointers in `ref_ptr<>`. Then there is no need to delete memory space allocated to the object by hand. It automatically deletes all spaces by these smart pointers. For example, two objects with `osg::Group` and `osg::MatrixTransform` classes store pointers in `ref_ptr<>` smart pointers.

```
osg::ref_ptr<osg::Group> root = new osg::Group;  
osg::ref_ptr<osg::MatrixTransform> arTransform = new osg::MatrixTransform();
```

Figure 8: Example of usage of smart pointer of OSG

(2) Scene Graph node organization

Before explaining node organization of scene graph, the concept of bounding volume is introduced. It is a simple physical space volume which closes a set of objects. OSG supports two kinds of bounding volumes include bounding sphere and bounding box. One model or a set of models can be set as a bounding volume which contains basic properties such as coordinates of center and radius of bounding sphere. So OSG adopts bounding volume hierarchy (BVH) for managing the whole structure of scene graph. Scene graph which adopts BVH usually utilizes a tree structure for node management (Wang, 2009).

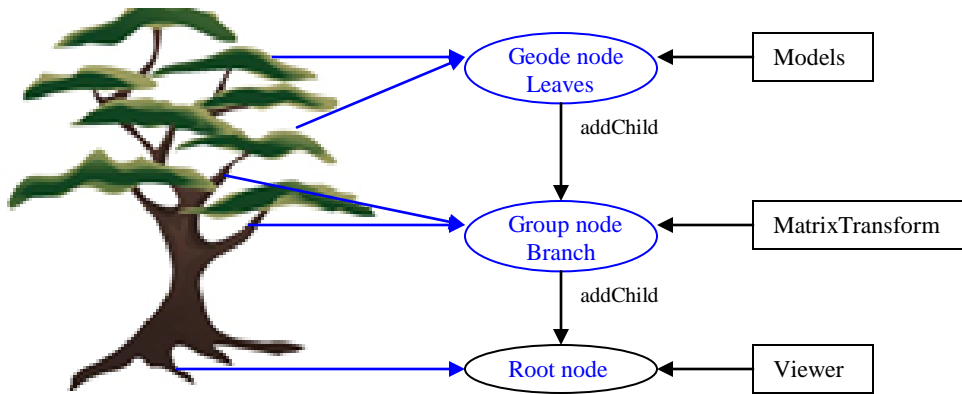


Figure 9: Tree structure of node management in OSG (Wang, 2009)

This tree structure organization can also explain the principle and advantage of smart pointer `ref_ptr<>`. If the root node is not referenced by application, allocated memory of the root node is released. This causes that memory space of all children nodes referenced by root node to be released automatically. If the group nodes are not be referenced by the root node, all their children nodes are deleted correspondingly, while the root node is not affected. So if memory space of the geode node is released, there are no effects on any other nodes but the geode node itself. This can be decrypted as the root, branch and leaf of the tree affecting each other. If the tree root is destroyed, the whole tree died; if a branch is destroyed, only this branch and its leaves died.

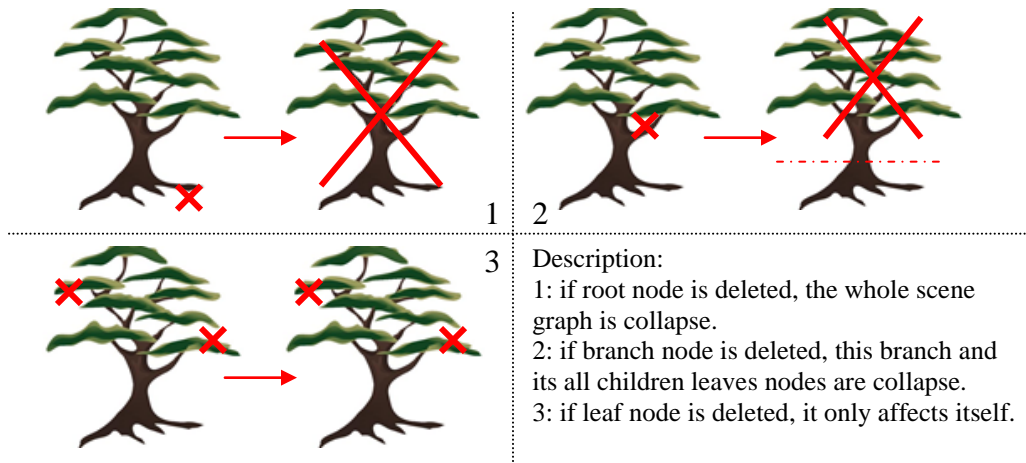


Figure 10: Relationships of nodes in the scene graph of tree structure

(3) Scene Graph dynamic update and cull

1) Node visitor

If elements in one object in OSG need to be modified with no effect on the object class, `osg::NodeVisitor` can be called. In this class, `apply` function is used for the node traversal and `accept` function is used for relating node which needs visiting. In Chapter 4, several AR applications are needed to create new classes which are derived from `osg::NodeVisitor`. New functions are rewritten in the `apply` function of the inheriting class. Specific flow charts of the node visitor are introduced Chapter 4.

2) Scene graph update / node call back

Interaction between virtual information with user is an important part of OSG. The interaction event is finished by scene graph update. In other words, when the interaction event happens every time, the same operation event is implemented. This is realized by

the class called `osg::NodeCallback`. Specific event handling method is introduced in the next Chapter.

3) Scene graph cull

The objects which do not appear in the extent of the camera are culled from the scene for speeding up rendering. AR application can adopt multiple markers to control the display of models. But if models are very complex and large-amount, the method of using multiple markers is not enough. If a model with numerous parts is shown on one marker which appears in the extent of the camera, the scene graph cull method of OSG is used in this situation. There are five kinds of culling methods: back-face culling, view frustum culling, small feature culling, occlusion culling and cluster culling. `OsgUtil::CullVisitor` is used for traversing all nodes in the scene graph, nodes which do not appear in the view field of user are culled.

4) Dynamic scheduling

In the BIM of large-field project, the volume of information data is sometimes huge. Especially in the urban planning, quantity and property data of building models are vast. In this situation, dynamic scheduling of information is used for offering relief of system. Information is only loaded when the scene graph is entering into the view field of camera. This work is realized by `osgDB::DatabasePager` which can cull nodes which do not appear in the view field of user, and start to render the scene graph which enters in view field.

3.3.3 OSGART

OSGART is a C++ platform development library that simplifies the development of AR applications by combining computer vision based tracking libraries. It combines ARToolKit, ARToolKitPlus, StudierStube ES with OpenSceneGraph. As the above section introduced, OSG is a mature and widely-used rendering library. It bases on OpenGL and provides high-level API for responding to the OpenGL calls. Both performance and development are optimized as its high performance of rendering techniques and cross-platform support. There are many approaches to video capture and tracking for video see-through augmented reality. OSG provides a generic framework in which any approach can be supported, through the use of plug-in modules, no matter which display devices. Therefore, developers can freely choose the video capture method and tracking method from a library of available modules, alternatively developing new plug-ins or compiling plug-ins with other SDK. By default, OSGART uses the ARToolKit library for video capturing and tracking.

3.4 Design of ARAC

In this research, ARAC was developed for two phases which contain indoor testing and outdoor implementation on construction site. This AR software application has utilized three frameworks: AR, OSG and OSGART. In the construction phase, AR library was utilized for the visualization of buildings components and simulation of construction process. So clients, managers and workers could check the construction progress,

understand the reason of construction errors quickly and find out the solutions. The schedule arrangement, construction progress and site layout have benefited from this AR framework. OSG is used for creating high performance scene graph and rendering effects. OSGART is the combination of AR and OSG. It contains libraries for various augmenting functions, such as interactive operations between users and digital models. It enables users scale, rotate and translate the models real-timely. Because of the complexity of the construction site and relative immobility of the construction team, users need the function of scaling and rotating of virtual models to check the specific parts they want to detect.

This AR platform provided users who were working on construction site additional information related to site activities, such as detailed dimension of pipelines, the interior structure of objects or guide of next steps. Users could access all these main site information conveniently and efficiently. Workers could finish tasks not only by their experience, but also by exact virtual guides from the original design graphics and construction planning.

In this study, ARAC with different functions were designed and developed. Firstly, preparations works for hybrid system development were conducted. Programming environments were set up for further developments. Then, dynamic link libraries of OSGART were built and would be linked as additional dependencies. Because the virtual building models were mainly built in REVIT Architecture, the RVT format files were needed to be converted to the formats that OSG can identify. Models with RVT formats

were exported as FBX formats in REVIT, then exported as OSG or IVE formats in 3DS Max. Finally, simple AR applications were created and tested in real environment.

Then, hybrid system was designed and realized three main functions. Applications were implemented to find out the real effects of augmentation. In part of information assisting, the virtual operation guides for users on site was designed. When this application was running for project team on site, it could identify and track the site scene. Next steps could be shown as the operation guide. Another important function of this application was geometry data display, especially in the projects with lots of shaded objects such as underground pipes. Hybrid representations (e.g. texts + 3D object) can be very useful in the situations in which different cognitive channels need to be provided. It is apparent that realistic presentations convey more intuitive information that can assist an individual's comprehension thus augmenting the cognitive process and activity. (Wang et al., 2004)

Simulation is a major part of the applications of virtual reality in AEC industries. In this research, construction simulation was also an important component. The difference between virtual reality and augmented reality is that construction simulation in AR is shown in real environment. There are three aspects related with simulation, including dynamic construction simulation, resource allocation and workers rigid body motion. This study developed the AR application of dynamic construction simulation.

Furthermore, interaction between users and models was also realized. It was carried out by using keyboard, mouse and marker to control digital objects in AR environment. Using another small-size marker to control 3D models which are displayed on a marker is more flexible than keyboard and mouse. Moreover, in the real practice such as urban planning, it is more convenient and effectively to change the positions and orientations of models. If members of urban planning team were discussing the city plan, they maybe surrounding the virtual models of city and wanting to change the situation of one model according to his/her opinion, it was convenient for this designer to use marker to manipulate the virtual models. In this case, all the team members were holding their own markers, all the people can operate digital objects shown on multiple markers at the same time, rather than look at a projection screen together. With this traditional method, users could not carry out corresponding manipulations according to their design suggestions.

In AR technologies of the incipient ones, marker identification and tracking are critical parts because nothing can be displayed in real environment if marker cannot be identified. The earliest and basic markers utilized the gradation for identification. There are only few markers by default with ARToolKit. The application with multiple markers needs to create much more custom markers. A marker generator called “ARToolKit Marker Generator Online” can catch picture of marker by camera and identify the gradation of the picture. Then a pattern file is created which can be loaded in AR applications. In the outdoor application, construction site picture is shot by camera and converted as PATT file. In other words, general marker with barcode and marker generated with any picture are both valid. But the marker created by photo picture is not stable and robust for

identifying. Especially, when the sun light is very strong on construction site, all objects are illuminated and reflect strong lights. So the gradation of outdoor pictures is not easy to distinguish for identification and tracking in AR application. In this outdoor situation, model tracking with markerless technology was introduced. Research of markerless tracking was reviewed and several relative ideas were proposed.

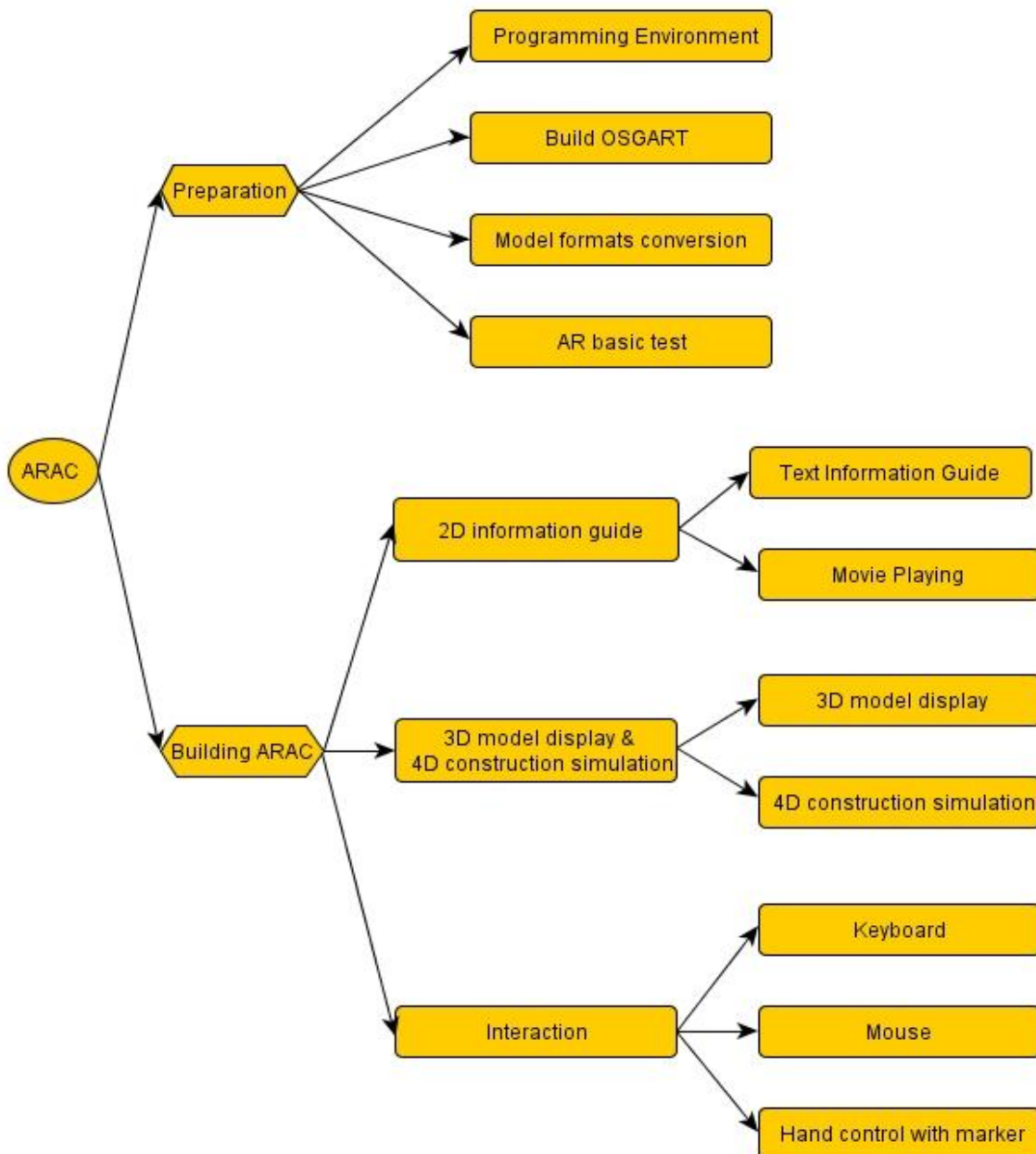


Figure 11: Flow of designing AR-aided construction system (ARAC)

3.5 Summary

In this chapter, the design of AR system was reviewed. According to the mainstreamed design methods, three tools were adopted, which were ARToolKit, OSG and OSGART. ARAC was constructed through the preparation stage and hybrid system building stage. During the prior preparation phase, the development environment was configured, DLLs of OSGART were built, file formats of virtual models were converted to the formats which could be read by OSG viewer, and a basic AR application was tested successfully. This AR hybrid system comprised of information assistance, construction simulation and interaction. In the next chapter, the course of setting up ARAC will be introduced.

CHAPTER 4 DEVELOPMENT OF AR-AIDED CONSTRUCTION SYSTEM (ARAC)

4.1 Introduction

This chapter presents the detailed development course of the AR-aided construction system (ARAC). As introduced in Chapter 4, preparation work will be introduced, and then the establishment of AR hybrid system will be presented in three parts. Information assistance part focuses on static virtual content, simulation part pays attention to dynamic virtual course which added time factor, and interaction part emphasizes the relationship between user and system.

4.2 Preparation

In the preparation phase, setting up the programming environment, building relevant DLLs and converting file formats of virtual content to OSG native formats were necessary.

4.2.1 Setting up Programming Environment

Before programming of software applications, the programming environment should be built. The course of setting up environment is introduced as follows. ARToolKit-2.72.1-bin-win32 as well as OpenGL driver, GLUT-3.7.6-bin and Direct X11, CMake 2.8 was

used for creating and configuring necessary project files for specific system and development environment. CMake was used to build the AR solutions for programming in Visual Studio environment on Windows operation systems.

Currently, the newest version of OpenSceneGraph is 2.9.9 and the most stable new version is 2.8.2. A simple application was built in Visual C++ 2008 with libraries of OSG_2.9.9 (3DVRI). The implementation result showed that the video frame was flickering, so this version is not stable. And its debug and release version which could be compiled in Visual Studio 2010 are not available, and “include files” of OSG is not yet upgraded for VS2010, OSG_2.9.9 cannot be compiled by VS2010 successfully. OSG_2.8.2 version were chosen and the executable files was built in Visual C++2008 Express.

During this course, it was possible that the exe file cannot be initialized. The missing DLL files or some DLL files which contain errors can be tested in Dependency Walker. According to its error report, missing release DLL files can be obtained (www.dll-files.com), missing debug DLL files can also be downloaded (www.dlldump.com), and put into directory in “C:\WINDOWS\system32”. Then the AR application could be initialized correctly. It is better to save the digital models and construction simulation in directory under “\$(OSG_ROOT)\data”. When running the executable file, the data which is cited in the program could be loaded directly from this directory.

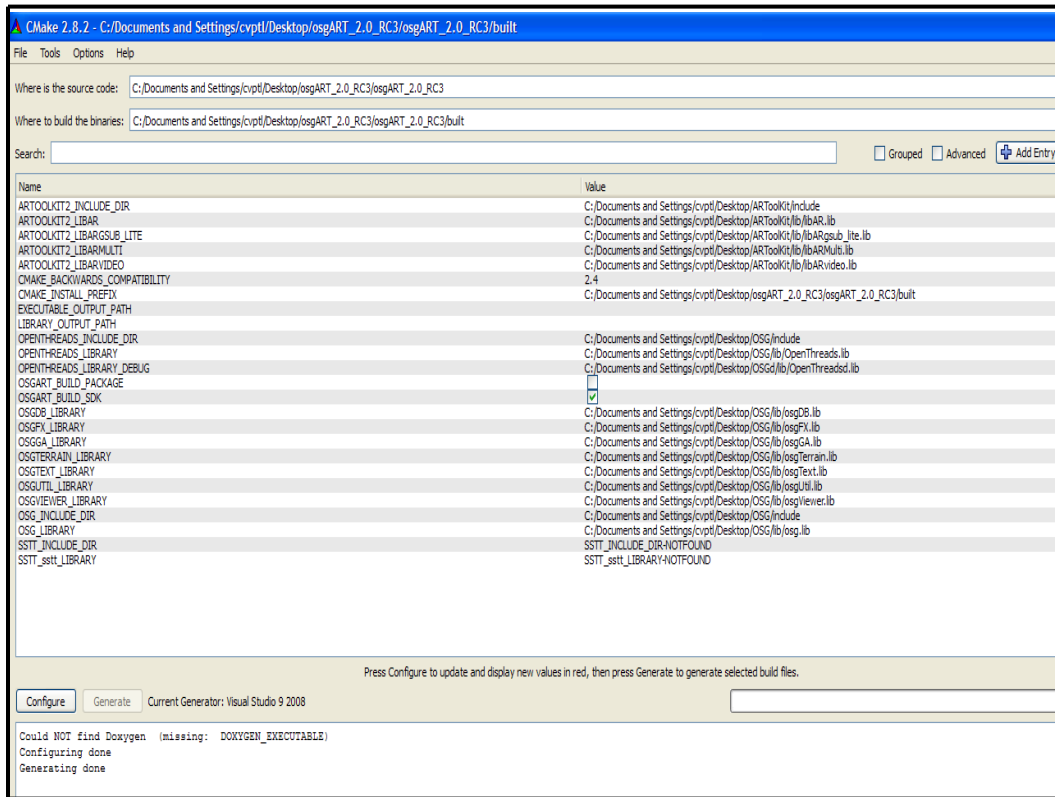


Figure 12: Building OSGART_2.0_RC3 by CMake_2.8.2

4.2.2 Building OSGART

(1) Configuration of OSGART

OpenSceneGraph2.9.9 is the newest version of OSG, while after compiling and compiling OSG2.9.9 and OSGART, an AR application was created. However there was a problem which was the video window was flickering and unstable. There was confliction between OSG2.9.9 and OSGART_2.0_RC3, so the stable version of OSG2.8.2 was chosen for built solution with OSGART. Because the root directory of OSG2.8.2 was set in advance, “include” and “library” files of OSG can be automatically set in default when OSGART is configuring.

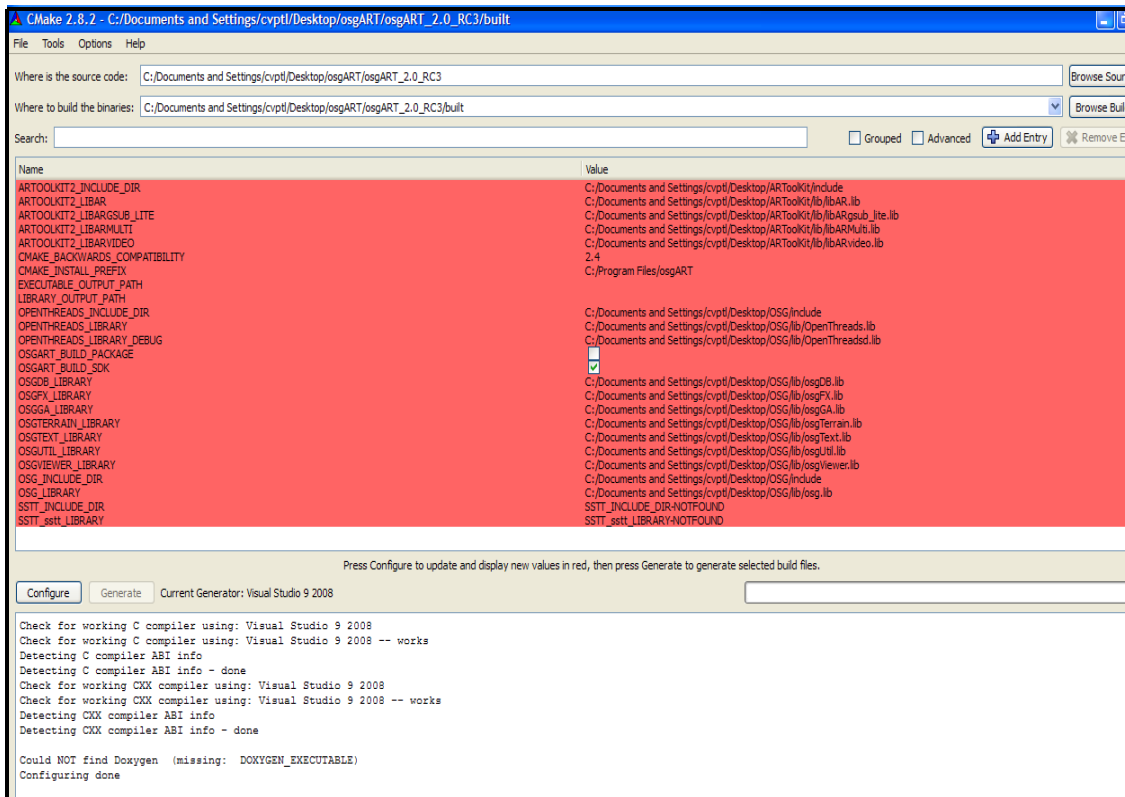


Figure 13: Setting up correct directories of include, library, DLL files of OSGART in CMake

(2) Generation of OSGART solution

After the correct configuration of OSGART, the solution was generated. As Figure 14 shows, “OSGART.sln” was opened with Visual Studio 9 (2008) and “ALL_BUILD” was built to generate binary files. “Debug” and “release” files both could be installed for different purposes.

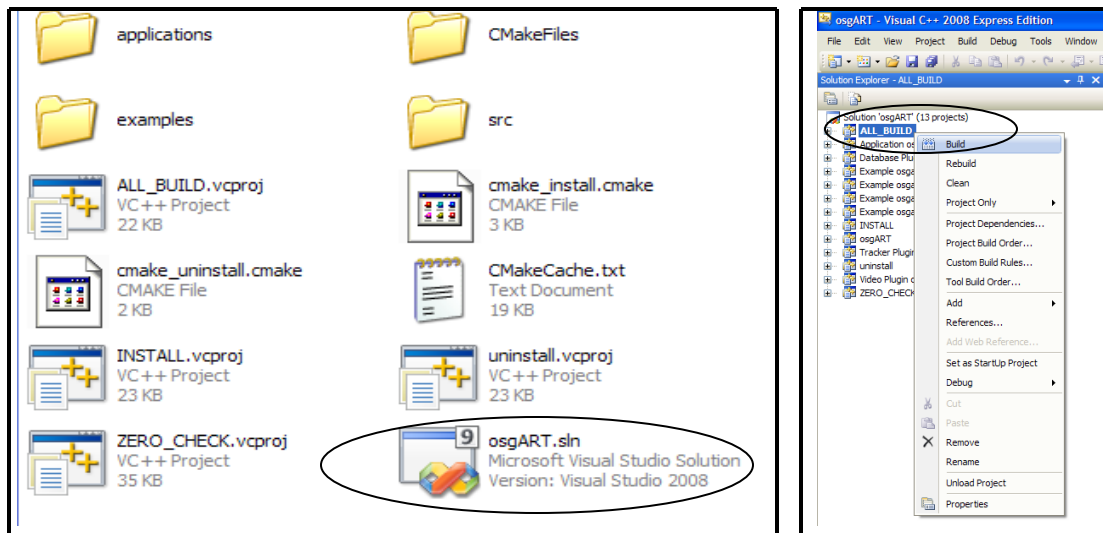


Figure14: Building all projects of OSGART, then library and DLL files were built

(3) The AR applications needed the outside linkage which contained libARvideo.dll, DSVL.dll. Finally, OSGARTsimple.exe was built and tested. As Figure 15 shows, a virtual 3D cube was displayed correctly in the real environment.

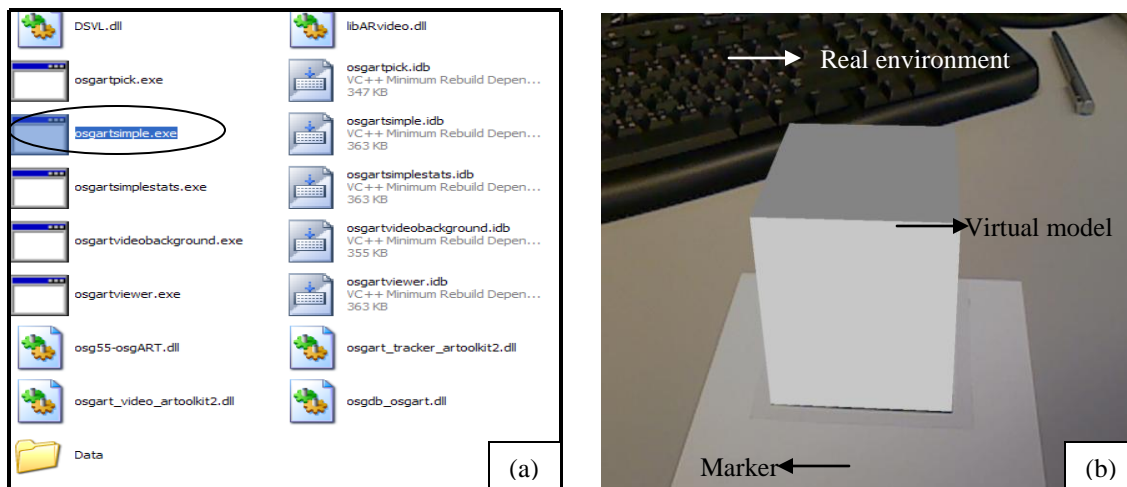


Figure 15: (a) Building basic AR application (b) A virtual model shown on a marker in real environment

4.2.3 Converting File Formats of Virtual Models

After building ARToolKit and OSG, a simple “release” exe file was built to test the effects of displaying virtual models in real environment. Although OSG supports 30 kinds of 3D model file formats, some data may be lost or some unexpected accidents may happen during the converting course. “Osgconv” is provided by OSG for converting formats such as OpenFlight, 3DS, Alias and Wavefront (OBJ) to OSG native formats which contain ASCII OSG and binary IVE. The Figure 16 shows this conversion method.

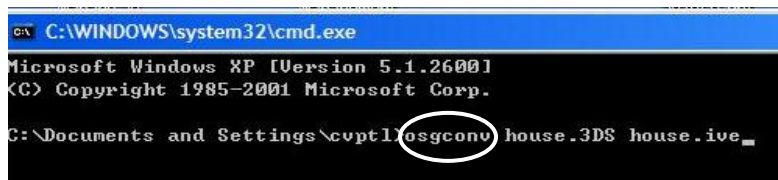


Figure 16: Using “osgconv” to convert 3DS to IVE file format

Before using “osgconv”, corresponding plug-ins are needed to read non-native format files. In this research, two easy steps were executed to convert 3D model files which were built in REVIT Architecture to file with native IVE and OSG formats. Firstly, 3D models are built in REVIT Architecture and exported as FBX files which was shown in Figure 17. Then the FBX file was opened in 3DS Max 2010 and exported to IVE file. In the second step, a conversion plug-in “OpenSceneGraph Exporter version 0.9.6” was installed as a plug-in in 3DS Max. “Osgviewer” is a in-built executable file to view OSG scenes. After the format conversion, the model with IVE format was tested in “osgviewer”.

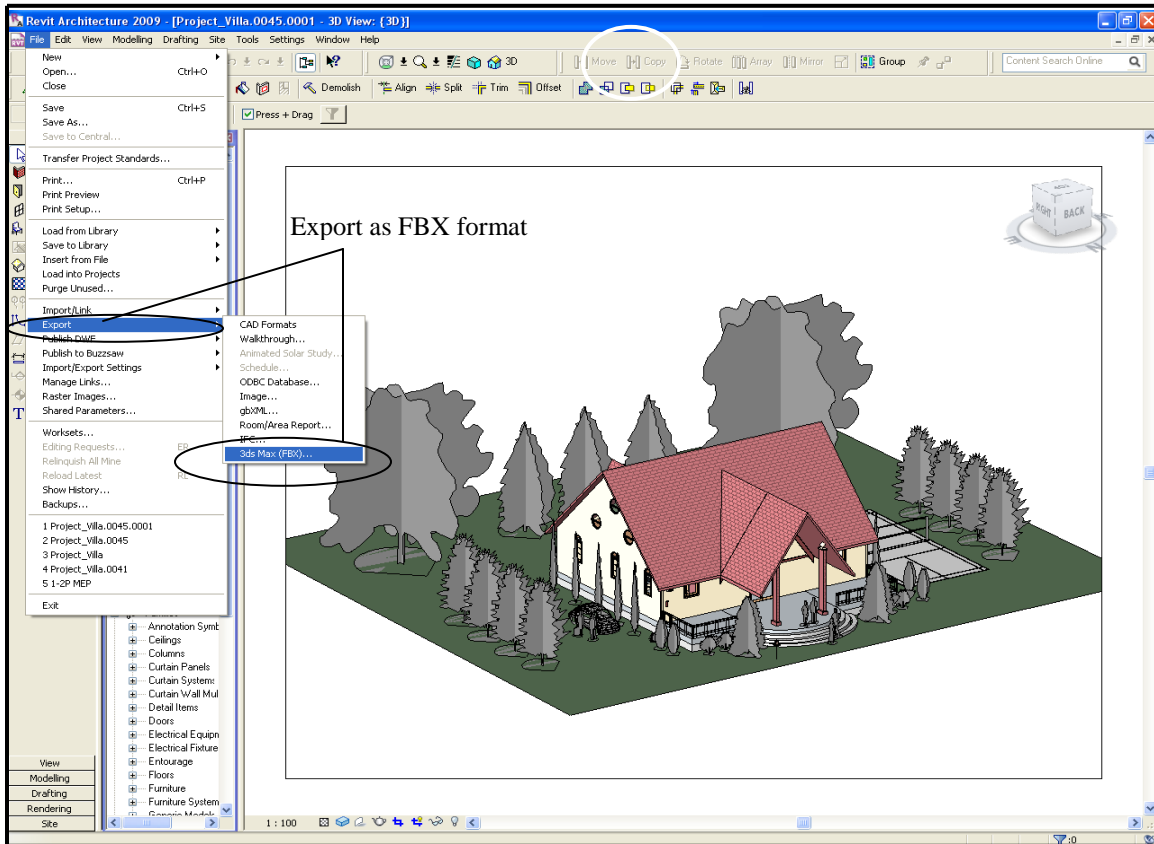


Figure 17: Building 3D models in REVIT Architecture and exporting as FBX format file

As Figure 18 displays, a light was added in the scene of the model. The reason for adding light in 3DS Max was that the lights of OSG, OSGART and the real environment would affect the illuminating situation of the model. In the AR programming course, some default lights would be turned down for correct lighting.

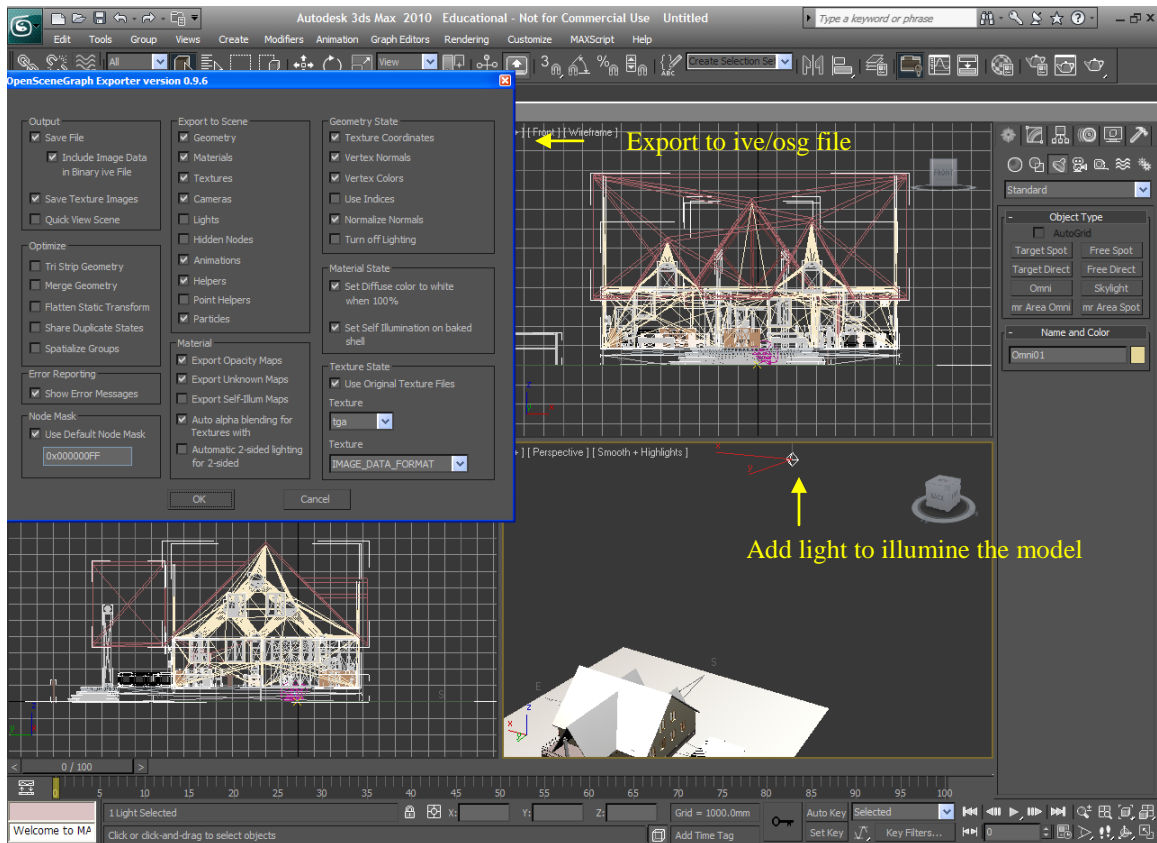


Figure 18: Adding light to illumine the model and exporting FBX to IVE format file

The two pictures shown in Figure 19 display the differences. IVE format model could save more data, while the material information of model was missed in the 3DS format model. Therefore, it was better to use the OSG native format files and minimize the conversion procedures.

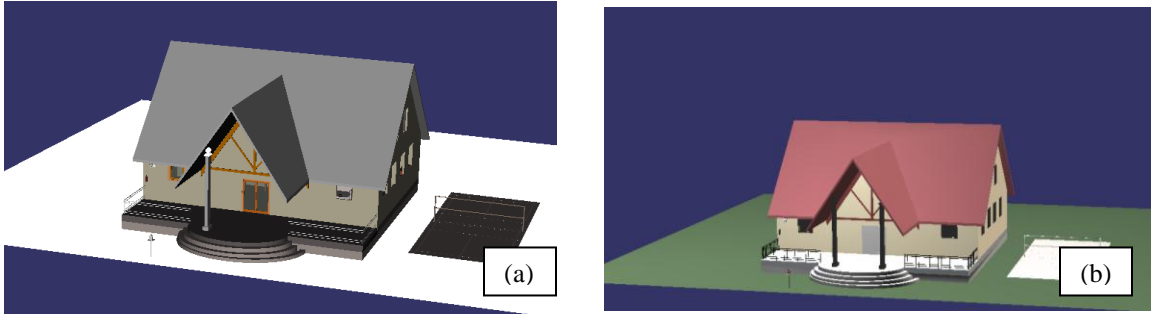


Figure 19: (a) Model with 3DS format opened in “osgviewer” (b) Model with IVE format opened in “osgviewer”

In order to testing whether OSG could read the mainstreamed kinds of format file, another model was built in SkechUp. There is a format convertor called “OSG Composer”. It supports importing 3D models from several kinds of standard file formats, such as SketchUp, FBX, OBJ, 3DS, DXF and DWG. However this software only provides a commercial license. Although commercial Google SketchUp Pro provides the tool to export 3D models as SKP format file, and 3DS Max commercial version 2010 provides the tool to importing SKP format files, as the trial versions of SketchUp and 3DS Max used, another method for model format converting was found.

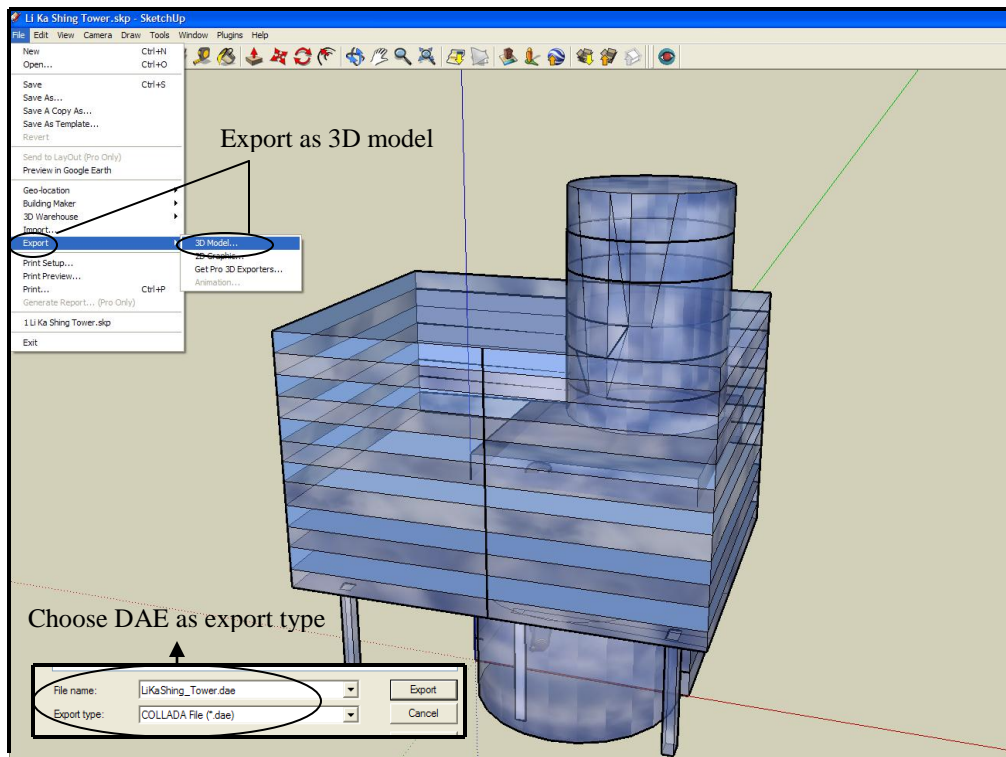


Figure 20: Building 3D model in SketchUp and export it as DAE format file

Figure 20 shows the easy method to convert SKP to DAE format file which can be read by OSG. When the DAE format model was opened in “osgviewer”, the model texture can be added to the model automatically when it was in the same directory with the model. The result of this course is shown in Figure 21.

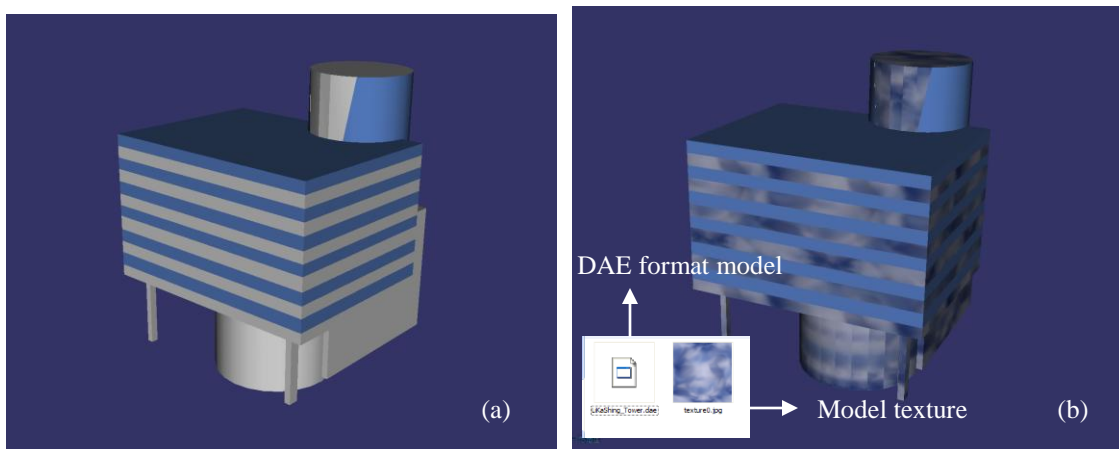


Figure 21: (a) DAE format model was opened by “osgviewer” (b) DAE format model was opened with texture file by “osgviewer”

4.2.4 AR Application Basic Test

After creating the virtual models and converting files to the format which can be read by OSG, an application was built in Visual C++ 2008 Express Edition with libraries of OSGART and tested the effects of augmenting. The virtual 3D models shown in Figure 22 were scaled down 100 times respectively in X, Y, Z directions. These virtual models were displayed on the accurate position and orientation on markers. Then, a hybrid system was designed and implemented with virtual information of SHUI CHUEN O project.

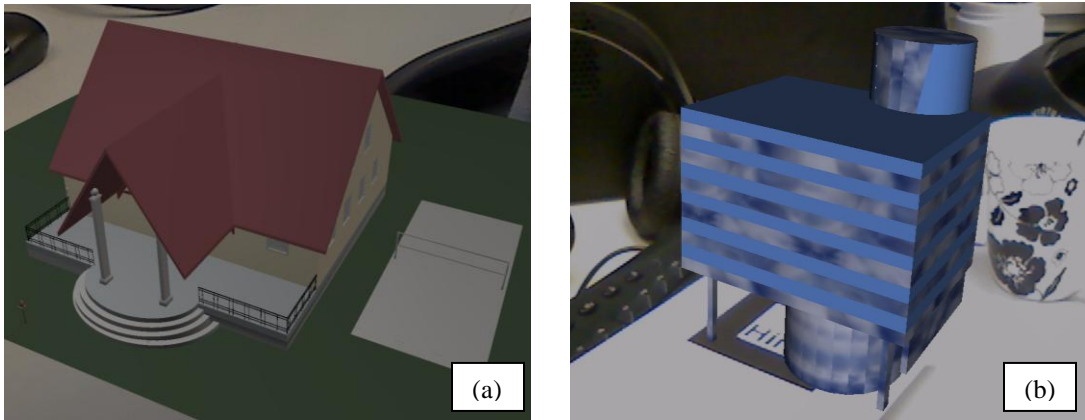


Figure 22: (a) Displaying IVE format model in real environment (b) Displaying DAE format model in real environment

4.3 Building ARAC

4.3.1 2D Information Assistance

In this section, the AR applications with two kinds of information assistance were developed. The text and geometry information could be extracted from BIM information anytime and displayed on construction site. These applications could improve the understanding of the building components for project teams. The second AR application attempted to play movie of construction simulation. As the file size of movie is much smaller than that of simulation built by models, movie was chosen depending on expected effect of users and practical need of construction.

4.3.1.1 Text Information Guide

Just like the situation of 3D models created in REVIT, building information were also built, saved and displayed together with models. Data of geometry, spatial relationships, light analysis, geographic information, quantities and properties of all building components has been important in BIM. As the preparation phase of the whole life cycle, construction planning stage has been assisted and improved by BIM technology. And as the practical construction phase, the site needs to be augmented with building information. In this research, text information assistance application was created for the sustainable utilization of the BIM information. Data of quantities and properties of building components and materials are saved as individual file which could be shown with corresponding components and materials. Addition to parameters of building, guide of assemblies and sequences of construction could also be shown. It helped users to quickly

create resource scheduling, operation arrangement, and exactly implement construction tasks.

The logical flow chart is shown in Figure 23. Class was custom for creating text which building information data can be attached. Then models with relative parameters were shown in real environment. In this application, the text alignment was set as facing to the screen all the time, namely, user could always watching virtual information even though the user was moving or models were translated and orientated.

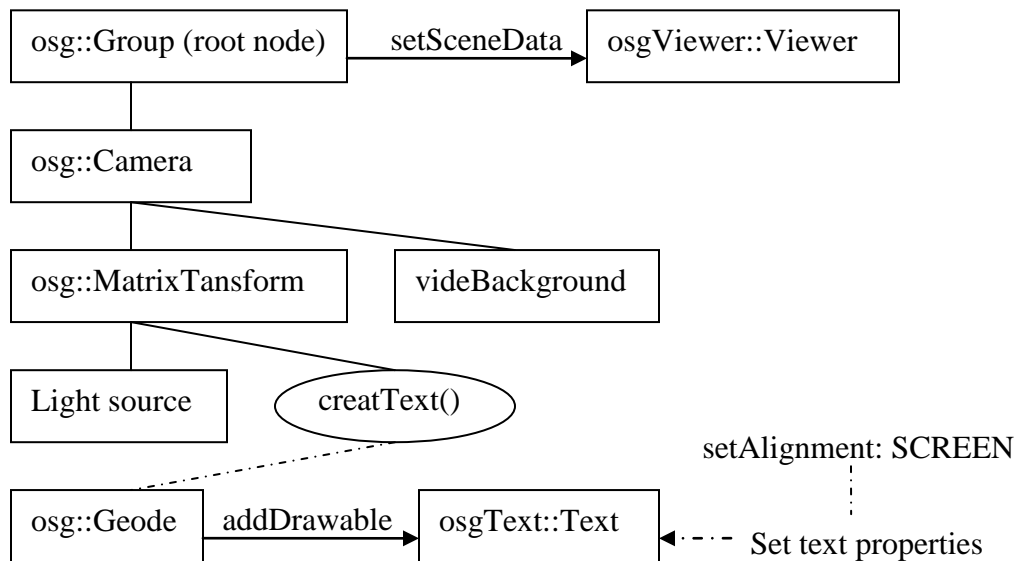


Figure 23: AR application for displaying text information

4.3.1.2 Movie Playing

Because the construction simulation which would be shown on construction site was built with 3D virtual models, the file size would be large and may slow down the implementation of AR application. An alternative method was introduced in this research.

Construction simulation built in related software were created into a movie, and then displayed in real environment for construction process guides.

There are two main plug-ins built with OSG can read movie files with formats such as AVI, MOV, QT, MPEG and FFMPEG. These plug-ins are “osgdb_qt” (or “osgdb_quicktime”) and “osgdb_ffmpeg”. The building procedures of “osgdb_qt” and “osgdb_ffmpeg” are introduced in below.

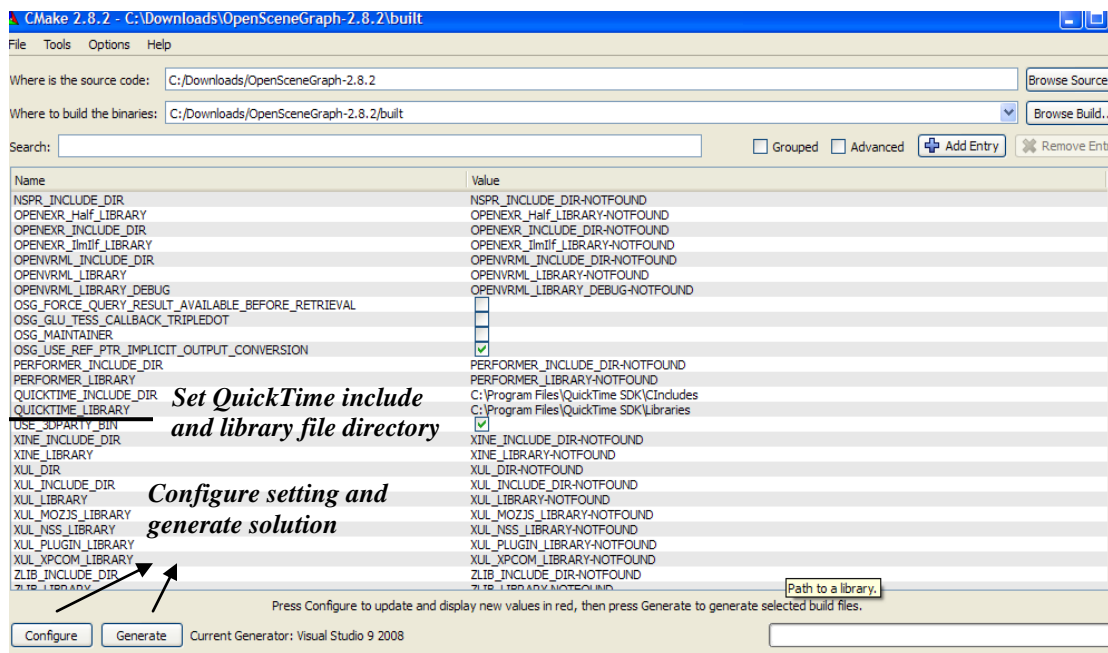


Figure 24: Setting “include” and “library” directories of QuickTime SDK

The QuickTime SDK was needed and its directories of “include” and “library” files were set in CMake for configuration. Figure 24, 25 and 26 show the procedures. When CMake checks the configuration was done, project can be generated with Visual Studio. Finally, the plug-in of “osgdb_qt” was built in Visual Studio environment. The procedure of building “osgdb_ffmpeg” plug-in was similar with “osgdb_qt”. In this section, a

walkthrough movie was created in REVIT Architecture. It could be opened in OSG viewer with plug-in “osgdb_qt”. However, when running the AR application, this plug-in could not be found. This problem will be fixed later.

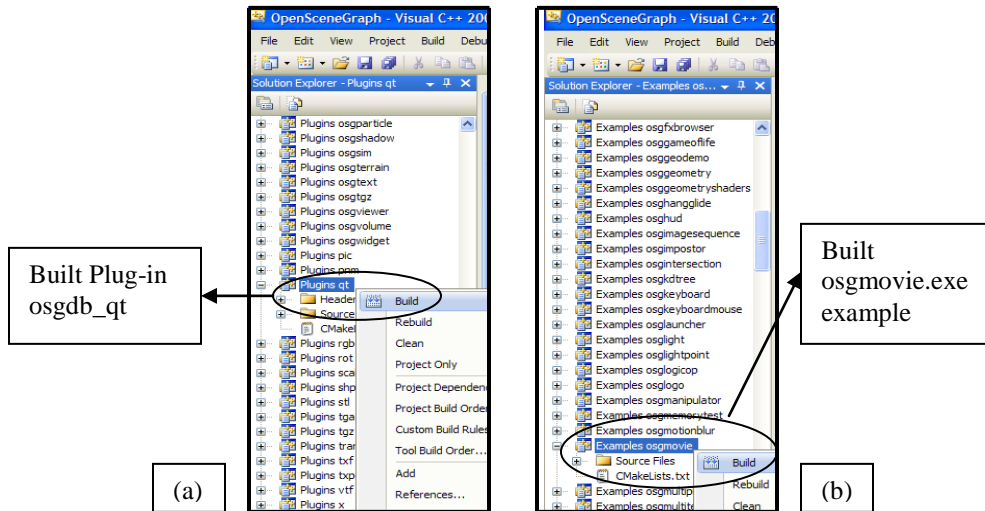


Figure 25: (a) Building plug-in of osgdb_qt.dll (b) Building Example of osgmovie.exe for testing this plug-in

The walkthrough movie was opened in “osgviewer” with the “osgdb_qt” plug-in. this movie was built in REVIT Architecture. And four key frames of this walkthrough were extracted from the movie. Every frame showed the scene which observed from different angles.



Figure 26: Key frames of movie of walk through built in REVIT

4.3.2 3D Model Display and 4D Construction Simulation

At present, software such as Delmia, Virtools, NavisWorks are specialized at procedure simulations. There are applications of construction process construction by these tools for practical construction projects. However, simulations of building construction in real environment have not been researched so much and there have been few applications in projects. In this thesis, the application of simulation which shows construction process was developed. For realizing this simulation process, a graphic flow of this part of program was designed. Figure 27 shows the logical flow chart. In this part, the node callback and switch node played important roles. In the custom simulation node callback class, a switch object was created and controlled the BOOL values of its children nodes in different frame values. Then another switch node was created in main function, in the

beginning, only ground floor model was set to display, then the node callback was set updated.

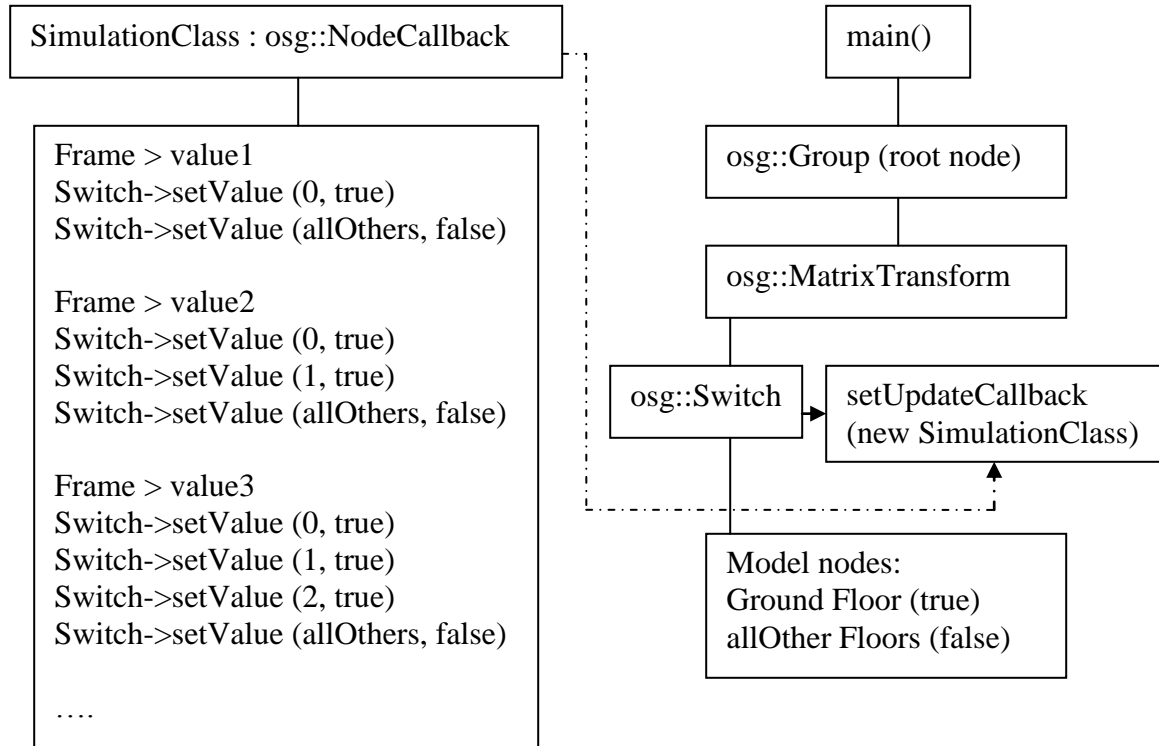
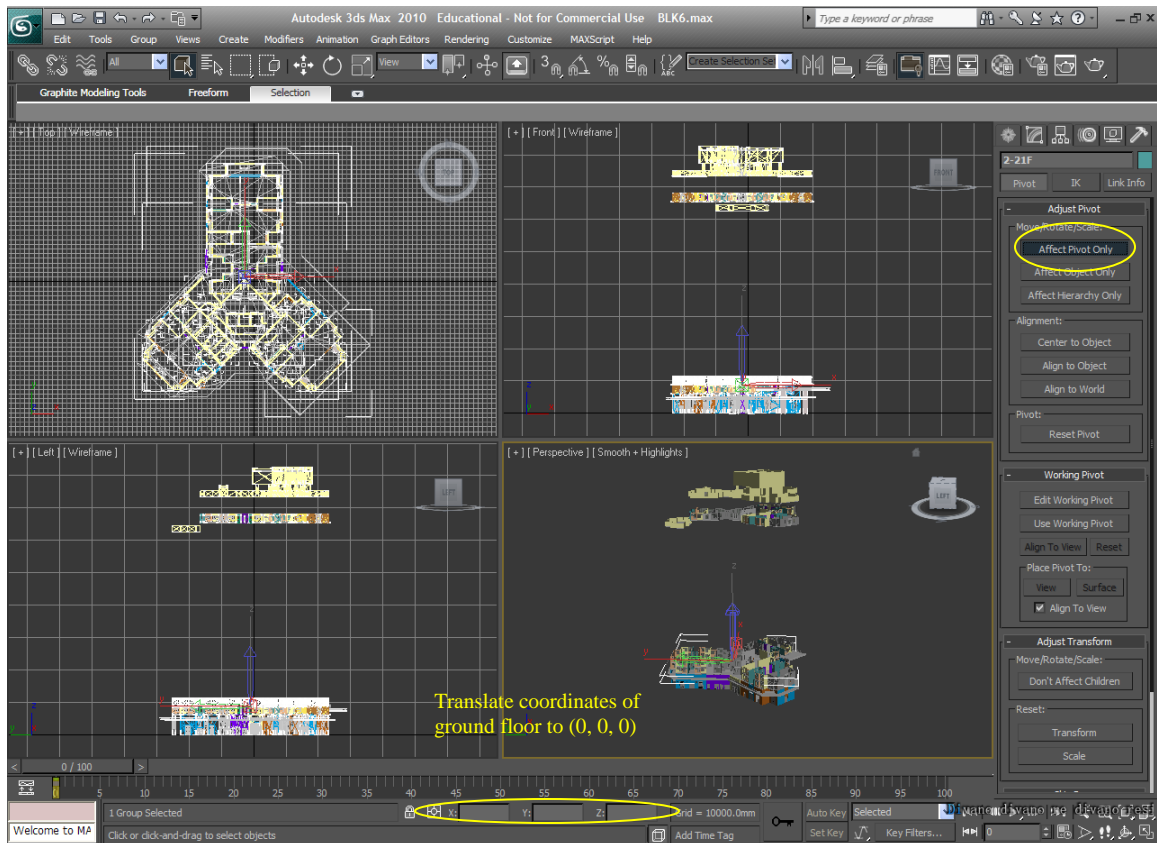


Figure 27: Simulation class definition and main function program flow

In this application, models were built in REVIT and exported as FBX format. Then models were imported into 3DS MAX and exported as 3DS format. The coordinates of models needs to be modified because the default model coordinates in AR environment is (0, 0, 0) of the attached marker. So before exporting 3DS format models, the bottom center of the whole building to origin point needs to be moved.



4.3.3.1 Keyboard

In addition to the visualization of digital information in real environment, interaction between 3D models and users is critical. As the most normal interaction method, keyboard controlling was taken into account firstly. For realizing keyboard control, a flow chart was designed as follows.

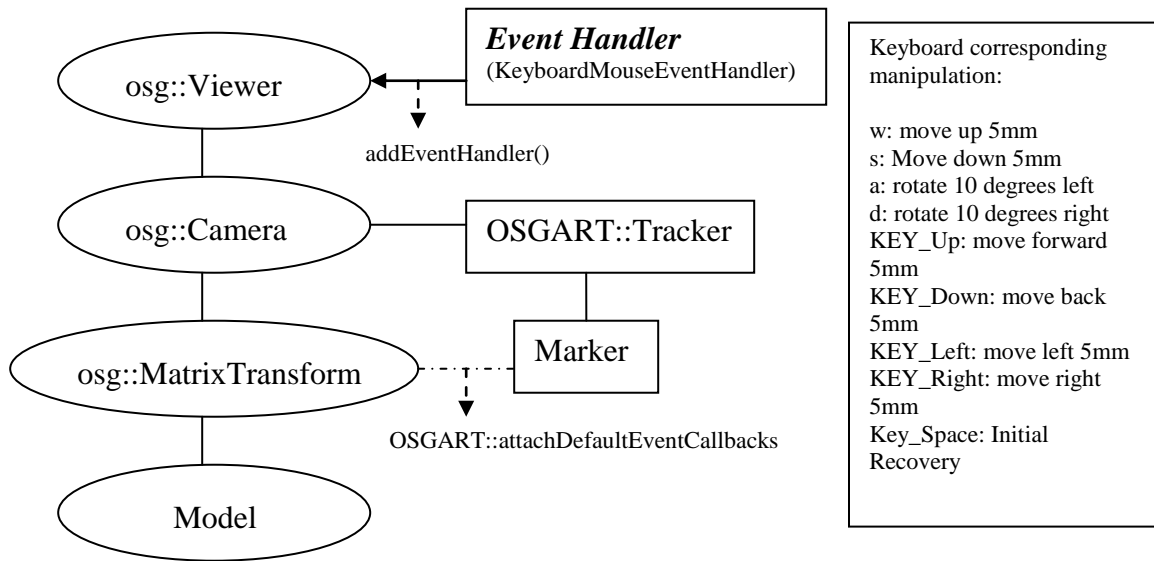


Figure 29: Designing interaction AR application with keyboard

An event handler needed to be defined and its constructor needed to be overridden. Then this event handler was added to the viewer of the whole scene in the main function. In the case of KEYDOWN, several keys were chosen for different manipulations.

4.3.3.2 Mouse

(1) Mouse Picks and Object Highlights

In the AR application which operated with laptop, the mouse interaction is necessary. There are two important parts which need to be realized. The first step is 3D digital models is shown in the real environment. The models could be chosen freely and quickly when they were clicked by mouse. Then corresponding operation should be executed right away. In this program, related model information window popped when user clicked one model.

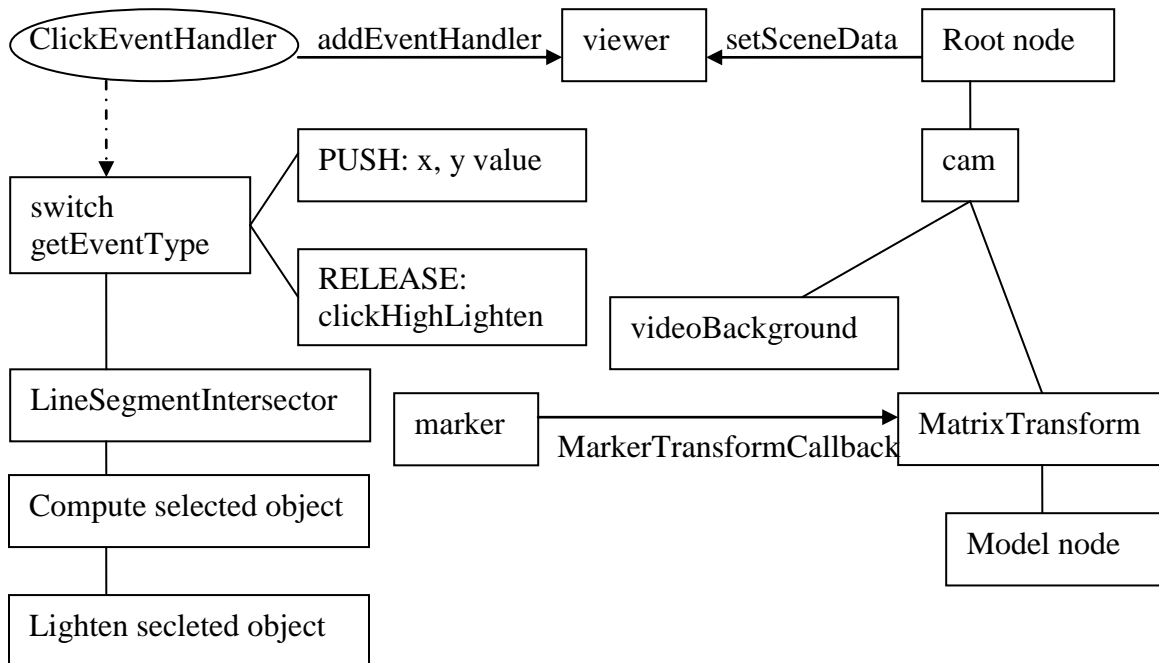


Figure 30: Flow chart of model high lightening when it is clicked

(2) Mouse Drags and Objects Matrix Transforms

In order to realize moving, rotating, scaling in the 3D coordinates when clicking, dragging and releasing mouse, the logical flow of program was designed which is shown in Figure 34. For normal manipulation of position and posture transform, it is simple to

set models under dragger or node of MatrixTransform (Wang and Qian, 2009). Users usually need more complex and flexible interaction methods in 3D matrix, such as the similar functions in REVIT, 3DS MAX, using several shortcut keys to execute the functions of translation, rotation and zooming, remembering manipulation history, undo and redo. It means several invokers link to several selectors. It becomes much more complex, so new method needs to be carried out. All lists of manipulations can be encapsulated into an object of command. Parameterized relationship can be introduced, rather than direct coupled relationship between invoker(s) and receiver(s).

As shown in Figure 31, there were three main parts which were designed to finish this function. The invoker gave commands and used two classes to transform the user manipulations to MotionCommand. Then the command manager fulfilled the relationship between the dragger and the selector. The last step was that the selection react received command and finally realized the user manipulations.

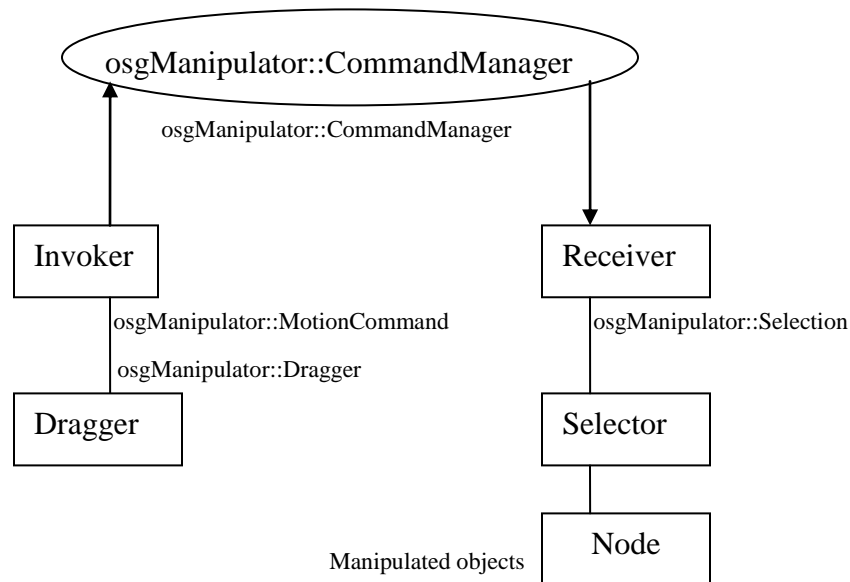


Figure 31: Method of realizing mouse manipulation to digital models

The specific node flow in the transformation function was designed as shown in Figure 32. The custom event handlers were added to the viewer, selection and dragger which were used for translating model along the axis. In this application these handlers were added as children of the group node. It was worth noticing that the node needed to attach into the marker is the object of MatrixTransform, rather than the node of the model and the selection.

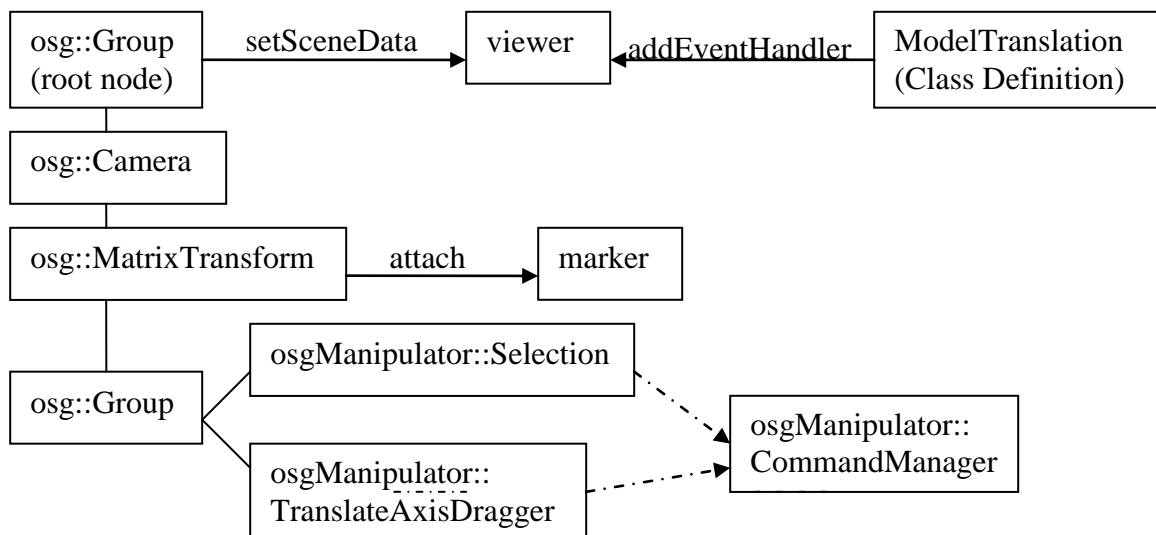


Figure 32: Translating virtual models along 3D axis

4.3.3.3 Hand Control with Marker

There are also two kinds of methods which are designed with regard to color glove and hand gesture inceptively. The essential ideas for identifying hand of these two methods

are similar. Two methods adopt the gradation between hand and environment. In this way, the approach used in this research has the same essential idea which is optical identification. Then these three methods can provide the functions of marker tracking and model controlling. In addition to the above two methods, hand control also could be adopted, with the attachment of small-size marker on the finger. These three methods were compared and advantages and disadvantages were analyzed. The final hand control way was chosen after the comparison.

(1) Hand gesture

Many researchers focus on the fields of hand gesture controlling of virtual models in AR environment. Handy AR approach was developed (Lee and Hollerer, 2009). This approach estimated a six-degree-of-freedom camera pose and segmented hand by a skin-color-based classifier with an adaptively learned skin color histogram. It can be compared with method adopted in this research in detail. Although the final effects are similar, the realization approaches are different.

(2) Color identification

Additional to designing algorithm of hand identification, bright colorful glove can be directly utilized for pretty accurate poisoning and tracking hand. A color glove was designed and corresponding hand model was created (Wang & Popović, 2009). Parameters of hand are updated all the time and can be used for controlling digital models which were shown in the real environment. So this approach could be referenced for handy interaction in AR application.

The designs of interaction methods need the consideration of real environment of executed applications. In the AR applications for indoor augmenting such as urban planning and facility maintenance and repair, keyboard and mouse are suitable for manipulating virtual models. While in outdoor environment such as construction site, more flexible interaction methods are needed. In this research, hand controlling method was designed and its flow chart is shown in Figure 35. There were two points for realizing this kind of control method. Firstly, the same as applications explained in above sections, a node call back was defined. In this class, distance between centers of two markers was calculated and set as a threshold. When the value of distance was small, namely the marker was close to a digital model, the model translated from marker A to marker B which was attached to the finger. Secondly, according to the situation of distance between two markers, models were set to be the states of on or off.

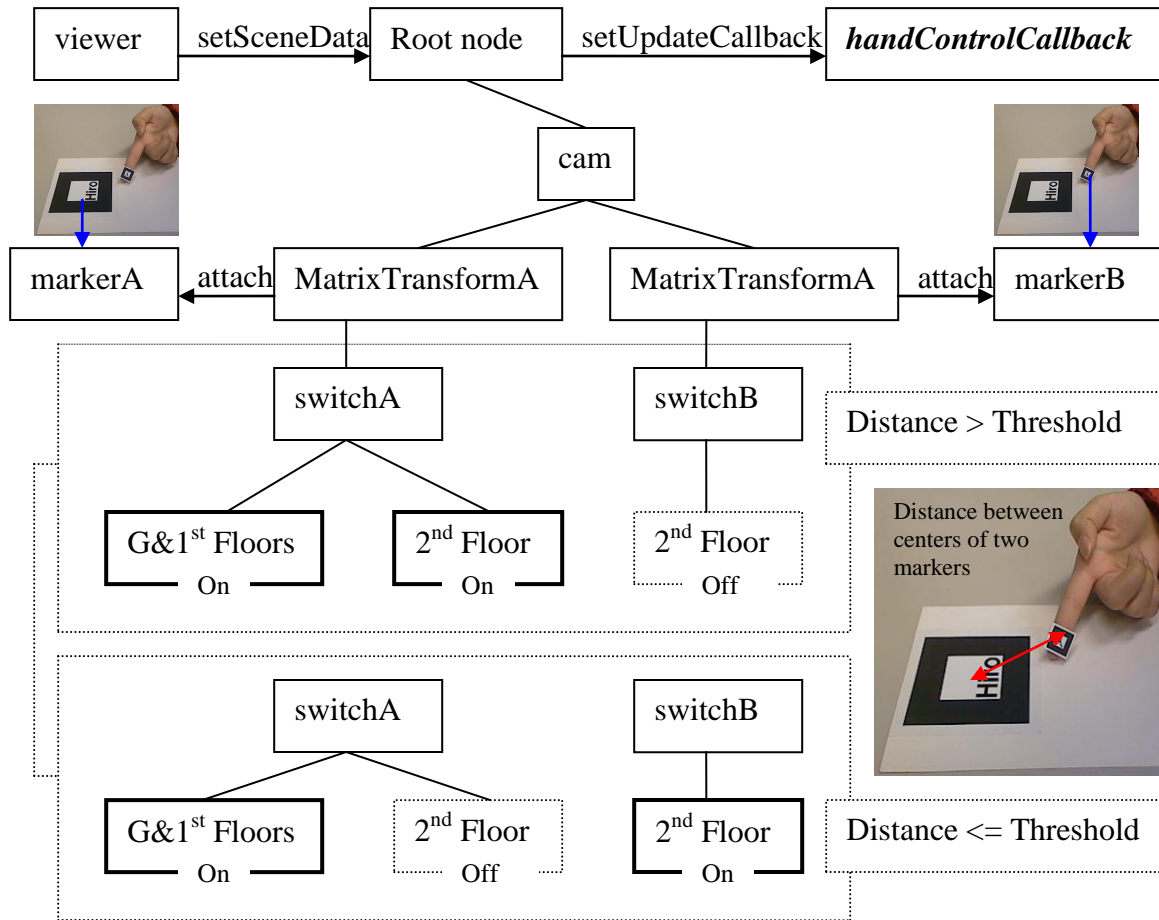


Figure 33: Hand controlling of model shown on marker A by marker B

4.4 Summary

According to the logical flows designed in Chapter 3, the ARAC was set up and the specific establishment course was presented. After finishing the preparation works for AR application development, virtual information guide, digital construction simulation and flexible interaction methods were introduced. The three main integrant of ARAC would help users to implement construction tasks with instant virtual information

visualization supports. The results of this system implementation and evaluation will be analyzed in the next chapter.

CHAPTER 5 IMPLEMENTATION AND EVALUATION OF AR-AIDED CONSTRUCTION SYSTEM (ARAC)

5.1 Introduction

The augmented reality system for assisting the construction phase was built, and then virtual content which included construction guides, course simulation were created. The course of ARAC implementation was carried out by two stages which were indoor tests and outdoor implementation on construction site. The system evaluation was executed followed by ARAC implementation.

5.2 Indoor Tests

Corresponding to the design flow of this AR system, the indoor tests were implemented in three main functional modules which were task operation guides, construction simulation and user interaction.

5.2.1 Text Information Guide

In the text AR application, when rotating the marker or moving the camera, 3D model was rotating or translating correspondingly, while text information was always facing the camera, namely user can observe related BIM data all the time.

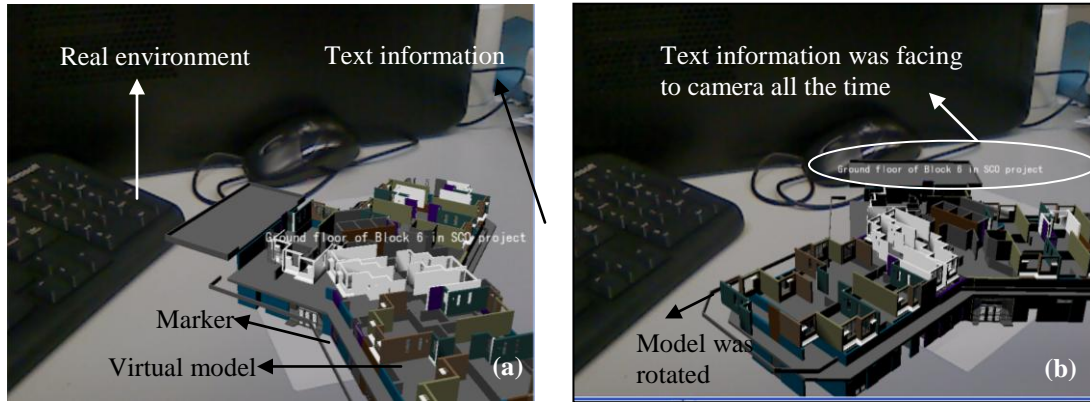


Figure 34: (a) Text information shown with model in real environment (b) Text information always facing the camera

5.2.2 Construction Simulation

The real effect of construction simulation is shown in the following screen shots. At the very beginning when this program is running, ground floor is shown in real environment, then other floor are appearing one floor by one floor every 2 second. Moreover, Gantt chart of construction procedure can be taken into account at the same time. According to the arrangement of construction schedule, the displaying time of each floor can be set correspondingly. This dynamical simulation course is shown in Figure 37.

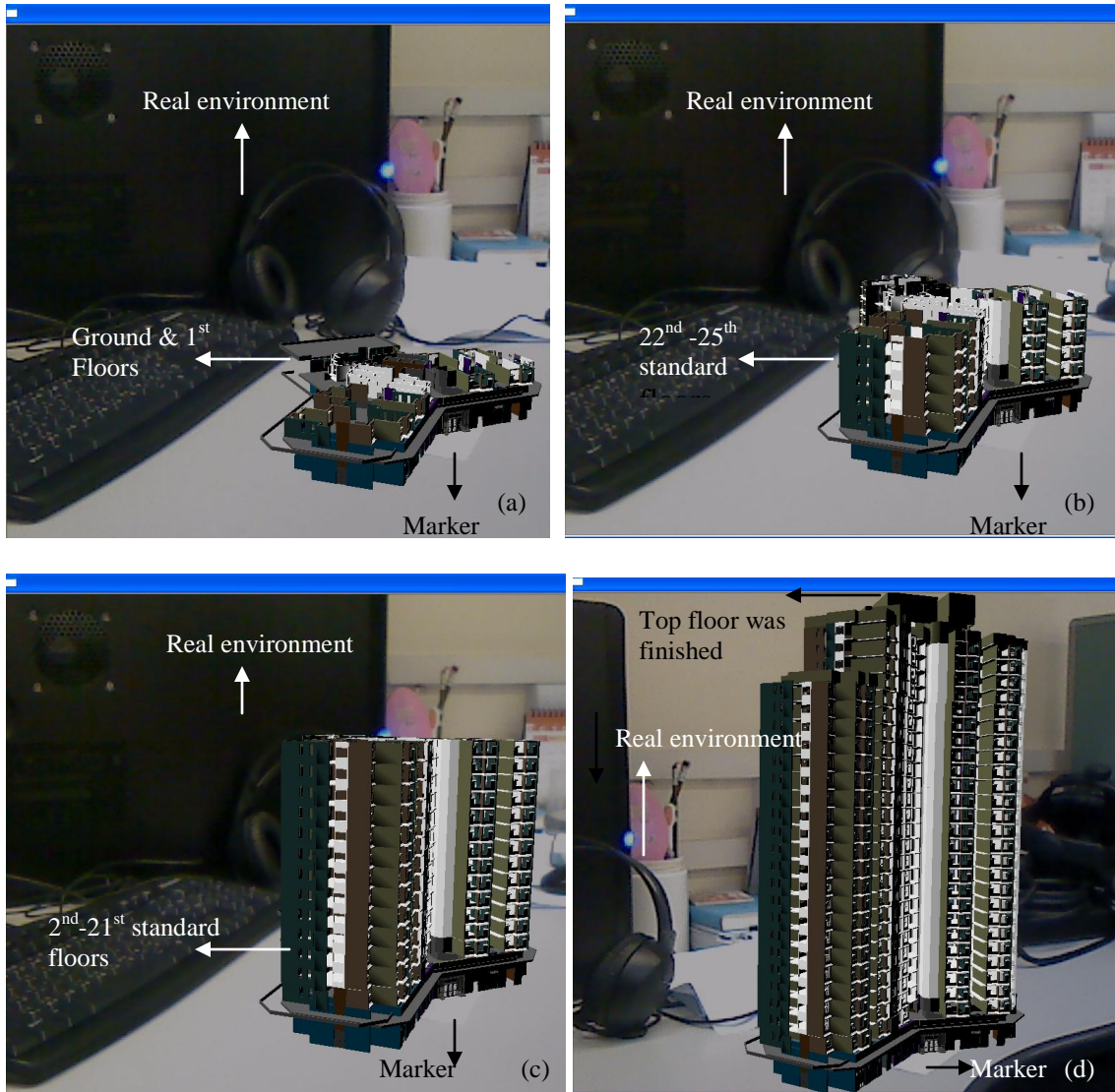


Figure 35: (a) Ground and first floors (b) 2nd-21st standard floors (c) 22nd -25th standard floors (d) Top floor is finished

5.2.3 Manipulating Virtual Objects

Two kinds of traditional interaction methods were built and a tangible interaction approach was set up. Users could use keyboard and mouse to control virtual objects and obtained feedback. Tangible AR interaction methods have been popular ones which

provide intuitive and easy user experiences. In this research, a small-size marker which was attached on the finger was used to manipulate virtual content.

5.2.3.1 Keyboard

As Figure 38 shows, the functions for moving up, down, forward, back and rotating were realized. When pressing the keyboard, models could translate or rotate correspondingly. Most users are familiar with this manipulation method. It is the most popular and traditional interaction approach.

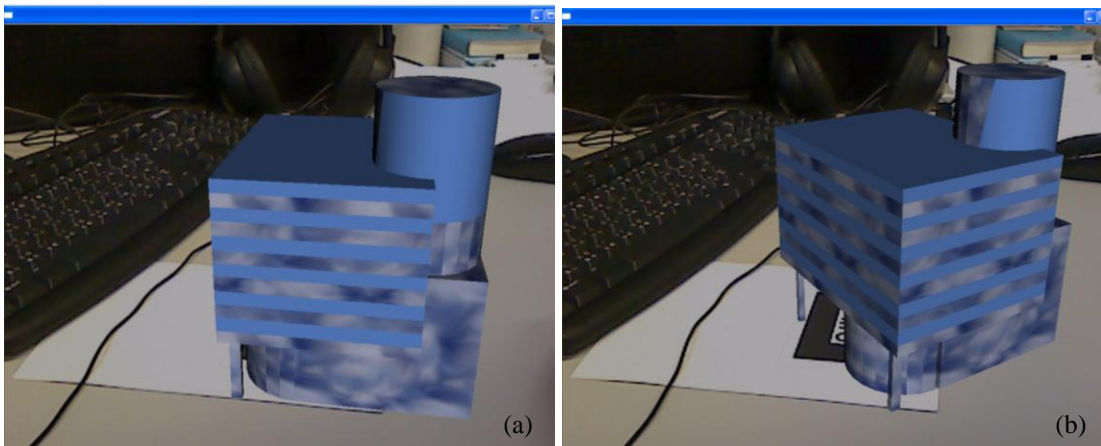


Figure 36: (a) Initial position of the virtual model in the real environment (b) 10 degrees left rotation of the virtual model

5.2.3.2 Mouse

(1) Mouse Picks and Object Highlights

This model shown was built and exported as FBX format in REVIT, imported to 3DS MAX and exported as 3DS format. Because all models are combined with triangles, highlighted models show white triangle lines. Moreover, every part of this model can be selected respectively as a triangle. The interaction effect is shown in Figure 34. When clicking the virtual objects in real context, part of the model which is a separate bound sphere in OSG could be highlighted. This function is useful in the case of large number of models, for attracting users' attention. It is also practical for collaborative augmented reality applications, such as urban planning. Multiple users and huge quantity of virtual models are suitable situation to use this function.

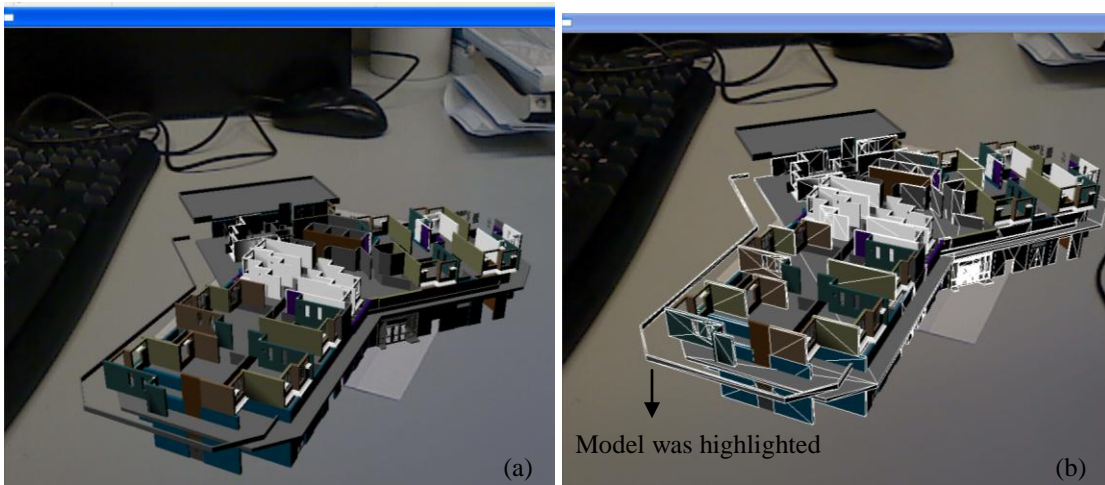


Figure 37: (a) Original model (b) Highlighted model

(2) Mouse Drags and Objects Matrix Transforms

In addition to the keyboard, the mouse is another popular control device for manipulating digital content. In this application, a virtual 3D coordinate axes was added in real

environment, together with 3D virtual models. It was clear and convenient for the user translating models in expected axes.

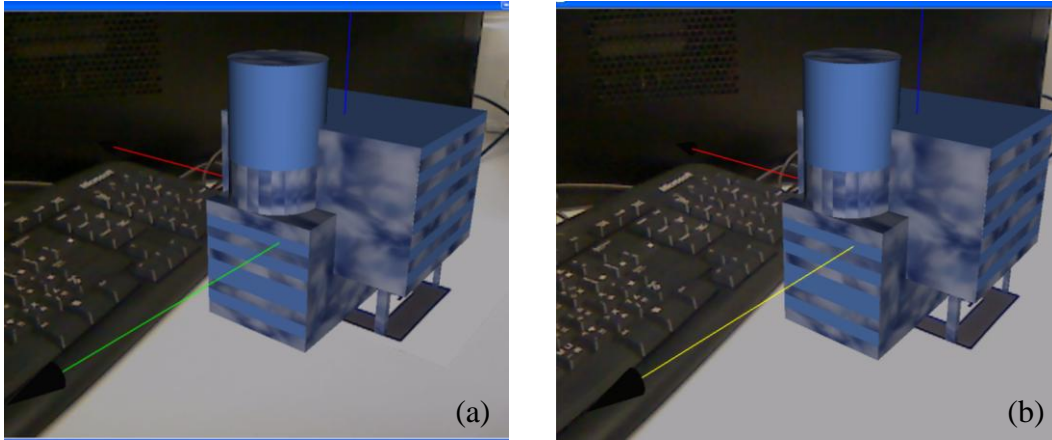


Figure 38: (a) Original gesture of virtual model and axis (b) Highlighted Y axis and translated model along Y axis

5.2.3.3 Hand Control with Marker

Screen shots of running application are shown in Figure 41. The difference of these two sets of models was the scale of 2nd floor model. In Figure 41 (a), the scale of 2nd floor model is smaller than that of ground & 1st floors. Because the pattern file of marker B used in program was not changed, while the size of this marker was scaled down for attaching on the finger, the coordinates of marker B was scaled down correspondingly. In the second set of pictures, the scale of 2nd floor model was the same with that of another model because the 2nd floor model was scaled up.

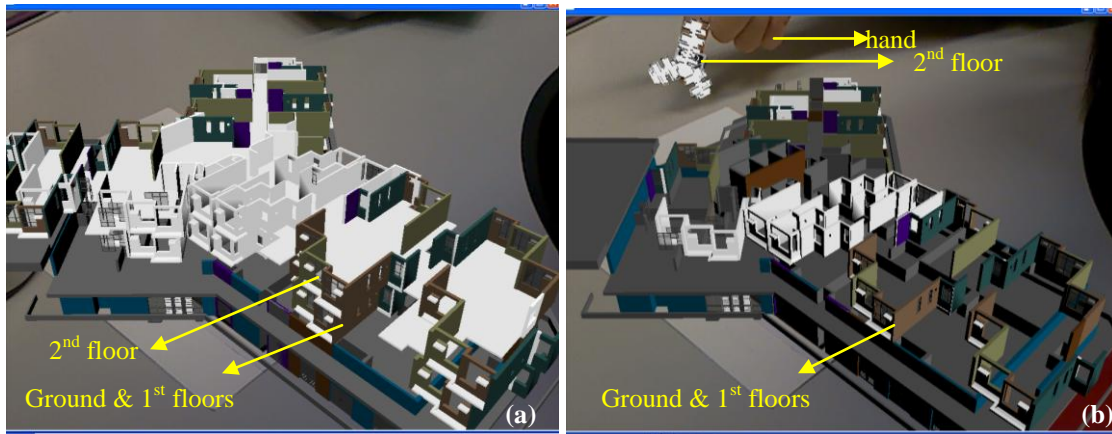


Figure 39: (a) Ground & 1st floor model and 2nd floor model (b) 2nd floor model was translated to the marker which was attached on the finger

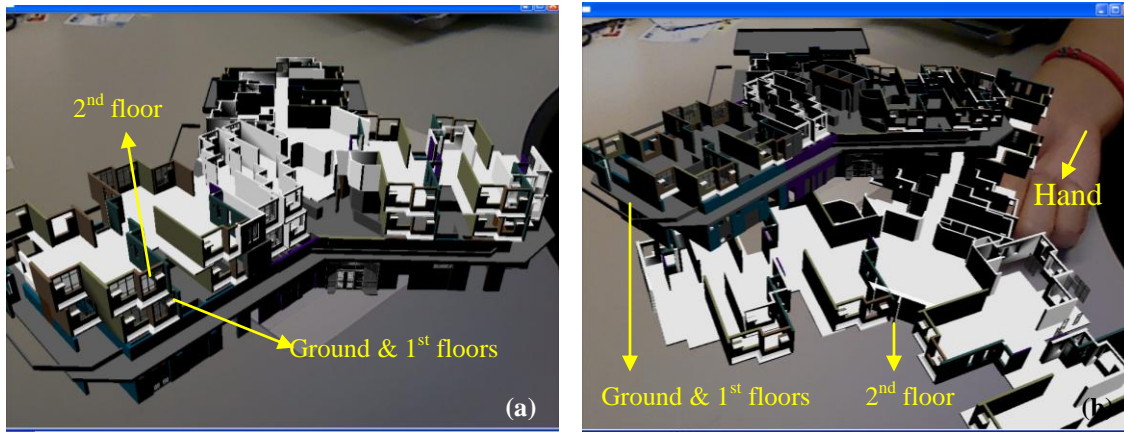


Figure 40: (a) Virtual models of Ground & 1st floors and 2nd floor (b) When hand was close to 2nd floor, 2nd floor model was translated to the marker which was attached on the finger (2nd floor model was scaled in its own marker coordinates)

5.3 Outdoor Implementation on Construction Site

Additional to the traditional marker used in AR applications, users can custom the markers with the marker generator. If the marker is loaded with libraries of ARToolKit, some rules of marker making should be followed. The surrounding part of the marker needs to be black for identification. There is a marker generator called “ARToolKit

marker generator online” was available for creating markers from any pictures or video frames. The detailed procedure of marker creation was introduced in Section 3.3.1.

Although this tool generates a pattern file of the marker for loading to AR program, it could be used for markerless applications. There are two methods of tracking virtual models on the construction site. The first one is using the traditional marker which needs to be created in big size for long distance observation. The second one is photographing large number of pictures of the construction site in different positions and orientations. Then all the pictures could be transferred to marker pattern files by the marker generator. Then in the program, every marker pattern is designed to display the model with right orientation and position. A large-size marker on the ground among the buildings was attached. When the camera was set to face the marker, a skyscraper was shown on the ground. This method for augmenting in outdoor environment uses a traditional marker with large size for clear gradation. Then the camera could identify it and track it accurately.

This research focused on AR application on the construction site, it is not practical to attach a large-size marker on site because the site is changing all the time. As introduced in the previous paragraphs, site pictures could be photographed and converted to marker pattern file by the marker generator. The theories of these two methods are same. They both utilize the gradation of picture to identify the data of position and orientation, and then track the marker or one object in a site photo.

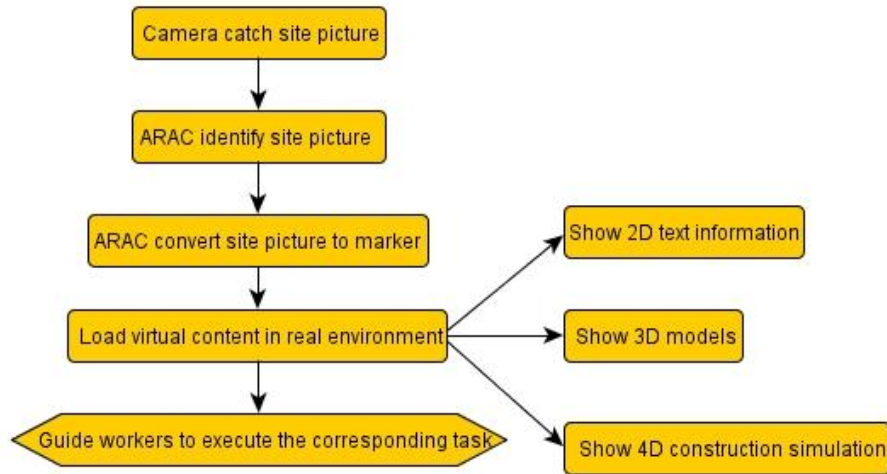


Figure 41: ARAC operating process on construction site

The flowchart of the operating process of ARAC is introduced in Figure 44. The site picture was caught by the camera and identified by ARAC. Then the picture was converted into corresponding marker. The virtual content could be shown on the marker. Because of the design of ARAC, 2D text information, 3D digital models, and 4D construction simulation were shown in real environment. Finally, all these virtual information were used for guiding the site worker to execute corresponding tasks. The photo shots of ARAC execution result on site are shown in Figure 45. “Welding the reinforcing bar” was shown in the real environment and guided site workers to carry out this task. As Figure 46 shows, 3D virtual building models were displayed in real context. 4D construction simulations could also be displayed for dynamical demonstration for the site worker for the next operation guides.



Figure 42: (a) Real environment of construction site (b) 2D Text information was shown as operation guide for workers on site

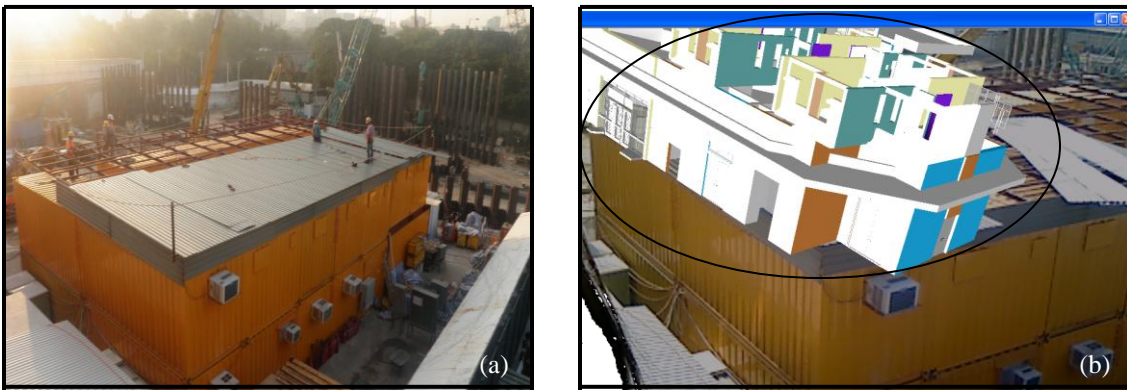


Figure 43: (a) Real environment of construction site (b) Virtual 3D model was shown and could be interacted with the user

5.4 Evaluation of ARAC

It is worthwhile to collect knowledge on user evaluations gathered in other disciplines and to bring it into AR settings (Dünser, Grasset & Billingham, 2008). Although there have been less research for the AR system evaluation, choosing an appropriate approach to evaluate ARAC is necessary. User-based experiments are critical for driving design activities, usability, and discovery early in an emerging technology's development (Gabbard & Swan, 2008)

The evaluation methods designed for other domains can be used for MR systems (Bach & Scapin, 2004). They identify three methods: questionnaires and interviews, inspection methods, and user testing. All AR user-based-evaluation publications could be classified according to evaluation type and evaluation methods. If the AR systems are evaluated by user evaluation type, they could be studied in four aspects: perception and cognition, user task performance, collaboration, and system usability (Dünser, Grasset & Billinghamurst, 2008). It was reported that if the AR systems were evaluated by user approaches and methods, they could be classified into five types: objective measurements, subjective measurements, qualitative analysis, usability evaluation techniques and informal evaluations (Swan & Gabbard, 2005; Dünser, Grasset & Billinghamurst, 2008). In Table 4, evaluation methods for AR systems are summarized. According to the popular evaluation approach and the practical situation of this research, task performance and objective measurements were adopted to evaluate the ARAC. At present, developments of AR system and applications of these systems in construction fields are at the emerging stage. So the real impact of AR technology in the construction phase needs to be evaluated to improve the application methods of AR technology in the construction industry. If the ARAC was evaluated by the user approaches and methods, objective measurement was used which employed a statistical analysis of the measured variables, and descriptive analysis. Task performance and objective measurements have things in common, although the emphases of evaluation methods are different. Dünser et al. (2008) reviewed 150 publications of user task performance and objective measurements and there are 48 common publications.

Table 4: Evaluation methods of AR systems
(Swan & Gabbard, 2005; Dünser, Grasset & Billinghamurst, 2008)

AR user-based-evaluation publications classification methods			
Evaluation type	Focus	User approaches & methods	Focus
Perception & Cognition	How human perception and cognition operate in AR contexts	Objective Measurements	Task completion times, accuracy, error rates
Task Performance	How AR technology could impact underlying tasks	Subjective Measurements	Using questionnaires
Collaboration	How multiple users interact and communicate	Qualitative Analysis	Formal user observations; Formal interviews; Classification or coding of user behavior
System Usability	Other ways of identifying issues with system usability	Usability Evaluation Techniques	Employ evaluation techniques that are often used in interface usability evaluations
		Informal Evaluations	Informal user evaluations and informal collection of user feedback

The popular evaluation methods of objective measurements and task performance have adopted both statistical analysis of the measured variables, and descriptive analysis. The results of selecting virtual object in AR context were analyzed from three aspects: objective measures, analysis of motion and subjective measures (Looser et al., 2007).

Table 5 summarized one important variable in ARAC. The maker played an essential pole for implement AR applications on construction site. Four kinds of tracking methods are compared. The advantages and disadvantages of four methods are analyzed from 7

aspects: accuracy and stability indoor, accuracy and stability outdoor, identification distance, identification angle between marker and camera, light affects, Cost, and applicable areas in AEC industries.

Table 5: Comparisons among four kinds of registration and tracking methods are analyzed.





Registration & tracking method	Fiducial marker 	Marker created by marker generator from real photos 	RFID 	GPS 
Accuracy & stability indoor	Accurate, Stable	NA	Accurate, Stable	Accurate, Stable
Accuracy & stability outdoor	Accurate, Stable	Inaccurate, Instable ③	Accurate, Stable	Relatively inaccurate, stable
Identification distance	distance/marker side length < 0.01 ①	No limitation (About 60m in this test. It depends on the camera configuration)	66m ④ 0-317miles	Registration by satellite. Tracking distance depends on marker kind.
Identification angle(marker, camera)	0- 85 degrees ②	Same with shooting angle of initial photo for generating marker	irrelevant	irrelevant
Light affects	Very Strong	Strong	No	No
Cost	Free	Free	Reader: \$20-\$5000, Tag: \$0.5-\$800 ⑤	Built-in GPS of smart mobile phone.
Applicable areas in AEC industries	Urban planning, Facility maintenance & repair	Construction photo with great & clear gradation.	Construction operation guide & process inspection, facility maintenance & repair	Various kinds of application with no high standard in accuracy

Table 5 Comment: ①identification angle between marker and camera is 0 (camera here is the internal one of HP EliteBook 8530w). Test is implemented in indoor lighting intensity. Marker side length is 0.08m and valid identification distance is about 8m.

②Test is implemented with indoor lighting. Instance between marker and camera is about from 0.01m to 2m.

③ Marker is generated by “ARToolKit marker generator online” which is more applicable in indoor marker generation. This tool is not so powerful in complex outdoor environment.

④This data is referenced by the experiment which is used 10W of RF power and 70W of amplifier. (Chris Paget, 2010)

⑤Price information references an online shopping website: <http://www.nextag.com>. It depends on the configuration of RFID reader and label.

5.4.1 Relationships among Multiple Models in AR Environment

Models can be shown in multiple markers for respectively manipulating different models.

In this application, two markers were loaded and two building models were displayed in real environment. As shown in Figure 47, when the villa model was moving around the tower, the lighting condition of tower was changing. As analyzed in Table 4, OSG environment itself took default global lights which illuminated from all angles. The Model with DAE format was also illuminated from various angles, while the model with IVE format which was exported from 3ds max was added an “omni” light. This light was set in the top-left of the villa model. So some areas cannot be lightened because of the position of “omni” light. Then in AR application, the models with different formats and lighting situation were added as node in OSG environment. Then the whole villa model which was added with an “omni” light was lightened because of the global light from all angles of osg viewer. When the models were displayed in AR environment, the lighting condition was changed. In general, the exterior light is divided into outdoor and indoor ones, because in outdoor environment sun light is too strong on sunny days, or when the

camera is located facing the sun, sun light is much brighter than the lights built in the software and the screen electrical light. But when the camera is not set towards the sun or it is cloudy, the “omni” light in the villa model would also affect the lighting situation of the tower model. The lighting condition of multiple models in indoor fluorescent light is similar with the outdoor cloudy condition. So in the lighting condition of the exterior, OSG and DAE model, there was no lighting direction, while in one of the exterior, OSG and IVE model, the light had direction and would affect other models in AR environment.

Table 6: Lighting situation of multiple models and interactive lighting effects

Software environment	Lighting situation			Light with certain position & direction
OSG environment	Default viewer global lights from all angles			No
REVIT->3ds Max “IVE” format	Import FBX file with no light. Add “omni” light (set in top-left of model)			Yes
SketchUp “DAE” format	Default global lights from all angles			No
Model added as node in OSG environment	1)OSG + IVE (global lights + omni light)			Yes
	2)OSG + DAE (global lights + globle light)			No
AR environment	Exterior light	Nature light -outdoor	Camera towards to sun	Yes (but sun light is too strong)
			Camera not towards to sun / Cloudy day	No
		fluorescent light - indoor		No
	exterior + OSG + DAE			No
	exterior + OSG + IVE			Yes

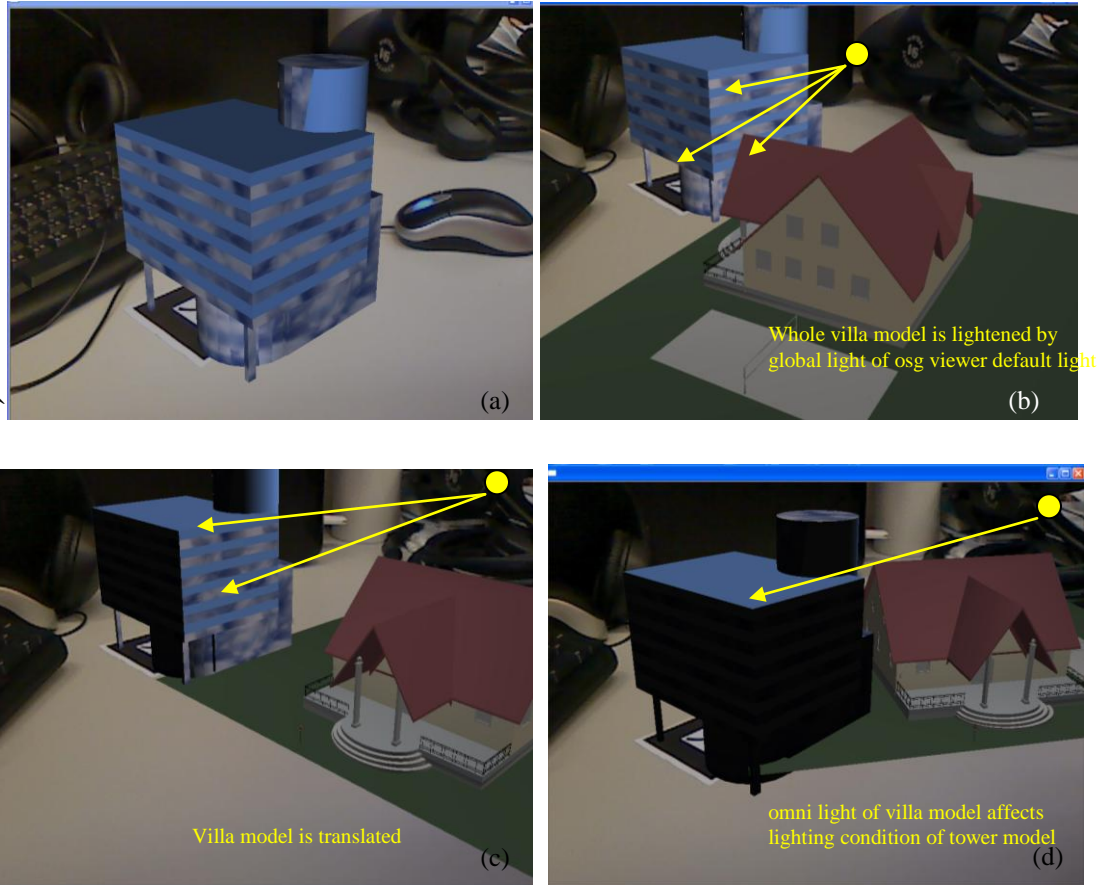


Figure 44: (a) only one model was displayed (b) Sun was set in the top and right of the house, Tower was lightened (c) House was translated, one side of the tower cannot be lightened (d) House was translated, several sides of the tower cannot be lightened

5.4.2 Influences of Real Environment to Virtual Models

Figure 48 shows the effects of the positioning method. Two issues need to be evaluated after the ARAC implementation. The virtual model was located in another position and displayed with no light. Because the construction site was allocated complexly and the marker generator could not identify subtle gradation, the model was not set on the right position. Another reason is that the experiment was implemented on a sunny day. The camera was facing to the sun, so the sun light which was captured into camera was too

bright to show the light situation of the virtual model. This means the virtual model displayed in real environment can be affected by outside factors. This finding could be utilized for sun light analysis of the effects of surrounding building environment to the virtual model which will be built.

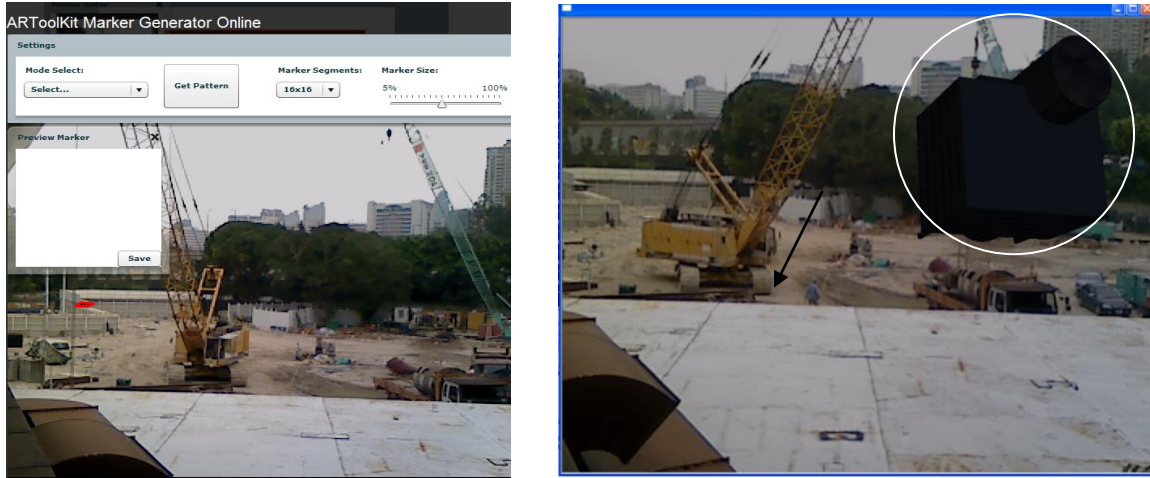


Figure 45: Virtual building model displaying on construction site.

5.5 Summary

This chapter presented the implementation results of ARAC system. The implementation course contained two parts: indoor tests and outdoor execution on construction site. Then this system was evaluated by two methods, which were task performance and objective measurements. Statistical analysis and descriptive analysis were both carried out to evaluate the ARAC.

CHAPTER 6 CONCLUSION

6.1 Summary

With the speedy development of virtual reality technologies, visualization for the whole building life cycle has been studied by researchers and applied in real AEC industries over the last decade. BIM information of the building project was created by computer-aided software for assisting architecture, terrain, construction, facility management. Some researchers have improved BIM by analyzing the constructability of design, the feasibility of construction methods and the accuracy of construction scheduling. Moreover, the BIM team could provide feedback to architecture design team, construction planning team, and facility management team. Then the design, construction and facility management could be improved. The potential of BIM has been explored and applied in the practical construction industry. While there has been a weak connection between BIM information and construction phase, because construction stage is quite different from other phases in building life cycle. BIM team could collaborate with design and construction team with the virtual modeling information. This virtual information were created, saved, transferred and improved on computer-aided software. But it has been difficult for BIM team collaborating with construction team because the site is complex and outdoor. It is unpractical to assist the construction process by taking the heavy devices to the site. So, this study was an attempt to realize the continuous utilization of BIM for the construction phase.

Through the literature review of toolkit of AR, scene graph rendering engine and BIM software, OSG, OSGART and REVIT were adopted for application development. ARAC was created for information assistance, construction simulation, and interaction with keyboard, mouse and hand. All functional components of ARAC were implemented in the SHUI CHUEN O project. The implementation results were analyzed. The light in one model could affect other models which were shown on different markers, even though these models were created in different software. This finding could be utilized for lighting analysis of buildings. It provides users the intuitive observation of building lighting. This AR framework could help project team on site to catch virtual building information in real time and get operation guide which updated coordinating to the process of construction.

6.2 Conclusion

6.2.1 Contributions

“Trying before building” approach was adopted by the Construction Virtual Prototyping Laboratory (CVPTL) in the Hong Kong Polytechnic University. Virtual information of architecture design, construction method and scheduling were created by the CVP approach. The Continuous usage of these digital information and analysis for construction stage were realized by the AR technology. There are several AR toolkits for research purposes. According to the situation of the construction industry, OSG was chosen as scene graph rendering engine and OSGART was chosen as toolkit for realizing the AR function.

ARAC was developed with multiple functional components and implemented in the practical project, namely SHUI CHUEN O project in Hong Kong. BIM information of this project was created with REVIT Architecture. At first, the preparation works were conducted. Setting up the programming environment in visual studio, building DLLs of OSGART and converting digital model format from REVIT to OSG were finished. Then ARAC was created with the tools of OSG and OSGART. The Text information could be displayed on construction site and checked by the users anytime and anywhere. In other words, ARAC could help users to obtain extra virtual information of building component, machines, resources and next operation steps. Moreover, users could freely manipulate the virtual models which were appeared in real environment. The value of BIM could be extended in the construction stage with the AR technologies.

6.2.2 Limitations

The ARAC applications were built as windows console projects. This means the executing information of these applications could be output on the console window. But the parameters, such as the marker pattern file and model file name, could not be input directly in the user interface. The parameters could only be set in the program by developers. The user interface provided scene graph viewer for displaying virtual models with properties. Although users could manipulate markers and models in real environment, they could not choose their expected BIM information directly on the user interface. So in the future works, all these AR applications would create as DLLs for building friendly interface. The user interface would enable user to set configurations of

the augmented scene graph more directly, rather than changing configurations in program by developers.

ARAC applications were tested in indoor environment and got the expected effects, while there were two problems happened when ARAC was implemented in the outdoor environment. When the traditional markers were used in the outdoor environment, the accuracy of marker identification would be reduced. The accuracy could be rising when the marker size is large, the distance between marker and camera is shot, and the camera has high configurations. When AR application was running in the dynamic outdoor environment such as the construction site, there may be machines or resources hide the marker from time to time. The tracking for marker would be unstable. So in future works, new method would be raised for poisoning and tracking more accurately. Because of the limitation of optical nature of the traditional marker, new technologies should be introduced, such as RFID and GPS. RFID uses electromagnetic wave and GPS uses satellite. They would be adopted for the accurate registration and tracking.

Table 7: Analyzing the limitations of makers adopted in this research.

Environment / marker / Identification accuracy	Fiducial marker	Marker created by marker generator from real photos
Indoor environment	High	High
Static outdoor environment	High (when marker size is large or distance between marker and camera is shot)	Medium (need large numbers of photos)
Dynamic outdoor environment (construction site)	High (when marker size is large or distance between marker and camera is shot); Difficult to set marker	Low (need much more numbers of photos than the static one)

6.3 Future research

After this phase of research, three potential research areas are worth studying. In summary, RFID could be introduced for more exact registration. Mobile devices such as smart phone could be used for more portable display. Gesture or color identification methods could be utilized for natural hand manipulation on virtual models.

6.3.1 RFID

(1) Brief introduction of RFID

Radio frequency identification (RFID) denotes technologies that use radio waves to identify people or objects carrying encoded microchips (New Oxford American Dictionary). AR+RFID Lab defined RFID as an automatic, wireless identification method using devices called RFID tags or transponders. An RFID tag can be attached to or incorporated into products, animals, or persons for the purpose of quick identification. RFID reader can obtain the information saved in RFID tags remotely, while the traditional barcode needs to be scan closely. When there are objects obstruct the optical communication between the label and scanner, barcode scanning would be interrupted.

(2) Choosing RFID tags

At present, there are three kinds of RFID tags: 1) Passive RFID tags have no battery and are driven by received electromagnetic wave which is sent by RFID reader nearby. Signal transmission is provoked by the reader. Then the information saved in tags is operated by the reader. 2) Semi-passive RFID tags have battery. The tags are inserted antenna which transmit signal back to the reader, leaving out of consideration of receiving electromagnetic wave. So it can improve the respond speed and efficiency. 3) Active RFID tags contain battery and can transmit signals autonomously. This kind of tags possesses read and write ability of longer distance. The tags have big memory capacity which can store information sent from the reader.

Because of the advantages and disadvantages of these three kinds of RFID tags, it is necessary to choose suitable ones according to the different working environments such as construction. The merits of passive RFID tags are long service life, low unit price, wide applicable frequency and extensive application fields. The demerits are passive tags are limited and restricted by local legislations strictly. The advantages of semi-passive and active RFID tags are long distance read and write abilities, easier permission by local legislations. They can also be used together with other sensors such as temperature, pressure and gas sensors. The disadvantages are high cost, short service life, and great environment influence of the battery. According to the respective merits and drawbacks, passive RFID tags could be chosen to use in construction phase on site. This kind of RFID tag could assist schedule arrangement and site layout, and also trigger the visualization of AR in the construction phase. Active RFID tags could be chosen for flow

monitoring in construction phase for materials and equipment and site planning with using GPS.

(3) Application in AEC industries

RFID is applied in the various fields of construction, such as quality inspection and management of concrete (Wang, 2007). Markers are suitable in applications indoor, while not enough for outdoor environment. In this research, as introduced in Chapter 5, two kinds of markers are used. One kind is the traditional fiducial marker and another one is marker converted by marker generator from real photos or pictures. Fiducial marker is printed on paper, so it is not suitable to use on the construction site. Although the converted marker can be identified in the outdoor environment, the accuracy of identification needs to be improved. Therefore, a new registration and identification method is conceived and hoped to develop in future works. In next section, mobile devices for AR applications are discussed.

Through the comparison and analysis among these methods of registration and tracking, fiducial marker is still one of the suitable methods in the indoor applications. Marker generated by relative generator is only applicable in photos with great gradation. While there are various and large number of building materials, machines and resources on site, it becomes difficult to create markers with clear gradation, especially in the sunny day. So this kind of marker is usually applied for indoor augmenting situations.

Therefore, in future studies new technologies of registration and tracking should be considered. The memory of RFID tag is limited, while the file size of virtual models of building are usually large. Even though the digital models could be converted to archive files by using “osgArchive”, the file size is still too large to be written into RFID tag. So tags are mainly used for poisoning, registering and tracking for models. Moreover, in robot fields, RFID is applied for calculating position of robot. So in future research, RFID could be utilized with fiduciary markers in AR applications for various phases of building life cycle, especially in the outdoor environment such as construction site.

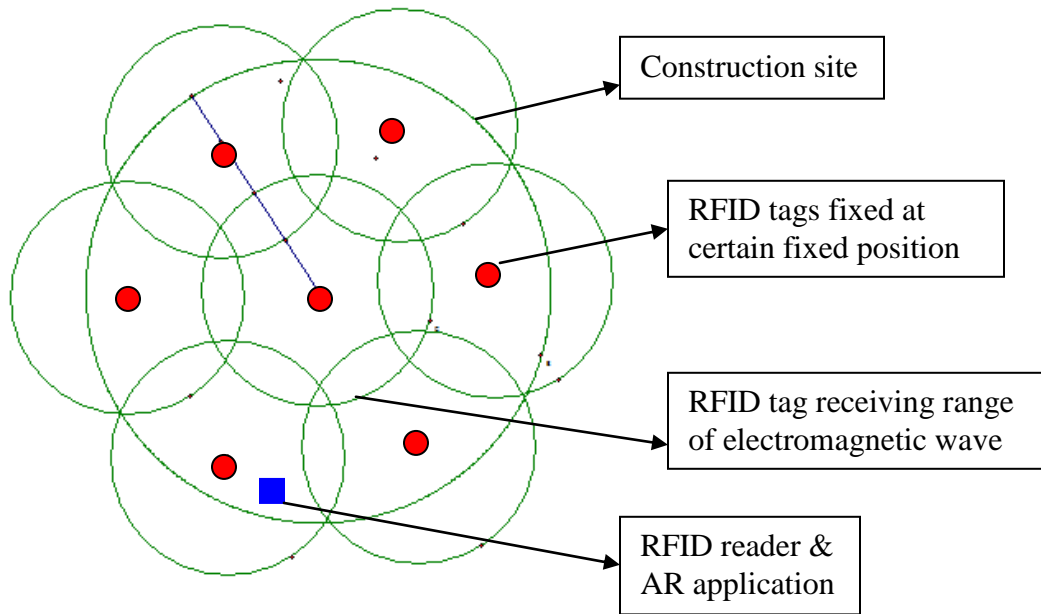


Figure 46: Setting RFID tags at fixed locations on site and receiving electromagnetic wave

A simple framework of RFID application with AR functions is shown in Figure 49. Several RFID tags are embedded at fixed positions on site. Relevant information, especially its position data, is rewritten into tag by RFID writer. In market some RFID readers are have the function of writers at the same time. The tag could receive

electromagnetic wave which covers the whole construction site. RFID reader could read multiple tags at the same time. Namely, RFID technology is used for positioning in AR application development.

6.3.2 Mobile Device

(1) Software

Firstly, OSGART libraries could be updated to the commercial version which provides much more high performance functions. As introduced in this thesis, ARToolKit is a software library which calculates the relative values of camera position and orientation to the marker in real time. ARToolKitPlus is extended from ARToolKit and focuses on handheld AR applications. From 2006 ARToolKitPlus was developed as a part of the Handheld AR project by Christian Doppler Laboratory at Graz University and has been succeeded by Studierstube Tracker.

In future works, Studierstube Tracker libraries could be used for AR mobile applications. It is a computer vision library which supports applications in PCs and mobile phones. Its memory requirements are very low and processing is very fast. Developers can extend Studierstube Tracker in any way. Its code base is highly portable as it does not depend on any external libraries. At present, it is conceived OSG and OSGART libraries could be used with Studierstube Tracker for mobile AR applications.

Moreover, two features of Studierstube Tracker are discussed here because they are helpful for the mobile AR applications on construction site. Firstly, there is no limits to video resolution, namely arbitrarily sized images can be identified and used for marker tracking. Images with 8 megapixels were successfully tested. Another important feature is Studierstube Supports for MATLAB camera calibration toolbox which is powerful in the area of image recognition. It means photos shot from construction site can be used for markers. In Chapter 5, the marker generated by ARToolKit marker generator from photo of construction site was difficult to be identified. Studierstube Tracker is helpful for converting site image to marker with great gradation. In the situation of using RFID for tracking, RFID tag may not receive electromagnetic waves if it is far away from the user who carried the RFID reader. So the ability of identification and tracking to complex construction site can solve this problem.

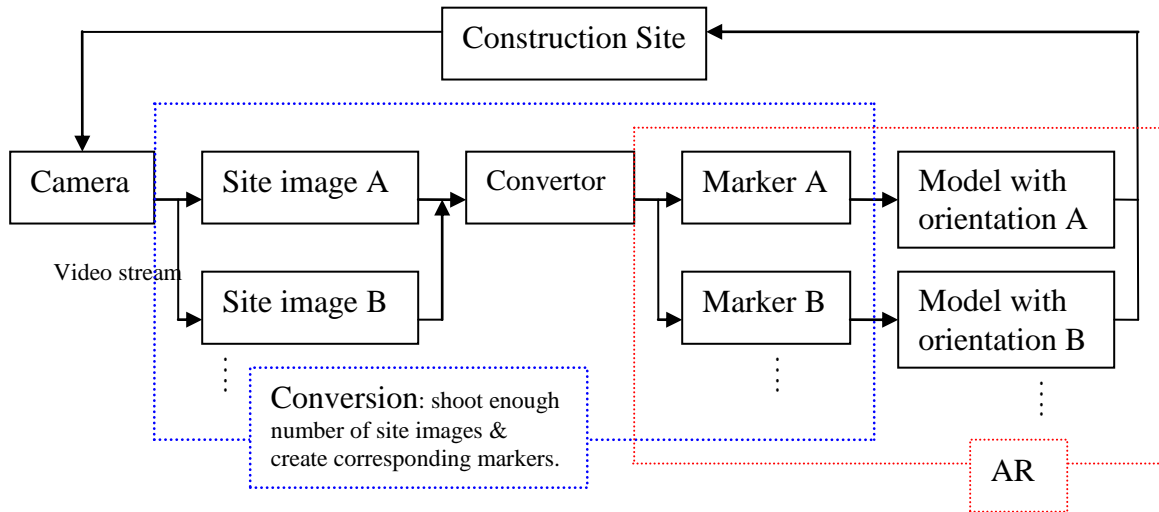


Figure 47: AR application development with Studierstube Tracker for construction scene tracking and model display in correct position and orientation.

(2) Hardware

Mobile devices would be adopted for displaying augmented environment. Laptop is still not light and mobile enough in the outdoor environment, especially on construction site. Because Studierstube Tracker can run on several platforms: windows XP, Windows CE, Windows Mobile, Symbian, Linux, MacOS and iPhone. So in future works, Windows Mobile and iPhone platforms would be chosen for the AR development. Applications would be developed with OSG, OSGART and Studierstube and run on mobile devices.

6.4 Concluding Remarks

In this research, the utilization situation of BIM information on construction site was analyzed. There has been a break of using BIM information in the building life cycle. Virtual information of the project was used during architecture design, construction planning and facility management, except for the project construction phase. So concepts and technologies of AR were introduced for continuous utilization of BIM information. ARAC was developed for information assistance and operation guidance, construction simulation, interaction with hand, and multiple model displaying. ARAC was developed with libraries of OSG and OSGART. All the functional components of ARAC were implemented with virtual models of SHUI CHUEN O project. ARAC realized the continuous utilization of BIM information from construction planning to facility management. Namely, it provides a new visualization method for project teams on construction site. Users on site could check 3D and 4D virtual information, such as virtual models, geometry of building component, operation process simulation. All the

needed BIM information could be loaded from ARAC with no delay, displayed on construction site with high-performance rendering effects, and integrated accurately with real environment and tracked consecutively by the moving users.

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