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Construction Project Control in Virtual Reality: A Case Study

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Abstract: The construction process is a very complex undertaking. Achieving an effective control for the construction project is very difficult. A Virtual Construction Project Control System (VCPCS) is presented in this study and applied to a practical construction project in Shanghai, China, say, Chia-Tai Mall. VCPCS is the first Virtual Reality (VR) system for a large-scale real construction project in China. In the system, various execution strategies of Chia-Tai Mall construction are tested and the optimal construction plan is obtained. This optimal construction plan does not only ensure the construction duration the shortest, but also reduces the cost significantly for the contractors. Moreover, VCPCS also is very helpful for reasonably arranging human, material and financial resource as the need of construction schedule and effectively managing the construction site. The proposed VCPCS will enable the project team to undertake inexpensive rehearsals of major construction process and test various execution strategies in a near reality sense, prior to the actual start of construction. Therefore, some irrational steps in the original construction intents are found out and revised, until the field technicians expertly gain mastery to the optimal construction plan. Thus, VCPCS reduces the construction risk and ensures the safety of the field construction.

Key words: Virtual reality, construction project control, project duration, construction quality, project cost

INTRODUCTION

A project was defined as (Turner, 1993): an endeavour in which human, material and financial resources are organized in a novel way, to undertake a unique scope of work, of given specification, within constraints of cost and time, so as to achieve beneficial change defined by quantitative and qualitative objectives.

Construction project control may be considered one of the most complex undertaking in industry (Bennet, 1991). A project, especially for construction project, has three essential features (Turner, 2003). Firstly, it is unique: no project before or after will be exactly the same. Secondly, it is undertaken using novel processes: no project before or after will use exactly the same approach. Finally, it is transient: it has a beginning and an end. Construction projects are usually performed in a changing environment by many different types of works. Controlling the construction project has a great deal of uncertainty and is subject to the influence of urgent events. Therefore, achieving effective control for the construction project is very difficult.

To achieve effective control of construction projects, a great deal of studies have been carried out. For example, Dvir *et al*. (2003) suggested that project success is insensitive to the level of implementation of control processes and procedures, which are readily supported by modern computerized tools and project management training. Hameri and Puittien (2003) used WWW-based technologies to improve projects' efficiency and success rate through improving project organizations to manage their knowledge. Al-Jibouri (2002) studied the problem of resource scheduling within given resource constraints on a sectionalized construction project. It has been found that the scheduling is very effective in the case of section management with co-operation between the sections. Abudayyeh *et al.* (2001) described the design and implementation of an Intranet-based cost control system by utilizing the internet as a mechanism for communicating project control data and information.

In the construction project, particular control have has to be conducted to ensure the whole construction process to be performed harmonically and continuously. Traditional computational methods and tools have some difficulties in dealing with large amount of construction information exactly and in time and cannot realize effective control. However, VR technology provides a useful way for effectively control the construction project.

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Virtual Reality (VR) has emerged as one of the most significant technologies during the last century. From its beginning in university computer laboratories almost 30 years ago, VR field has matured to commercialization within the past few years. The first head-mounted display was demonstrated in the 1960's (Sutherland, 1965, 1968) and in the mid-1970's, Myron Krueger performed the first experiments on what he defined artificial reality. The term Virtual Reality is credited to Jaron Lanier, who coined it in the early of 1990's (Machover and Tice, 1994). Computer scientists created a virtual environment using an interactive visual display that makes user feel as if they were immersed in a synthetic space (Ellis, 1994; Rosenblum *et al.*, 1995). Virtual reality is a combination of previously technologies, such as computer graphics, computer simulation, artificial intelligence and multimedia. Generally speaking, virtual reality offers the opportunity to create virtual environments where a large number of physical variables that influence our behavior can be controlled precisely and simultaneously. Furthermore, in a virtual environment we can record our motor response and use them to interact with and manipulate the same environment.

Ahmed and Walid (2003) presents a framework for a new planning approach that will utilize Virtual Reality (VR) modeling technologies coupled with object-oriented technologies to develop an integrated virtual planning tool called Virtual Construction Environment (VCE). The proposed VCE will enable the project team to undertake inexpensive rehearsals of major construction processes and test various execution strategies in a near reality sense, prior to the actual start of construction.

It is very important to help the technicians to find out situations interfering the construction process and to develop tactics for solving them. VR provides an ideal environment to do those works and train technicians for the construction industry. Saying VR ideal just has the following reasons:

- Virtual reality is fully interactive, where the operators decide what will be done next and how. VR requires the operators to act and react and all objects in VR could be easily understood.
- Virtual reality is unique in its emphasis on the experience of the human participant. VR focuses the operators' attention on the experience while suspending disbelief about the method of creating it.
- Operators interact with virtual reality in the way they would with the real world. Special skills do not have to be learned for operating the computer.
- Virtual reality provides an exciting and stimulating tool for training.
- VR can be performed repeatedly. Therefore, the error or collisions can be easily corrected till an optimal scheme is realized.

Except these, many valuable works for construction control have been introduced in the literatures. For instance, Parkinson and Hudson (2002) identified the problems associated with making adequate educational provision to enable the effective teaching and learning of a complex subject such as design, within the restrictive educational environment of virtual reality. Caneparo (2001) applied Shared Virtual Reality (SVR) to architectural and urban design for a large-scale project. Gardiner and Ritchier (1999) considered the emerging technology of virtual reality (VR) as a tool to help manage and make sense of complex management information systems. (Shelbourn *et al.*, 2001) presented a case study of how to use VR technology in a laboratory environment to train industrialists and students to use integrated systems. Duffy (2000) provided a connection between the lessons learned in concurrent engineering in manufacturing industries with applications to risk management training in the service industries. Many other researchers are making their devotions to utilize VR technology to the construction engineering (Shapira and Laufer, 1993; Sawacha *et al.*, 1999; Whyte *et al.*, 2000; Retik, 1996; Kunii and Retik, 1997; Bourdakis, 1997; Aouad *et al.*, 1997).

In this study Virtual Construction Project Control System (VCPCS) for Chia-Tai Mall construction is presented. This is the first VR system for a large-scale real-life construction project in China. The objectives and difficulties of Chia-Tai-Mall construction are proposed. This study also introduced the framework and the implementations of VCPCS. The optimal construction plan selected from various construction strategies is carried out by testing in VCPCS. The optimal construction plan shortened the construction duration and reduced the construction cost for the contractors. VCPCS is useful for the technicians of the construction site to arrange human, material and financial resource effectively and to expertly gain mastery to the optimal construction plan by training in virtual environment. In VCPCS, some collisions that would happen as the original construction intents are found out and revised. In practical construction, the optimal construction plan is employed and the whole construction process is completed with no collision. Effective control for Chai-Tai Mall construction is realized.

Introduction of Chia-Tai Mall: Chia-Tai Mall is located in Shanghai, China. This building is a frame structure with 10 floors, in which reinforced concrete is employed from 1st to 7th floor, while prefabricated-steel from

8th-10th floor. The steel components come up to more than 3000 in number and weigh up to 5600 tons. According to the contract, all steel components have to be installed in only 85 days. $40,000 per day will be fined for delay of construction.

Steel components employed in this project include four major parts:

- Steel frames: The frames consist of columns, girders and ribs.
- Steel skylights: Three skylights are designed in this building-east skylight, west skylight and arc skylight of central section. Mast cranes are used to hoist this part of components and tower cranes are used as transitional tools.
- Steel stairways: There are 15 steel stairs in this building. The mast cranes are used to hoist this part.
- Steel over bridges: Two usefulness over bridges are emplaced over the central patio of this building. Seven horizontal over bridges are built for walking. Other three are for business. The shape of the over bridge girder is trunk in cross section. Mast crane hoist this part of components and tower cranes are used as transitional tools. The largest girder span of business over bridge comes up to 33 m and the weight of the heaviest one comes up to 48 tons.

The Chia-Tai Mall construction takes have particular features:

- The operation conditions would be very poor. Some activities would be performed high above the ground and others would be taken under the ground.
- Multiple types of activities must be performed cooperatively and spatially cross each other.
- Material supply, labor force arrangement and other changes easily take place on the construction site.
- All of activities are usually expected to complete in the shortest duration.

The Chia-Tai Mall construction not only takes so many components to be hoisted in just 85 days, but also has very complicated construction environment. So, it is very difficult to achieve an effective control for the project.

Objectives of project control: Project control is the application of knowledge, technologies, skills and tools to project activities in order to satisfy the contractors' requirements and expectations. Control also includes taking preventive action in anticipation of possible problems. The objective of construction project control includes schedule control, quality control, cost control, risk control and so on. It is almost an axiomatic of construction control that a project may be regarded as successful if the project is completed on time, within budget, without any accidents, up to the specific quality standards and investors' satisfaction.

Project schedule would be influenced by many factors. The contractors' attitude to the project duration is an issue of principle. Therefore, contractors' expectation to the project duration needs to be clear. As usual, to the contractors the shorter project duration the better. Construction duration is increasingly important because it often serves as a crucial benchmark for accessing the performance of a project and the efficiency of the project organization. Project delays can lead to the project cost overruns as well. Thus, to the construction project managers should pay more attention to the schedule control. Especially to the large-scale project, schedule usually is a critical factor among the control objectives.

Achievement of acceptable levels of quality in the construction industry has long been a problem. According to an ASCE study (Ferguson and Clayton, 1998), quality can be defined as meeting the requirements of the designer, constructor and the regulatory agencies as well as the owner in construction industry. Quality control is the foundation of quality assurance. The construction quality is influenced by some factors, such as project cost, schedule, operating characteristics, etc.

The application of ideas from control theory is easy and obvious when applied to a particular object such as cost control. Cost control is an activity that compares cost performance against the cost plan, adjusting them dynamically by reference to the changing circumstances in the project. It is related to the essential benefit of the contractors.

Risk is the possibility that events, their resulting impacts and dynamic interactions may turn out differently than anticipated. Construction projects are high-risk games characterized by substantial irreversible commitments and high probabilities of failure. Risk control is thus a real issue. In risk control of a construction project, construction safety is one of the most important objectives.

To Chia-Tai Mall construction, schedule control is a critical factor in the project control objectives. Because schedule delay not only lead to the project cost overruns, but also makes the contractor to be heavily penalized. To control the project schedule effectively, determining the optimal hoisting sequence of components and the working path of the cranes is the critical points. After obtained correct hoisting sequence of components and the working path of the cranes, the duration can be shortened and the hoisting can be performed safely and smoothly. The purpose of reducing project cost and construction risk can thus be reached. Thereby, the project can be controlled effectively.

However, there are some difficulties in effectively controlling the schedule of this project. For example, all steel components have to be hoisted high above the ground. Collisions easily occur among the components, the tower cranes, the mast cranes and the crane cables.

Because of the influence of various factors, it is considerably difficult to implement effective control for the construction project. When the construction scheme is being framed, some factors could not be forecasted which would interfere the construction process and preventive action can not be taken. For instance, multi-equipments would work and multi-activities would be performed synchronously at a large-scale construction site. According to the traditional way, it is very difficult not only to harmonize the time relationship of activities, but also to exactly express the spatial relationship of equipments and components. This is not in favor of project control, so much as to impact the engineering safety.

For instance, the over bridge girders and the components of the skylights would be placed in the patio. The mast cranes to hoist them would be also contemporarily installed in the patio. So, at the time of hoisting them, collision would easily occur. It is difficult to complete the construction without thorough plan.

The construction would progress successfully unless the effective control plan is taken. Determining the correct hoisting sequence is very important. If it is not correct, it is possible that some of the components could not be placed on their designed-position for the sake of the narrow space.

If the collision occurred, a serial of problems would happen. After the collision occurs, it takes time to solve those problems. The schedule of the actives must be influenced and the project duration might be delayed. On the other hand, substantive human resource and material have to be collected to deal with it that will cost a lot. Undoubtedly, these factors will raise the project budget. Moreover, collision may destroy some components and cause some accidents. If the damage degree is not serious, it is not easy to be identified, which may cause some potential imperfections in construction quality and safety, even makes the project out of control. So, in the hoisting of this project, collision should be avoided. Only these issues solved, the effective control of the project could be achieved.

VCPCS framework: The VCPCS framework consists of two main parts: a Virtual Interactive Interface (VII) and a set of Technician-Aid Modules (TAM). Control decisions developed by the technicians are based on a dynamic interaction between the technicians and these two parts during the interactive virtual sessions.

Virtual interactive interface (VII): The VII is a dynamic virtual setting that will allow the technicians to rehearse constructing the facility in a near reality sense. The virtual rehearsals will be based on manipulating the components and cranes models. While navigating and interacting with these models, the technicians will be able to analyze project constraints and test various execution sequences and methods. These models are object-oriented and data-driven. Information can be represented in an object-oriented modeling environment due to its prominent characteristics in data representation, such as geometry, component type, physical and material characteristics and so on. The core of the VII module is a reconstruction window. Within this window, technicians can reconstruct the facility by bringing components together in the perceived order of execution. The construction steps can be selected and attached to each assembly. Construction intent can be reviewed and questions can be posed to the technicians on potential changes. As the technicians construct the facility, each step will be recorded to capture their thinking process on what methods will be used and the order in which the assemblies will be constructed. Construction steps recorded during the virtual sessions can be retrieved for further modifications/review by other technicians, either independently or collaboratively. The VII will also allow technicians to perform space and accessibility collision detection the operations. This will be achieved using a set of objected-oriented graphical libraries. Additional site information and activities, such as site conditions, temporary facilities and so on can also be modeled to support the virtual construction process.

Technician-aid modules (TAM): Technician-Aid Modules (TAM) are developed to provide the technicians with necessary support information for the project control. It will consist of three main parts: databases, Structured Information Module (SIM) and Assistant Information Processor (AIP), which will be described as follows.

The TAM includes different databases that enable storing and retrieving required information. These databases include the construction strategies, alternative means and methods and resources. Each assembly in the 3D model is attached to a record in the database.

The SIM consists of graphical and non-graphical information. Graphical information is associated with the 3D objects in the CAD environment. This type of information benefits from the use of the object-oriented technology, that enables information organization into objects that directly symbolize the entities in the real world. The technicians envision this information by directly manipulating the 3D object in the VCPCS. For example, by manipulating the 3D object representing a piece of mast crane, the technicians may extract information such as the productivity of the crane (e.g., maximum capacity and maximum lifting height). Non-graphical information is textual information not directly associated with the 3D objects of the models.

The third part of TAM is the Assistant Information Processor (AIP). The IPA allows for capturing user input, processing project data, extracting and filtering user requests for information and feedback. An assemblies sequencing procedure will capture and record the users movement and manipulation of the 3D objects to create the logical relationships of the assemblies.

Implementation of the project

Critical techniques

Modeling: For different objects, three kinds of modeling approaches might be adopted for the construction industry (Gardiner and Ritchier, 1999; Ellis, 1994) these are to build a library of standard parts, to rely on imperfect model conversion through translators and to use VR as an interface to a central database. The usefulness of these modeling methods has been demonstrated in some real-life construction projects (Mohamed and Stewart, 2003; Al-Jibouri, 2002; Kumi and Retik, 1997; Bordakis, 1997).

For simulating the construction process, these modeling approaches might be adopted. For instance, if there are some floors that have same outlines in a building, Boolean operation or solid extrusion can be used to produce a floor whose outlines were picked up from two-dimensional graph. And then, modeling will be quickly realized by using coordinate transformation and spatial array. The floors, columns and beams could be modeled in this manner.

Motion simulation: In virtual reality, movements are usually described by geometrical transformation such as shift and rotation. After getting parametric model, motion picture will be produced by interpolating parameters. Numerical interpolation approaches are useful in motion simulation. Through numerical interpolation, movement will be factually simulated and the requirement of computational ability to the system will be reduced. Complex computation will be avoided if simple interpolation approaches are found. The nonlinear movement of components could be controlled by numerical interpolation, such as quadratic interpolation, cubic interpolation and Hermit interpolation.

Construction plan optimization: Virtual construction tests are applied to the initial construction program. Some collisions are detected and effective actions for solving collision are taken. The construction plan is then optimized in terms of following aspects:

Optimization of the arrangement of crane cables: Virtual hoisting site is shown as Fig. 1. Because the mast cranes work high above the ground in narrow working space, collision likely occurs. By means of virtual simulation, collision between components and the crane cables will be easily detected for the collided parts will change their own color automatically. Thus, the arrangement of the crane cables will be adjusted by trial until the satisfactory results are acquired. In the initial plan, when hoisting the curving girder by the mast crane B', collision occurs between the secondary mast and the crane cable, as Fig. 2 shows. With virtual tests, this problem is solved through adjusting the anchor positions of the cables.

Optimization of the hoisting plan of west skylight: In the original plan, the plinth height of the mast crane A' is 35 m. According to this plan, the rooftree cannot be installed because the collision will occur between the bracket beam and the secondary mast of the crane, as Fig. 3 shows by means of virtual simulation, the collision doesn't exist by raising the plinth height of the mast crane A' to 40 m.

Optimization of the hoisting plan of west arc girder: Arc girder will be hoisted horizontally in the original plan. Collision occurs between the girder and the secondary mast, as Fig. 4 shows. With aid of virtual simulation, the arc girder to be inclined from horizontal changes to 18° and collision is avoided.

Optimization of the hoisting plan of the central over bridge: In the original plan, the length of the secondary mast of the mast crane C' is 17 m. The walking over bridge will be installed before hoisting the central over bridge girder. When hoisting the central over bridge girder, collision occurs between the central over bridge girder and the walking over bridge, as Fig. 5 shows, Collision is avoided by lengthening the secondary mast to 22 m, through virtual simulation presented in the study.

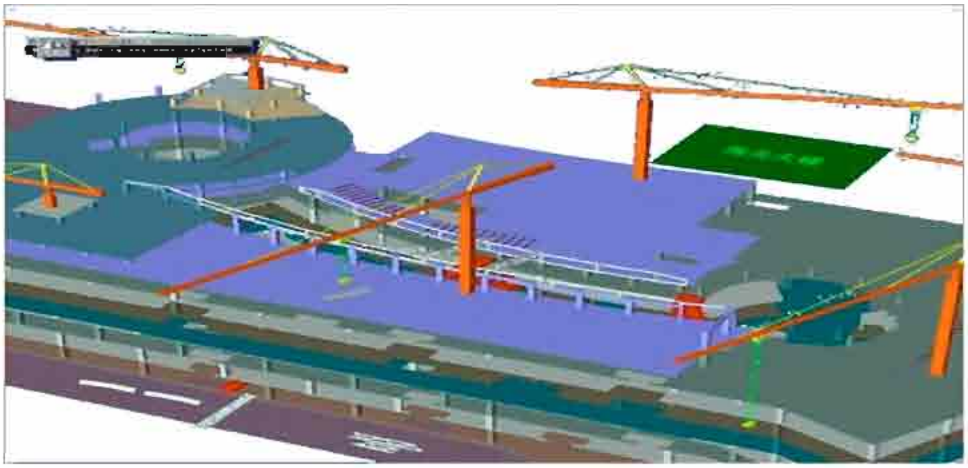

Fig. 1: Virtual hoisting site

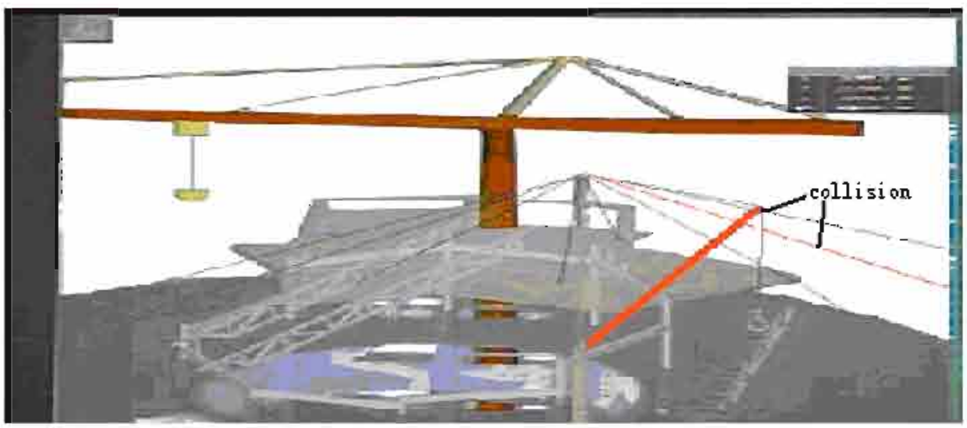

Fig. 2: Collision occurred between the secondary mast and the cable

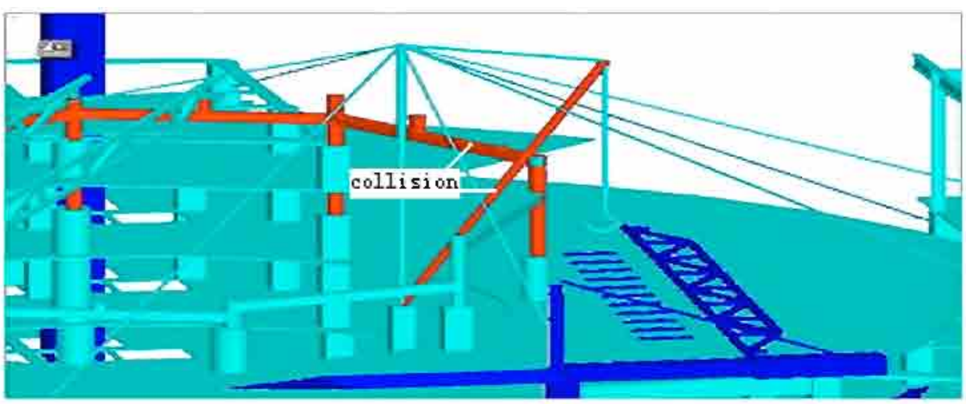

Fig. 3: Collision occurred between the bracket beam and the secondary mast of the crane

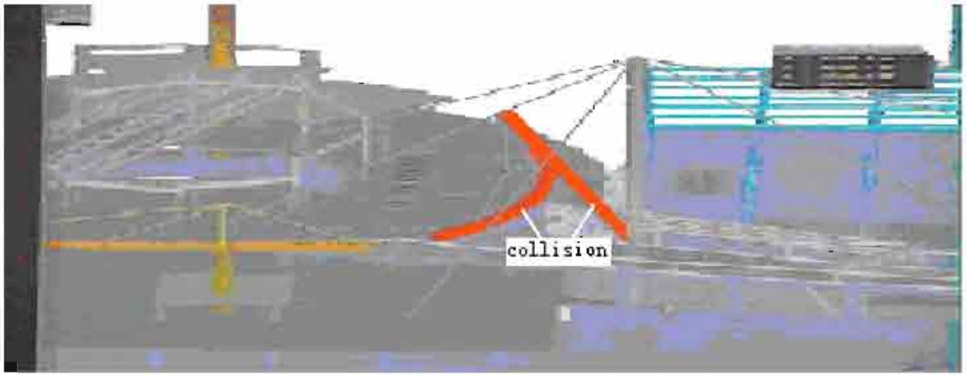

Fig. 4: Collision occurred between the girder and the secondary mast

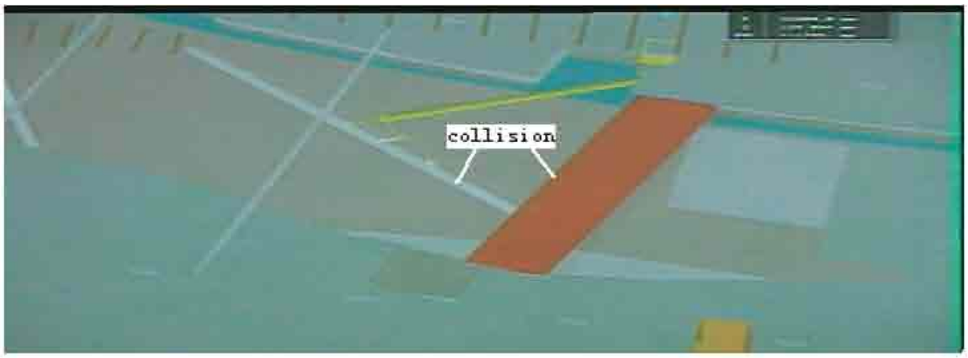

Fig. 5: Collision occurred between the girder of central over bridge and the walking over bridge

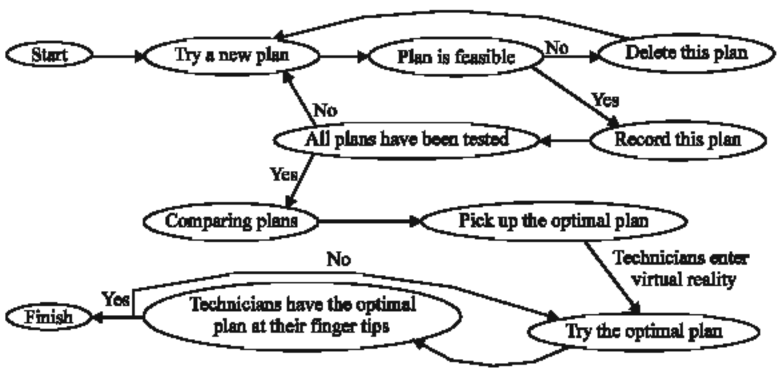

Fig. 6: Construction training program in virtual reality

On the whole, no collision occurs in the practical construction by using the optimal construction plan obtained from virtual simulation technique.

All of the works above are propitious to the project control. Avoiding collisions can make the construction to be performed smoothly. A lot of time could be saved that would otherwise be used to deal with the collisions in the construction site. The project duration and cost would be reduced.

VR-based training: The efficiency and the safety performance of the construction could be achieved by training the technicians in an effective way. Training technicians for construction project is based upon the steps as showing in Fig. 6. After entering the VR environment, the technician starts to perform the construction steps according to the manuscript plan. If the collision occurs or the activity duration is longer than the maximum that the investors demand, the construction intent will be modified. By virtual testing in VCPCS, some feasible plans are produced. An optimal plan is picked out according to the results of comprehensively considering the cost, schedule, quality, safety performance and other factors. All technicians of the construction site enter the virtual environment to examine the optimal plan again and again until they are adequately cognizant of various problems that would be met in real construction and thereby expertly gain mastery of the construction plan.

Project control: In VCPCS, various construction plans are verified repeatedly. Some unfeasible construction intents are exorcized. The optimal construction plan is obtained according to the results of balancing the relationship of schedule, quality, cost and risk. VCPCS also provides an ideal training environment to the field technicians.

VCPCS improved the construction efficiency, enhanced the safety performance level, shortened the construction duration and reduced the construction cost.

CONCLUSIONS

Applying VR technology to the construction project, not only are the manuscript construction intents rectified and optimized, but also can technicians immerse into virtual environment and adjust every detail of the construction steps to gain experience they need to finish their tasks effectively. All of these are favor of implementing effective control to the construction project. VR really is an ideal tool for the construction industry.

VCPCS presented in this study is the first application of VR system to a large-scale practical construction project in China. In VCPCS, various construction intents are tested and the optimal construction plan is obtained. VCPCS also provides an ideal for construction training to the field technicians.

Chia-Tai Mall construction has been finished. The optimal construction plan is verified in real life construction. In practical construction, all construction steps are performed exactly. No collision occurs. Construction schedule is content with contractor's demand, because the construction duration is controlled according to the result of simulating the optimal construction plan in VCPCS. The technicians complete all works effectively for they have gained enough experience in virtual environment. VCPCS takes immense economic profits to the contractor. The effective control for Chia-Tai Mall construction realized.

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