In this paper, the virtually real construction model (component and process) of the Hong Kong Housing Authority standard block, specifically developed functions of the virtual reality application and the role of Design-For-Safety-Process are discussed. The benefits of design using virtual reality are then discussed followed by a review of the overall concept of the construction model, the virtual reality functions and the role of DFSP. The rest of the paper discusses the concepts used to build the virtually real construction model universe.

2. IMPROVING CONSTRUCTION DESIGN USING VIRTUAL REALITY (VR)

With today's technology, developing visualisation applications is not a serious problem in terms of technology and cost. Research into visualisation in construction has included safety training (Hadipriono and Larew, 1996), generating construction plan (Faraj and Alshawi, 1996) and visualizing construction components and processes (Adjei-Kumi and Retik, 1997). In the construction domain, VR offers advantages as follow:

- Reducing end user's effort and task to transfer by imagination the 2D data from the bulky construction drawings to a 3D mental picture of a project.
- Integrating information from different project participants (architect, structural engineer and M/E) into one universe. This can detect incomplete and ambiguous design information prior to the construction stage.
- Facilitating a user with a virtual walkthrough in which he can check any corner and location of the virtual project at a controllable distance and speed.

Since VR has benefits as described, a research question is posed, can virtual reality be used to improve the design contents in terms of a Design-For-Safety-Process?

3. THE OVERALL INTEGRATED MODEL

The overall model consists of the virtually real construction model (construction components and processes) and DFSP (see figure 1).

An interface is needed to integrate the virtually real construction model developed in World Up[TM] and the DFSP developed in Visual Basic. This integration is possible since both software support active-x technology.

3.1 Model Development Phases

The overall model implementation is divided into three phases. Phase one is the development of virtually real construction components. Phase two is the development of virtually real construction processes. Finally, phase three is the development of DFSP. At the time this paper is written, phase one has been completed.

3.2 Model Scenario

A user can perform a virtual walkthrough to assess the virtually real Hong Kong Housing Authority standard block construction components and processes.

For the purpose of the virtual walkthrough to assess the construction components, processes and DFSP, three virtual reality functions, collision detection, terrain following and pick geometry, developed in World Up[TM] are used.
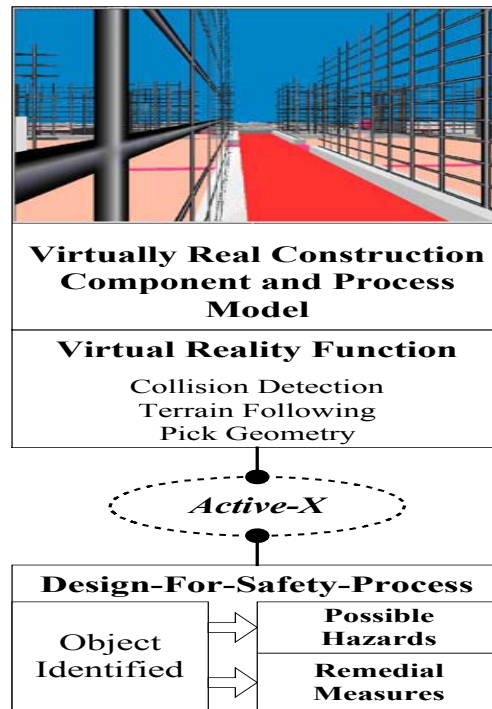

| Virtually Real Construction Component and Process Model |
| Virtual Reality Function |
| Collision Detection
Terrain Following
Pick Geometry |

Active-X

Design-For-Safety-Process		
Object Identified	→	Possible Hazards
	→	Remedial Measures

Figure 1. The Overall Model of Virtually Real Construction Model and DFSP.

3.2.1 Collision Detection

Collision detection enables the system to detect whether a collision has occurred between two objects. The collision is detected if the object bounding box collides with another object bounding box.
In this overall model, collision detection facilitates a better real walkthrough environment since the user is not allowed to walk into an object modeled, such as a wall. Also, it alerts the user if he is struck by a moving object, such as an object being transported.

3.2.2 Terrain Following

Terrain following facilitates the user to walk following a terrain provided such as a floor level. This terrain following has two benefits:
Providing the user the ability to maintain his walking plane.
Providing a fall mechanism due to different levels of terrain. This enables a fall related to height mechanism if the safety plan has not been implemented properly, e.g. an uncovered open slab.

3.2.3 Geometry Picking

Geometry picking is used to select an object in the virtually real construction project by pointing the mouse at the construction component intended. The selected object, construction component, is needed to trigger the DFSP database.

3.2.4 Design-For-Safety-Process

General Electric developed guidelines for product design in the 1960s, but a significant benefit was not realised until systematic Design for Assembly (DFA) was introduced in the 1970s. Other design for 'something's; such as manufacturability, inspectability and quality; were developed in the 1980s. Then, in 1990s, DFX has been used as an umbrella for all of these terms.

The potential of DFX is enhanced by the availability of a powerful representation tool such as virtual reality, where design can be represented in three-dimensional graphical data and a walkthrough function enabling the user to discuss any aspect of the object in a virtually real location.

Virtual reality of components and processes of a construction project will be used to develop a Design-For-Safety-Process (DFSP) methodology which aims to point out the safety hazards inherited by the construction components and activities.

The main idea of DFSP is derived from Design for X-ability (DFX). DFX aims to design a product from many viewpoints or characteristics (Gutwald in Prasad, 1996) with the following benefits:

- Achieving a product exhibiting better qualities of X, i.e. Design for Manufacturability (DFM), Design for Assembly (DFA), Design for Disassembly, Design for Quality and Design for Environment.
- Early failure detection.

Since DFX is an umbrella, the methodology development depends on the specific domain of x-ability developed. For example, Design for Manufacturability is designed by utilising theories, such as the Taguchi method, and design axioms. However, The most important consideration is that DFX must work as a guideline to evaluate the design. This can be achieved by developing the DFX as an online or offline purpose (Huang, 1996). An online DFX checks its data/knowledge base to ensure that the design decision being considered will not violate the DFX rules. On the other hand, an offline DFX evaluates design decisions after they are made.

In this research, DFSP will be used as online guideline. Contents of the guidelines are compiled from a theory and an axiom. Adams's theory of accident causation (Adams, 1976) is proposed since it consists of a tangible approach compared to other accident theories. The idea of using Adams theory is to obtain better safety guidelines since Adams theory mentions unsafe conditions which trigger occurrence of accidents. The axiom is compiled from safety regulations and safety best practice. The safety regulations and safety best practice will also be used to compile the most common unsafe conditions. In addition, this axiom is also used to compile the knowledge of what remedial measures are needed in order to prevent the occurrence of accidents.

A mechanism of hazard recognition, geometry/object picking, possible hazard information and remedial measures recommended by the safety guidelines can be seen in figure 2.
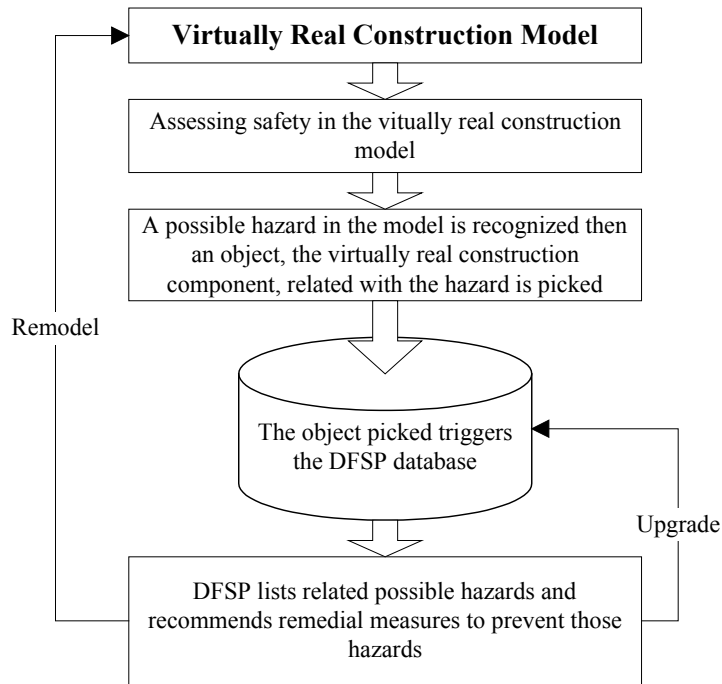
Figure 2. Hazards Recognition and DFSP Mechanism

4. CONSTRUCTING THE VIRTUAL REAL CONSTRUCTION MODEL

The virtual real construction model is developed using World Up™, a virtual reality software by Sense 8 Corporation. The construction components are constructed using primitive geometries, such as block, sphere and cylinder, and imported object created from 3D-modeller software, 3D Studio Max™.

After the creation of construction components (phase one), the next phase is the modelling of construction processes. At this phase, the concept of countering is used as a simulation engine so that the virtually real construction model can mimic the construction process of the actual world.

4.1 Reusing of Object in a Universe Development

The nature of typical building construction projects, having similar construction components, provides benefits in the development of a universe in terms of reusing one object to create other similar objects. Reusing of building construction objects in World Up™ exists in several conditions:

Reusing objects for different locations. In construction, no two similar components occupy the same location, i.e. two walls with the same size are installed at different positions. The reusability of an object depends on the type of object source itself.

If the object source is a simple object created using World Up™, such as a sphere, block or cylinder, a subclass representing the object can be created and used to create many similar objects with similar properties. The value of 'translation' property can be modified to place the duplicate object in the location desired.

If the object source is created by World Up™ modeller or a third party modeller, the object source can be reused by adding it to the universe through the 'resource browser'.

Reusing objects with different dimensions. Construction components can be created by using primitive geometry, i.e. columns and beams can be created using the block, primitive geometry. The block geometry object source can be stored as one unit of length, width and depth. This one unit object source is used in the universe as a column by stretching the length, width and depth. Several columns can be created by using this object source, however, modifying the value of the stretch property of any column, for example, also changes the other columns from the same object source, the siblings. For example, in order to create a column from the same object source and also with an independent length, width and depth control, the new column must be assigned as a 'ForkImported' object, a function of World Up™.


4.2 Simulating the Construction Process

Adjei-Kumi and Retik (1997) noted that present planning systems, which use CAD technology to generate and simulate the process of constructing a facility graphically, only go as far as the visualisation of project schedules at the component level. They proposed to visualise the construction components and processes in Provysis. That visualisation of construction processes, however, does not mimic the real processes of a construction project. Provysis only fades in the construction component assumed to be constructed and fades out the successor components, instead of showing how the object/component is transported and installed.

Bick et al. (1998) developed a visualisation system in the manufacturing domain. In this system, the simulation supports object translation from one location to another location in a specified time. The translation of the object is determined by using origin and destination of object location while time control is achieved by specifying when the process takes place, t_{start} and t_{end}.

In the real world, location and time are the most important variables, in order to represent a dynamic environment. Changing the value of these variables determines where the object will move in terms of location and how long the movement is in terms of time.

These two variables are also important for the purpose of simulating the virtually real construction process. The most basic construction process is translation and rotation of an object. Other processes such as installing and removing an object can be derived from the concept of object translation and rotation. For example, installing a prefabricated wall can be simulated as translation from the stockpile location to the destination location.

In order to transport an object from the origin location to the destination location in a specified time, four user variables - *origin of location, destination of location, starting time to move and duration of translating* - must be defined. Origin of location and destination of location are user defined properties that can be represented as x_0, y_0, z_0, x_t, y_t and z_t. The object moves by changing the value of its translation properties from x_0, y_0, z_0 to x_t, y_t, z_t (figure 3). The duration for transporting is used to display a smooth movement of the object instead of leaping from one location to another location.
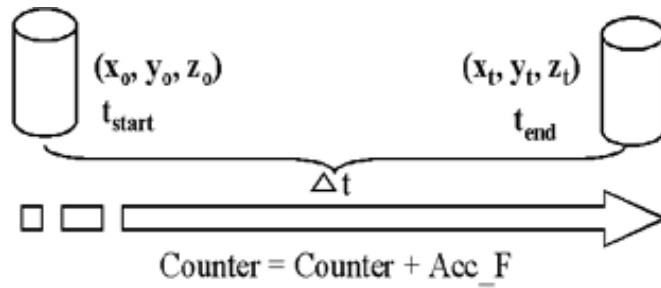
•Origin and Destination of an object location: (x_o, y_o, z_o) and (x_t, y_t, z_t)

•Countering system: Counter = Counter + Acc_F

•Start time to move (t_0) and end time to move (t_{end}).

Figure 3. Object Translation Mechanism

A more complex translation can be achieved by increasing the number of location user-defined properties, such as origin of location (x_0,y_0,z_0), middle of location (x_1,y_1,z_1) and destination of location (x_2,y_2,z_2). This method creates two phases of movement, from the origin to the middle (phase one) and the middle to the destination (phase two). Since this method creates two phases of movement, the duration of object translation must be distributed linearly in order to achieve a constant speed of translation (see figure 4).

$$\text{Distance Phase 1 (D1)} = ((x1-xo)^2 + (y1-yo)^2 + (z1-zo)^2)^{0.5}$$
$$\text{Distance Phase 2 (D2)} = ((x2-x1)^2 + (y2-y1)^2 + (z2-z1)^2)^{0.5}$$
$$\text{Total Distance (Dtotal)} = D1 + D2$$

$$\text{Duration of Transporting} = \text{Ttotal} = \text{ObjCtr}$$

$$\text{Phase 1 Duration (TD1)} = (D1/Dtotal) * \text{ObjCtr}$$
$$\text{Phase 2 Duration (TD2)} = (D2/Dtotal) * \text{ObjCtr}$$

Figure 4. Linear Distribution of Translation Duration

4.3 Countering System as a Simulation Engine

In World Up™, the location of an object in the virtual world can be determined by setting the value of the translation property.

Adjei-Kumi and Retik (1997) noted that the main purpose of PROVYSIS[TM]'s process data, such as start times, finish times, duration and graphical images, is to facilitate the visualisation of the simulation of the generated construction schedule. They integrated the VR application with a project management tool, Primavera Project Planner. This system supports the usual practise of scheduling in the industry, but it does not explain how to control the time scale. Time scale factor is important to adjust a speed level so that the user can analyse the VR simulation at a desired and controllable speed. If the simulation is

too fast, it may cause dizziness to the user and it will be difficult to observe the simulation, while a slow simulation may cause impatience.

In order to represent time in the World Up™ universe, a counter system is used (see table 1). When the simulation is run, World Up™ goes through the entire simulation loop for each frame that the simulation is run. The counter works every time World Up™ simulates the universe. The counter is increased every time that a new cycle of simulation is started. Since the counter will be increased every frame, an object can be designed to translate whenever the object start counter (OSC) is equal with the counter for a certain duration of ObjCtr (see figure 5). For example, an object will be triggered to translate or move, when the counter is the same as OSC, 300, for the duration of 100 (ObjCtr). So, the object will stop at its last position when the counter is 400.

The increment of the counter determines how fast the object moves. This increment can be determined by creating an acceleration factor variable (Acc_F), which is a time scale (see figure 5). The greater the factor, the faster is the translation of the object. This time scale factor influences only the speed of counter calculation, not the number of frames per second at which the universe is rendered, which depends on the computation capability of the computer, number of polygons rendered, number of pixel filled and the display card. The faster the frame rate is rendered, the better quality of graphic animation is achieved.

Table 1. Scheduling Comparison between Real Practice of Construction and VR Simulation.

	Real Practice	VR Simulation
Time Control	Calendar	Counter
Task Started	As Specified Date, i.e. 1 Jan 2000	As Specified Counter, i.e. when the universe counter reach 200
Task Completion	Number of Days, i.e. 5 days	Number of Counter, i.e. 100

```
Counter = Counter + Acc_F
            |
            v
    If object start
    counter (OSC) =
        Counter

    Yes = Moving
            |
            v
""""""""Phase One
if (Counter - OSC) <= TD1
X = Xo + (X1 - Xo)/TD1 * Counter
Y = Yo + (Y1 - Yo)/TD1 * Counter
Z = Zo + (Z1 - Zo)/TD1 * Counter
end if

""""""""Phase Two
if (Counter - OSC) > TD1 and (Counter - OSC) <= ObjCtr
X = X1 + (X2-X1)/TD2 * (Counter - TD1)
Y = X2 + (Y2-Y1)/TD2 * (Counter - TD1)
Z = Z2 + (Z2 - Z1)/TD2 * (Counter - TD1)
end if

"""""" Object on the Position
if (Counter - OSC) > ObjCtr
X = X2
Y = Y2
Z = Z2
end if
```
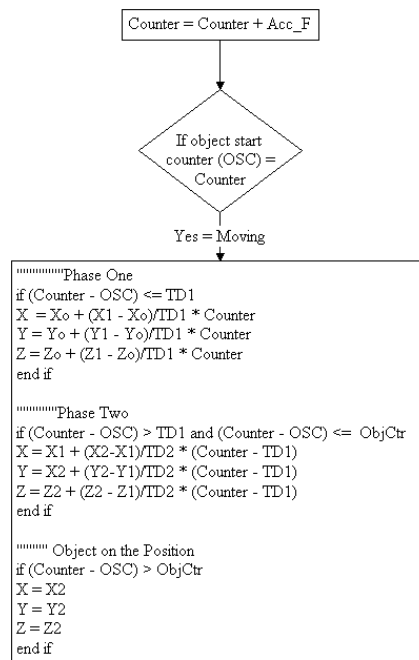
Figure 5. Countering System for Simulation Engine

7. CONCLUSION

The traditional approach using 2D drawings results in bulky and separated design drawings and philosophies. This problem leads to difficulties for an end-user in order to create a 3D mental picture for construction purposes. VR can integrate this design information into one universe and also add in design content such as the construction processes, methods and safety planning.

The overall model proposed consists of virtually real construction model (components and processes), virtual reality function and DFSP, an online safety guideline. The integration of virtually real construction model and DFSP aims to stimulate the safety hazard identification and shows remedial measures needed to prevent the occurrence of the accidents. Three virtual reality function, collision detection, terrain following and geometry picking, are utilised in this model to provide a better walkthrough environment, a fall related to height behaviour and an object picking to trigger the DFSP database.

During the development of virtually real construction components, the reusability concept is important in constructing the VR universe since it can minimise development time and cost. Reusability can be achieved by using the inheritance concept of object orientation. Inheritance can be created by applying the concept of generalisation-specialisation which is also supported by World Up™.

During the modelling of construction processes, two important variables, location and time, are identified for the simulation purpose. In order to translate the object, the location variable must be defined with at least the origin of location and the destination of location variables. The time for object translation can be distributed linearly if the location consists of three points or more, such as (x_0, y_0, z_0), (x_1, y_1, z_1) and (x_2, y_2, z_2) in order to obtain a constant object translation.

Since time must also be represented for the simulation purpose, a counter system, counter = counter + Acc_F, is proposed which can simulate a time standard, such as a calendar, in the actual life. The universe counter will be increased by the factor of "Acc_F" (acceleration factor), which also functions as a time scale to adjust the speed of the construction process as desired by the user every time a frame is calculated by World Up™. An adjustable speed control of simulation is important for user friendliness. If the simulation is too fast, the user might get dizzy and might not be able to analyse the simulation properly, but a slow simulation might cause user's impatience.

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