DIGITAL PROTOTYPING

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Abstract. This paper summarises existing technologies for both visual and physical prototyping of buildings. It recounts the R+D carried out in the ABACUS Group at the University of Strathclyde to secure the seamless transition of a digital prototype for a building from a PC model to a Virtual Environment Laboratory, for interactive immersive viewing, and subsequently to a Rapid Prototyping facility, for the creation of a physical scale model. Examples are drawn from architecture practice and from architectural education..

1. Introduction

Central to the complex, ill-understood, human activity of design is the activity of modelling - the business of creating an abstract representation of the concept for the eventual building which exists within the minds-eyes of the design team.

The paper-based plan, elevation and perspective drawing together with physical hand-crafted scale models, served the architectural profession well over a number of centuries. It is only since the 1960s that digital technologies have emerged to complement the modelling capabilities which were the stock-in-trade of the profession for so many years.

Visualisation of buildings is, of course, well established in architectural education and architectural practice and 3D visual representations of buildings have, to some degree, replaced the expensive and time-consuming requirement to construct a physical scale model to explain the scheme to the client/user body. Real time animation of digital models, particularly in immersive VR environments gives a significantly more realistic experience than can be obtained through the use of a model-scope with a physical scale model of the proposed design. On the other hand, there is something quite compelling about a physical scale model, which can be handled, taken apart and reassembled.

This paper describes the complementary conjunction of a Virtual Environment Laboratory (VEL) for immersive viewing of digital visualisations and a Rapid Design and Manufacturing (RDM) facility for the fast production of physical scale models.

2. Current and Emerging Technologies

2.1 VIRTUAL REALITY

The ubiquitous facility for the 3D colour and texture rendered visualisation of buildings during their design is, typically, the 42cm monitor screen which forms part of the configuration of a conventional CAD workstation. The model of the building is created by keyboard strokes and mouse movements from "outside" the virtual world which is then viewed through the "window" of the screen.

Immersive Virtual Reality (VR) systems allow the user, having created the virtual world in a conventional CAD system, to "step through" the window and, in effect, enter the virtual world. Typically however, the user has to "step back" through the window to effect design changes using the conventional CAD tools, an activity which is time-consuming and effort intensive and which, consequently, relegates the use of VR to a mere presentation tool rather than an integral part of the design process.

Recent research and development has, however, resulted in prototype software (JCAD-VR) specifically focussed on architectural design which provides, *within* the virtual world, the tools for creating, modifying and visualising the virtual world itself (Conti, G and Ucelli, G, 2002).

JCAD-VR has the following capabilities:

- design takes place *within* the virtual world itself
- all members of the design team (and the client body) can populate and interact within the virtual world.
- the system is entirely "platform independent" and distributed i.e. each member of the design/client team can be located anywhere and deploy any form of graphics interface, from the conventional CAD workstation monitor to an advanced immersive "reality room".

Leaving aside the conventional CAD monitor screen, the main categories of VR graphics interfaces (within each of which there are many variants) are:

- Head Mounted Display

The first VR interfaces were based on a helmet into which was incorporated two LED screens (one for each eye) and a position sensor to determine in which direction the user is looking. Such devices are appropriate primarily for viewing building interiors as opposed to exteriors but they are cumbersome and give virtual access only to one person.

- Fake-Space Tables

A number of people simultaneously, through stereoscopic spectacles can view an object which appears to "hover" above a table top. Viewers can walk round the object at will. This technology is most appropriate for viewing a building from the outside and is unsuitable generally for visualising interiors.

- Caves

The typical Cave has 3 walls, (say 3 x 3 metres) a floor and a ceiling onto each of which is stereoscopically projected the view of the virtual world appropriate to the direction of view of the 2/3 users, who stand within the cave. A strong feeling of immersion is induced but the resolution of the display may be compromised by the use of mirrors in the back projection in order to reduce the space taken up by the system and there is a degree of discontinuity at the edges of the 5 planes.

- Reality Rooms

Typically, a Reality Room comprises a single large screen configured to fill the core of vision of the 15-30 people accommodated within the room. In its simplest form the screen may be a 160^0 (horizontal) by 40^0 (vertical) curved in the horizontal plane; at the top end the screen may be a quarter hemisphere. The images from a number of projectors, located behind and above the viewers are "edge-blended" to give a complete high resolution display which may be mono or stereo-scopic.

2.2 RAPID PROTOTYPING

Rapid Prototyping (RP) is the term used to describe the creation of 3D physical (scale) models directly from digital data sources. A wide range of technologies are already in existence and new technologies are emerging. Two classes of technology can be identified: "subtractive", where material is removed from a block (similar to the computer aided manufacture of components by milling or turning a block of metal) and "additive", where the object is built up layer by layer.

The current technologies include:

- Polyurethane Foam Cutter

This subtractive method uses a computer controlled hot wire to "carve" a 3D solid shape out of a block of polyurethane foam. The maximum size of the model, typically is 100x100cm. The technique is cheap and fast but suitable only for rough early-stage representations of building form.

- Stereolithography

This additive method works by laser-curing a photosensitive resin. It offers high accuracy and good surface finish but is expensive.

- Selective Laser Sintering

This additive method works by sintering (i.e. crystallizing) a polymer powder using a carbon dioxide laser. A wide range of materials can be used but the equipment is expensive and bulky.

- Laminated Object Modelling

An infrared laser is used to cut layers of paper which are then stacked together. Large objects are possible but the resulting object has poor strength. This is the technology used by Frank Gehry's office during the design of the fish-shaped pavilion for the Barcelona Olympic Village in 1992.

- Genisys/Prodigy

This additive technique extrudes and lays down filaments of polyester polymers to form the object. The object has good mechanical properties but the process is slow. The process is appropriate to the creation of fine structural details for buildings.

- Three Dimensional Printing (3DP)

3DP and Fused Deposition Modelling work by "drawing" with latex on successive layers of powder in much the same way as a 2D plotter draws with ink on successive sheets of paper. On completion, the powder which is not bonded by the latex is blown away to reveal the 3D object. As will be described below, this relatively first and cheap process is highly appropriate for modelling buildings.

3. Experimental Configuration

At the Department of Architecture at the University of Strathclyde the Faculty of Engineering has made two major investments in technology for digital prototyping.

3.1 VIRTUAL ENVIRONMENT LABORATORY

The Virtual Environment Laboratory (VEL) (Figure 1) is a reality room similar to a 15 seat theatre with a 5 metric wide, 2 metre high screen curved in the horizontal plane to subtend an arc of 160^0. The SGI Onyx2 system has 6Gb RAM, 12 processor and half a terabyte of storage. It generates simultaneously three views of the virtual world all from the same eye point (which can be moved in real time) but separated in direction of view by some 53^0. Each view is projected from one of three high resolution Barco projectors at a rate of 25 frames per second. The three views are "edge-blended" to display a single seamless panoramic image on the curved screen, to fill the viewers core of vision. Although the projection is monoscopic, the sense of immersion is extremely strong and viewers have the impression of navigating a real environment in real time.

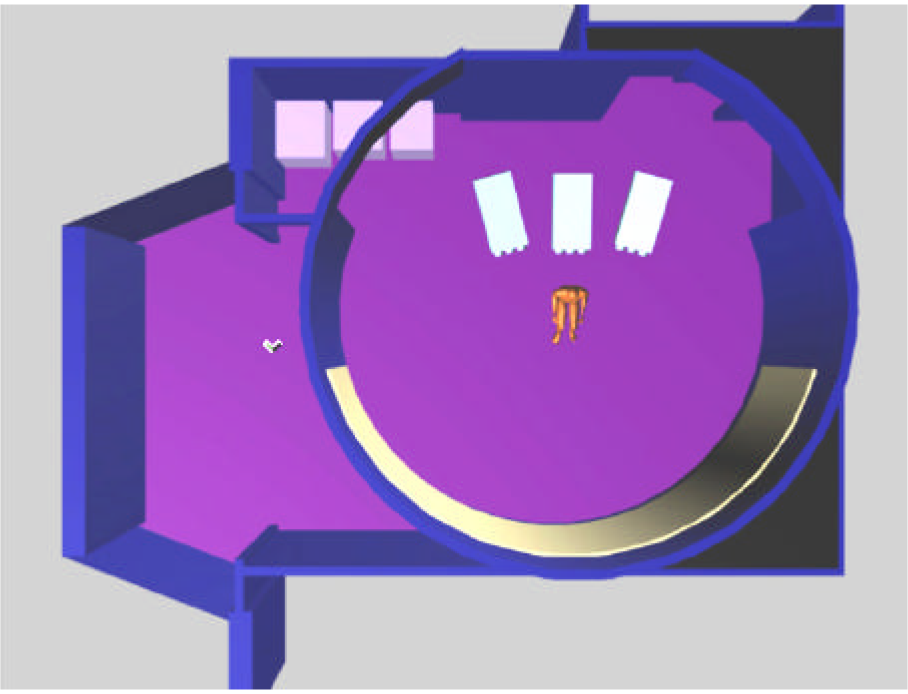

Figure 1. The Virtual Environment Laboratory at the University of Strathclyde.

3.2 RAPID DESIGN AND MANUFACTURING CENTRE

The Rapid Design and Manufacturing (RDM) Centre has a number of technologies for the creation of scale physical models, including a Genisys/Prodigy machine and a 3D Printer manufactured by the Z Corporation.

Three-Dimensional Printing (Figure 2) is a rapid prototyping process developed at the Massachusetts Institute of Technology. This technology does not use lasers, rather it is similar to ink-jet printing. The process begins with the deposition of a thin layer of powder over the surface of a bin (the printable area). This bin is fitted with a piston for incremental lowering as the part is built a layer at a time. A roller mechanism spreads the powder over the surface of the bin. A CAD drawing of the part, again sliced into consecutive layers, is used to distinguish the cross section of the part to be built. Next, an ink-jet printhead moves across the powder surface spraying small drops of binder material only in specific locations corresponding to the cross section of the part. The piston supporting the powder bed lowers so that the next layer of powder can be spread. The process continues until a solid part is complete. Depending on the powder material and binder used, this process may require post-processing. Due to the support of a powder bed the part can be built with overhangs, undercuts and internal volumes.

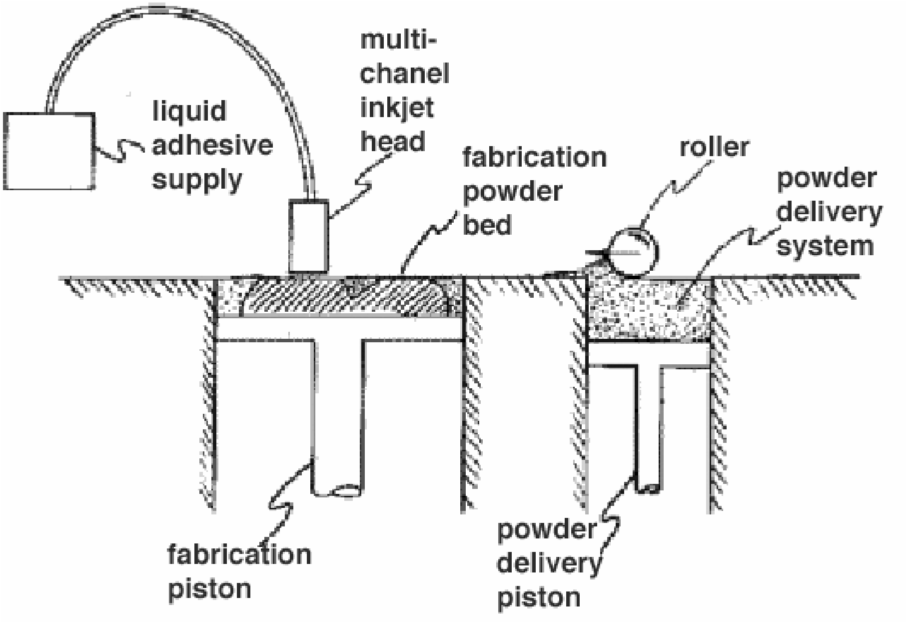

Figure 2. The 3D Printer from Z Corporation

The VEL is located in the Department of Architecture and Building Science and the RDM Centre is located in a building just 100 metres away. Although both facilities are heavily used for R+D and Consultancy, time is set aside for undergraduate and postgraduate student use.

4. Experimental Outcomes

The Architecture and Building Aids Computer Unit, Strathclyde (ABACUS) determined to explore how the two facilities - the VEL and the RDM Centre - could be used in conjunction both for architectural practice and for architectural design education.

4.1 USE IN ARCHITECTURAL PRACTICE

Speculatively, ABACUS decided to model the Millennium Tower which was then under construction on the south bank of Glasgow's River Clyde. Plans and elevations were converted into data for Autodesk's 3D Studio Viz on a

PC with a view to porting the model to the VEL and subsequently to the RDM Centre.

A number of problems were encountered in the process of exporting the 3D model in VRML format to the VEL. Certain objects, especially railings and stairs appeared rotated and distorted; this problem was solved by "collapsing the stack" and converting the model into an editable mesh before exporting it in VRML format. The resulting image, photographed from the VEL screen is shown in Figure 3.

The attempt was then made to use the same electronic data to create a physical scale model in the RDM Centre using the Z Corporation 3D Printer. This required conversion of the data to the Stereolithography Tessellation Language (STL), a process which proved not to be straight forward and software had to be written to apply Boolean operations to non-mirrored objects. Figure 4 shows models of two sections of the Tower manufactured at different scales.

The experience with the Millennium Tower and the resulting software developments gave the research group confidence to engage in a real live project involving the Ove Arup Partnership and the architectural practice Page and Park. The project sought to design a temporary roof structure for an unused but important building - the former Sheriff Court - in the centre of Glasgow.

The 3D model of the existing building and the new roof structure were modelled in a PC environment, then ported, without difficulty to the VEL where it could be viewed within the context of a textured mapped representation of the surrounding buildings (Figure 5). The structural engineers and architects met in the VEL to discuss and iteratively modify the proposal for the roof structure.

Thereafter, the digital data was passed to the RDM Centre. The existing wall elements were created using two different powders in the 3D Printer and two variants of the roof structure were created using the Filament Extruding Technology (Figure 6). In the case of the roof, software was developed to automatically (and fractionally) increase the slenderness ratio of some elements, in line with the structural constraints of the filament technology.

The roof structure involves a complex joint detail which was also modelled in the VEL and created, full scale, in the 3D printer (Figure 7).

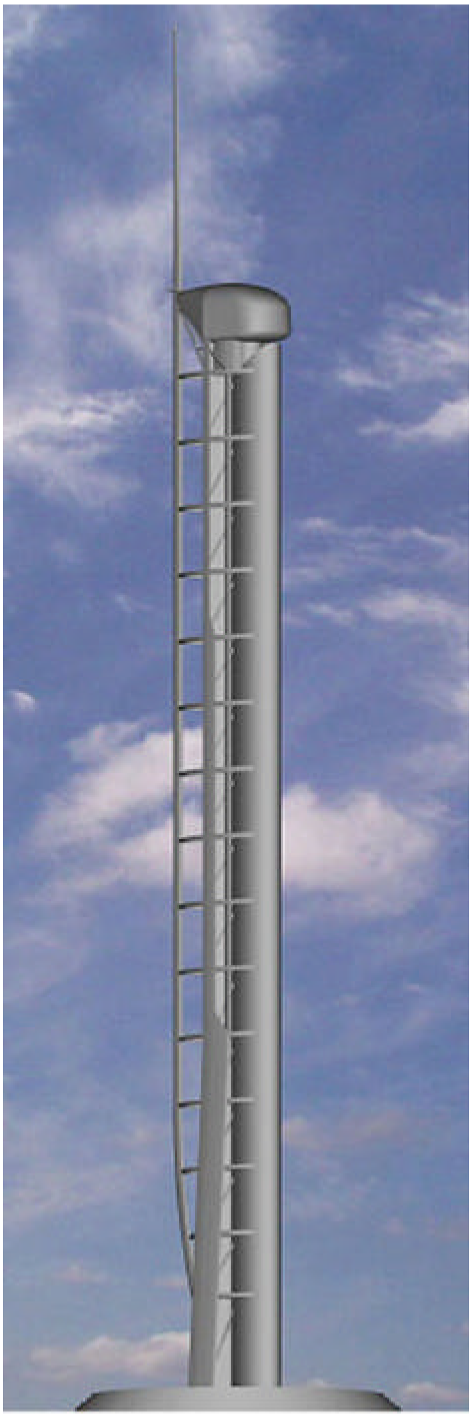

Figure 3. Glasgow's Millennium Tower as Viewed in the VEL

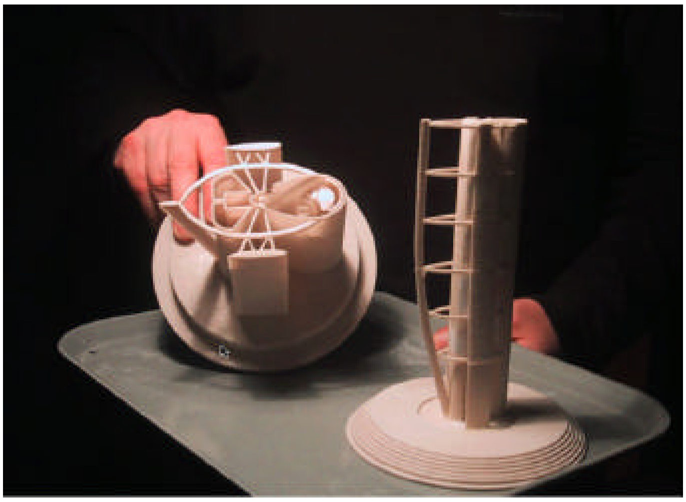

Figure 4. Physical Models of the Millennium Tower at Two Different Scales.

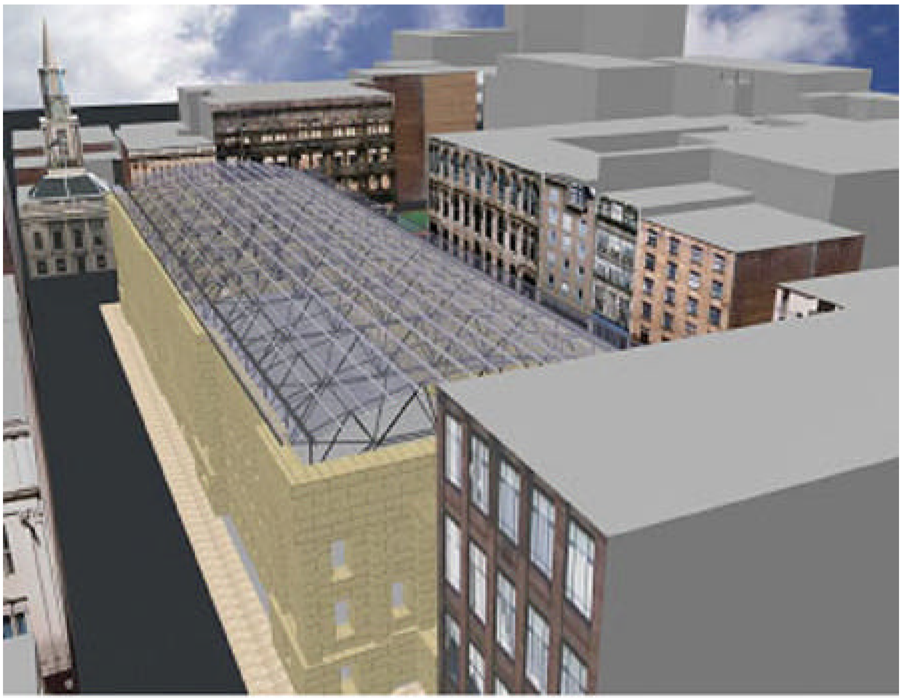

Figure 5. Proposed Roof Structure for the Sheriff Court viewed in the VEL.

Figure 6a. Two Alternative Roof Structures Modelled in the RDM Centre.

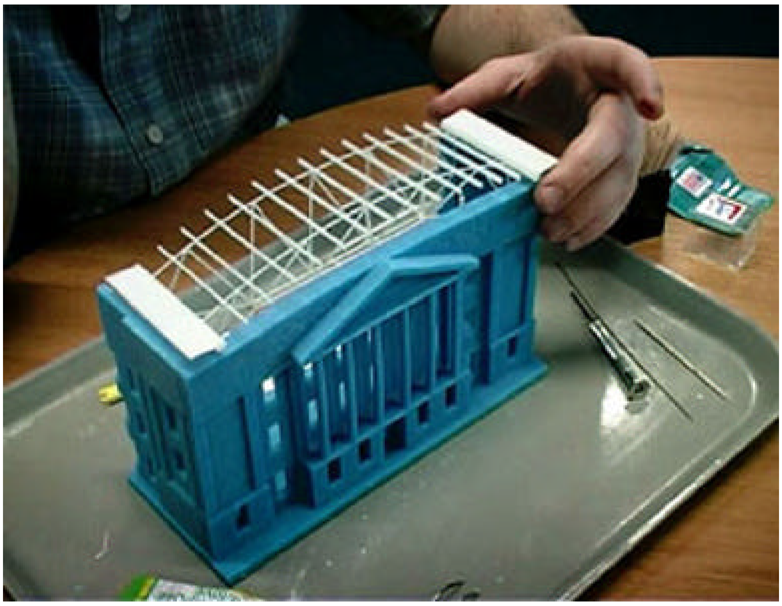

Figure 6b. Two Alternative Roof Structures Modelled in the RDM Centre.

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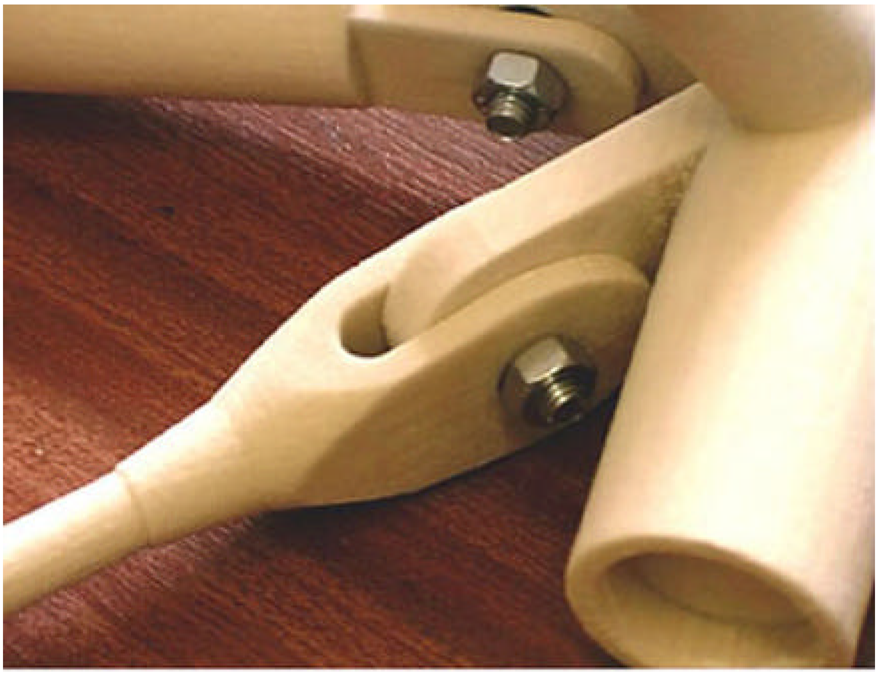

Figure 7. RDM Model of the Joint for the Roof Structure.

4.2 USE IN ARCHITECTURAL EDUCATION

The experiences gathered in the cases described in 4.1 and the resulting software which was developed to make the transition from PC to VEL to RDM quite seamless, opened up the opportunity to offer these facilities to students.

In the second semester of academic Session 01/02, two students on a 3 year VR elective class taught by the author, were given the opportunity to port their urban housing schemes (built in Form Z) to the VEL and subsequently to the RDM. The experience was trauma-free and two exquisite scale models, both constructed to two parts, were created. Figure 8 shows one scheme in the context of a wooden model of the site and Figure 9, for the other scheme, contrasts the visual and physical prototypes.

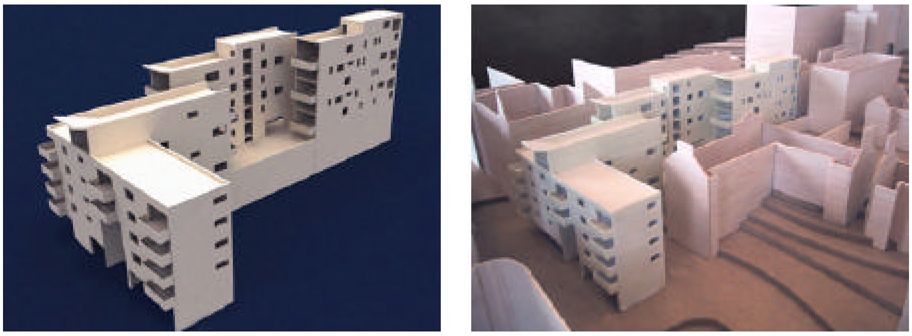

Figure 8. RDM Model of Student Housing Located in Wooden Site Model.

Figure 9. *Comparison of Visual and Physical Model of Student Housing.*

5. Conclusions

The stage has been reached at which the feasibility of student projects being featured in the Virtual Environment Laboratory and being manifest as beautiful physical scale models, is proven. It has emerged that the modeling environment of choice in the Department - Form Z - is perhaps the most appropriate for the transitions although 3D Studio Viz is also acceptable.

The Department has agreed an annual budget to meet the material costs (typically £50 - £100/model) for rapid prototyping of some 10 models each Session.

Two important areas of investigation remain

i. Whereas the JCAD-VR systems opens the door to the use of visual prototyping throughout the design decision-making process, the use of physical prototyping as a design, rather than a presentation, aid needs to be explored.

ii. ABACUS is currently exploring how the prototyping loop can be closed, by digitally scanning hand-crafted or rapid prototype (RP) produced physical scale models. This relationship between VR, RP, "Shape-grabbing" (SG) and the design team (D) is diagrammatically represented in Figure 10.

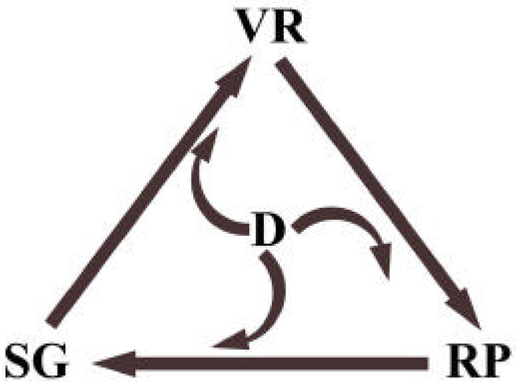

Figure 10. Relationship between VR, RP, Shape Grabbing (SG) and the Design Team (D).

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