3D-Scanning and 3D-Printing for Media Experimental Design Work In Architecture

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ABSTRACT

Architects and designers use multiple media to explore and express design solutions. The physical model remains one of the most important media to represent the architect’s work that cannot completely be substituted by computer graphics.

The experimental use of various media is of major importance for architects. Nevertheless, the author of this article is convinced that architects and designers will continue to make physical models. During the design process, however, the designer might wish to transfer the design idea into the computer. If he has already made a physical model, it will take him much time to recreate the same model on the screen by means of his CAD programs. This would be different if it were possible to digitize the existing physical model and then to continue designing on the computer. In this paper, the author describes some 3D-scanning methods based on computer tomograms. Also the inverse combination of modeling and digitizing would be useful. So-called 3D-printing methods could help architects to transform their model on the screen into physical models during or at the end of the computer supported design process.

In this paper, the author will give a survey on how designers can use input and output devices to generate digital data from a physical model and - vice versa - to transform a digital design solution into a physical model. The reader will get an impression of both procedures from the examples given.

INTRODUCTION

In general, the traditional architectural model has not lost significant impact in spite of computer-aided design. Digital techniques can not so simply replace the possibilities offered by using various materials to build a model which reflects spontaneous design ideas: speed, flexibility, creation of spatial effects, the chance to check and modify, or create design and functional associations by experimenting with material and form. We are convinced that the construction of traditional architectural models will continue in early stages of the design process, but not for design presentation.

We know, however, that digital and non-digital methods are not totally incompatible, which means that designers may use traditional non-digital methods during an early phase of designing but later make use of digital methods. In these cases, architects must often do the same work twice as the 3D physical model must be constructed again by means of a CAD-system although the basic design solution has already been found. The question is whether it is possible to transform physical into digital models automatically at least to a certain extent.

In addition there is an increasing tendency among designers to take on design projects without regard to spatial distances. Architects design one model in London and another one in Berlin for a project to be realized in Tokyo. We call this kind of organizing architects' designing activities: work in "fractionised" offices. It is no problem to exchange CAD-data sets or digital graphic files using networks such as Internet. But it would appear impossible at first sight to make physical models immediately available for a staff working at distant offices. This poses the question as to whether immaterial "transport" of a material architectural model is possible and, if so, which technology is required.
3D-SCANNING - DIGITAL PROCESSING OF SPATIAL ARCHITECTURAL MODELS

The decisive task when transforming physical models into digital form consists of capturing digitally the spatial structure. The available technical procedures for digitizing architectural models may be judged by three criteria:

- the possibility to digitize the outer forms of the model with sufficient precision
- the possibility to capture also the inner geometrical structures of the model without dismantling the construction parts
- the possibility to differentiate automatically if possible, between different materials of the model in order to capture semantic contexts of similar construction parts for the future building on the one hand, and to capture the topological connections of geometrical structures on the other hand.

Another important criterion is whether and to what degree the data produced can be understood by the CAD system used subsequently. This is one of the usual interface bottle-necks but it cannot be regarded as a basic criterion when judging the technical procedures: engineers can program additional software if necessary.

Let us therefore consider the various technical procedures available for digitization of architectural models:

- Digitizing by a mechanical probe:
  Capturing of 3D coordinates of single points of the model by lowering the scanning tool onto the points to be digitized. This procedure only permits digitization of the outer structures and the structures inside the model which are accessible from the outside. It is neither possible to differentiate between different materials used in the model nor to establish topological connections.

- Remote digitizing using a large-scale photogrammetric method:
  The model is captured photographically from different directions, 3D coordinates are calculated by means of corresponding points of the model. It is impossible to differentiate automatically between different model materials, topological connections cannot be established.

- Digitizing using laser-aided measurement methods:
  3D coordinates of the outer shape of the model are scanned by a laser beam. It is impossible to differentiate between materials.

- Digitizing using phase-shifting methods:
  A well-defined and well-contrasting moiré is projected on the model and recorded by a video-camera. Uneven points of the object produce characteristic changes in the moiré thus permitting to determine the surface points. This method does not permit a differentiation of materials used.

- Digitizing by means of computer tomograms (CT):
  This method which has been used in medical diagnosis for some time produces a 3D model (voxel structure) of the object. The 3D object is completely scanned reducing the object to a sequence of pixel strata which can be rebuilt to a surface part according to the sequence of the strata and the distance between them. Due to the high energetic performance of the scanning beam which can also penetrate solid material, the inner structure of architectural models can also be captured. As different materials are differently absorbed, the measurements make it possible to draw conclusions about the materials used.

Since computer tomograms open up interesting possibilities when applied to architectural models, we wish to describe this method more precisely and to illustrate it by some examples. In analogy to the method of image scanning, we can call this method 3D-scanning. (Nuclear spin tomograms, also used for medical diagnostics, are not appropriate for the scanning of architectural model parts because this method requires a certain percentage of hydrogen atoms which are usually lacking in architectural model materials.)

The following examples illustrate first experiments and test series made with computer tomograms. Figure 1 shows a traditional architectural model (for presentation) with the corresponding 3D scanning pictures as horizontal and vertical cross-sections produced by computer tomograms.

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Figure 1. Traditional architecture model and corresponding CT images as cross-sections.

Figure 2. Traditional architecture model (design model) and corresponding image produced by CT voxel data.

*Figure 2 above shows another typical architecture model (design model) used for experiments which helped to find out in detail which materials of the model and which of its inner and outer structures can be captured by CT.*

The material used for the inner walls and the facades was cardboard with rather a homogeneous material structure. The vertical wooden supports of the facade situated at the back of the building were also homogeneous. The roof was made of corrugated cardboard with a relatively high percentage of air-filled chambers. Parts of the outer structure of the building consisted of metal and wire. We carried out supplementary test series to examine further typical model materials such as various synthetics and to evaluate their specific appearance in a tomogram.

In order to limit the quantity of data, we scanned only part of the model. There were 228 strata in all scanned with an accuracy of 0.5 mm (the total model volume scanned measured 25.6*26.6*11.4 cm) and subsequently put in single data files. As every stratum comprised 512*512 voxels of height and width and as every CT value required 2
byte, data storage totaled 120 MB. The quantity of data could be greatly diminished if the CT values were stored as 12 bit information instead of 16 bit, and if the files were compressed again by adequate compression methods to reduce storage volume.

Figure 3 shows one of the cross-sections scanned. On the (movable) supporting surface you can see the section of the model with its dark ceilings and walls that contrast well with the lighter background i.e. the space around the model. The color value of a single voxel represents the CT or Hounsfield-value named after Godfrey Hounsfield, who developed CT. This value is equal to the calculated reduction of the X-ray when passing through the material at a certain voxel position.

Contrary to our expectations, the space surrounding the model is not of homogeneous white but seems to be interfered with a "noise" varying in its intensity. These disturbing pixels result partly from the specific technique of CT pictures, and partly from the mathematical reconstruction of the voxels based on the signal stream of X-rays.

In addition, the signals can only be scanned with a limited accuracy. As a result, small or thin structures of the building cannot be fully represented. Thus when scanning the test model, the roof made of only one layer of corrugated cardboard was shown only incompletely in spite of the high accuracy of 0.5 mm needed in medical applications.

For further processing of CT data within CAAD systems, data must be transformed into another format as the voxel model differs considerably from the usual representations of volumes, i.e. Boundary Representation (BR) or Constructive Solid Geometry (CSG).

The correct distinction of CT data representing aerial space and those representing various model materials is the precondition for successful data transfer. This is referred to as classification. Only after this has been done, can voxels of the same material be collected in "reasonable" constructive units, aggregated and formatted according to CAAD rules. Neither of steps are by any means easy due to the specific character of CT data.

a) Classification of voxel data

For each voxel, a CT-picture provides only one piece of information, namely its Hounsfield-value. As different materials can produce equal values, the material can not be precisely classified simply by examining the Hounsfield-value. However, further information can be obtained by examining larger groups of neighboring voxels. Homogeneous distribution of the voxels indicates homogeneous material with dense and homogeneous composition. The repetition of patterns of varying values indicates less homogeneous material compositions.
It is possible to classify voxels by different methods ranging from simple statistical considerations of how the voxels are distributed within a limited area to complex comparisons of pattern structures with structures already known. The choice of the method depends on how precisely the material is to be identified and on the materials themselves.

The method used to classify our test model was to be as simple as possible. We considered the following two approaches:

- Firstly, we used a simple threshold value method to differentiate between space voxels and material voxels, selecting a very small threshold value which made it possible to distinguish between space and material. Model parts filled with large air chambers were exposed to an expand-shrink-procedure and thus closed. Though the method produced satisfactory results, it must be applied carefully because of its generalization effects (see Figure 4 above).

- Secondly, we applied maximum-likelihood-classification used in the processing of satellite imagery. For certain test areas, statistical basic information was calculated (such as range of values, average, standard deviation etc.) and then stored as a signature typical of the material. Then each voxel was examined as to what extent it could be classed as belonging to which signature and then assigned to the material with maximum likelihood. Figure 4 below shows the results of this classification reduced to the two classes “space” and “building material”.

Figure 4. Classification of CT data: threshold value (above) and maximum-likelihood method (below).

The results of the maximum-likelihood-classification had to be subsequently adjusted to take into account nonhomogeneity of the material. This was necessary because the aim was not to provide precise information on the building material, but rather an accurate reproduction of the spatial form of the object in order to provide the CA(A)D system with full information on the structure of which the building material is only one aspect. However, extreme
care had to be taken when selecting the classification parameters, in order to reduce the risk of important details becoming blurred in the course of the necessary generalization. Research is currently underway at the University of Kaiserslautern in Germany to find a solution to this problem.

b) Aggregation of voxel groups

Based on the results of the classification, the voxel structures belonging to material could be analyzed and processed conform to CAAD standards. It seemed plausible to choose ceilings, walls and roofs as first constructive units. The problem then was to know to which constructive and semantic context the discrete voxels belonged. This task is no problem for the human observer as the complete procedure of sight and perception is based on this faculty. In order to cope with this task man takes into consideration not only the objects seen but also his experience and his expectations concerning the objects around him. We recognize quite rapidly which voxels belong to a wall because we know that a wall is a vertical plane and therefore are able to perceive the voxels forming such an object. The imitation of this procedure by a computer proves to be a difficult venture as the computer must then also draw on knowledge from past experience about all kinds of objects occurring in architectural design models.

In the simplest case we can assume that ceilings are more or less horizontal, walls more or less vertical, roofs horizontal or inclined and that their surfaces are planes. In addition, walls and ceilings are usually perpendicular to each other. Window and door openings can be classified geometrically: they form rectangular spaces in walls. However, considerable derivations from these assumptions are possible. Though there still are many difficulties to overcome and many steps to be taken, computer tomograms seem to be the only technology by which - at the present state of the art - architectural models can be digitized in a way that meets with requirements such as rapidity, automation, completeness and differentiation of the construction parts. Moreover, investment costs, stay within tolerable limits assuming the cost calculations of medical institutes. These costs are likely to decline further as tomographical equipment is finding its way into new markets (e.g. luggage control by X-rays at airports).

3D-PRINTING - COMPUTER AIDED MANUFACTURING OF ARCHITECTURAL MODELS

3D-scanning transforms solid models into digital ones. The corresponding inverse procedure is referred to as 3D-printing (also known as "rapid prototyping" or "solid freeform manufacturing"). This term includes all model manufacturing procedures which operate by gradually fitting together and joining material and thus building up a model (additive procedures) in contrast to subtractive procedures such as 2D-laser cutting, 3D-milling. The following examples may be quoted (for detailed information see Streich/Weizgerber 1996):

- **Laminated Object Manufacturing**: Automatic stacking of 2D construction part contours produced successively for example according to the 2D cutting method
- **Beam Interference Solidification**: polymerization of a photosensitive mixture at the intersection of two laser beams at right angles to each other
- **Holographic Interference Solidification**: interference hardening in a chemical reagent due to hologram illumination
- **Sterolithography**: gradual polymerisation by thermal influence of a photosensitive reagent
- **Liquid Thermal Polymerization**: gradual consolidation and binding of layers of semi-polymerized material foils by means of laser
- **Solid Foil Polymerization**: semi-polymerized foils are exposed to laser beams thus gradually building up and joining to solid layers
- **Selective Laser Sintering**: gradual fusion or sintering of layers of thermoplastic particles by laser beams
- **3D Printing and Gluing**: gradual gluing of layers of construction material in powder form
- **Fused Deposition Modeling**: gradual build-up of layers of construction material by means of a fusion nozzle
- **Ballistic Particle Manufacturing**: build-up of molten construction material by means of piezo-electric nozzles.

3D-scanning and 3D-printing can be mutually complementary. It is possible for instance to use scanned data of an architectural model to produce a duplicate model by means of one of the above mentioned computer aided pro-
Two further figures are given below to illustrate the potential of 3D-printing: Figure 5 shows a model house from a housing estate designed as a contribution to the 1993 South American Biennial of Architecture for poor sections of the population of Santiago de Chile, on the left as computer graphics, on the right as a stereolithographic model. Figure 6 shows the award-winning German pavilion designed by Auer & Weber for the EXPO 1992 (Sevilla) which had not been built: on the left a general view of the stereolithographic model, on the right a detail of the model.

**Figure 5.** Computer graphic and stereolithographic model of an architectural design study.

**Figure 6.** Stereolithographic model of the German Pavilion for the EXPO 1992 (Auer & Weber).

**CONCLUSIONS AND FURTHER WORK**

The possibilities of using 3D-scanning and 3D-printing in a mutually complementary manner should in future be utilized in particular in the sector of media experimental design in architecture. The present article has shown examples of the basic potential of the techniques referred to.

Future research should show how architects can apply 3D-input procedures to the early phases of design activity, and indeed research in this very direction has already begun in the author's department. This area appears particularly interesting because architects are still inclined to revert to the construction of traditional models in the early phase of design. Until now there was no solution to the problem of how to transfer these manually produced drafts rapidly and if possible automatically into the digital world of computers. The reverse can also be necessary, i.e. the digital structures of an architectural design may be needed in the form of an architectural model, possibly even at a different location. The combination of 3D-scanning and 3D-printing could solve this problem. Furthermore, experimenting with these technical possibilities could open the door to previously unknown opportunities for the designing architect.

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REFERENCES


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