PHYSICAL MODELS OF GIS OBJECTS BY RAPID PROTOTYPING

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ABSTRACT:

In recent years new technical solutions for the fast and inexpensive production of mechanical parts were developed. The prototypes are built by computer-controlled devices using a numerical description of the part. The prototypes serve mainly to judge on the form and appearance of the final parts. The available technical solutions for rapid prototyping were evaluated to build physical models of three-dimensional GIS objects. A recently introduced device, the 3D plotter Z406, is able to produce physical models in full color. A number of models were built using the 3D plotter, visualizing 3D choropleth maps and conceptual surfaces derived from demographic and economic data. The experiences and results in building 3D multicolored models of GIS objects are described, including the costs involved to build the models.

1. VIRTUAL REALITY AND PHYSICAL MODELS

Advanced visualization techniques have been used for some time in architecture and planning. The architect or planner is able to inspect buildings and landscapes which are not existent in reality (yet), but are stored as numerical models in a CAD or other information system. The technical possibilities stretch from photo-realistic images over stereoscopic views to walk-throughs or flights over a virtual landscape.

Despite the availability of virtual reality technology it is remarkable that physical models of buildings are still requested in architectural competitions. VR provides more visual information than the simple view on the building. For example the interior can be visualized under the varying light conditions and perspectives during a walk-through, or a view from inside through the windows can be generated. Why are the physical models still requested? The cost of model building is a marginal quantity in relation to the cost of the competition or even the real building. VR is still rather expensive when several persons have to view the building simultaneously. Probably architects have a special preference for hand-made objects. The haptic experience, the possibility to feel an object with their own hands, is certainly an important factor as well.

Physical models of three-dimensional GIS objects, however, are rarely realized. The missing tradition of model building is one explanation, the other is that the cost of building a model is not a negligible quantity in relation to the overall cost of spatial analysis. If the physical model of a building has advantages over VR in certain cases, it is possible that real models of GIS objects lead to a new quality in visualization, and subsequently to a better insight into the processes forming the environment.

In recent years new technical solutions were developed which enable the fast and inexpensive production of mechanical parts directly from a CAD system. The prototypes serve mainly to judge on the form and appearance, in certain cases to evaluate the mechanical function. Usually the prototypes are not exposed to the mechanical stress that their real counterparts have to withstand, for example the prototype of a steering wheel for a car. Thus it is not necessary in most cases to use the same material of which the final part will be made.

Rapid prototyping can also be applied to create physical models of three-dimensional GIS objects. In the following chapters the technical alternatives for rapid prototyping are described, with special attention to their application in cartography. Models of discrete and continuous surfaces derived from demographic and economic data serve as examples for rapid prototyping of GIS objects. The term *rapid prototyping* is also used in software technology, describing the fast and inexpensive development of computer programs.

2. TECHNICAL ALTERNATIVES

2.1 Main groups of rapid prototyping

The different ways to produce prototypes can be subsumed under three groups which have their equivalents in the arts:

- *Michelangelo*: A block of material is treated with a tool until the final form is reached. A block of marble is transformed into a sculpture.
- *Rodin*: The model is built by accumulating small amounts of material. A sculpture or a scaled model is aggregated from plaster or other plastic material.
- *Chillida*: The material is formed by strong forces, like a blacksmith transforms a rod of iron into a sickle.

An example of the Michelangelo group is a numerically controlled milling cutter. Although low-cost devices have been available for a few years, numerically controlled milling is usually not fast and mostly expensive. Thus milling is not applicable in most cases for the rapid prototyping of GIS objects. Methods of the Chillida group are rather rarely used or are secondary for the creation of GIS models.

2.2 Assembly from layers of material

The model is built from layers of material by a computer-controlled device. Principally only 2½D surfaces (only one z value at any point in the x-y plane) are possible because each layer needs a solid base. Concave parts must be reoriented in space to become a 2½D surface. If this is not possible, the part has to be assembled from convex subparts. Some prototyping methods solve the problem by providing a second material to fill hollow spaces. The ma-

terial is removed after the model has been built. Some materials are also sturdy enough to bridge caverns.

Several alternatives have been developed for the assembly by layers of material (for detailed descriptions see Cooper 2001 or Dimov and Pham 2001):

- Paper. The layers are cut out in paper and assembled from bottom to top until the part is finished (laminated object manufacturing, LOM). The parts outside the model must be removed manually.
- Powder. The device deposits a thin layer of a powder, consisting of starch, plaster, photopolymer or metal. The parts of the layer belonging to the model are fixed by spraying an adhesive, by polymerization with UV light, or by local heating with a laser beam. When the first layer is fixed the second layer is deposited, and so on. The loose powder is removed. Certain devices allow the recycling of the unused material. The model can be infiltrated with a fluid after buildup to improve the mechanical and thermal stability.
- Thermoplastic material. The layers are deposited by a moveable print head similar to an inkjet print head. The material is melted in the head before deposition, or is hardened by UV light.
- Stereolithography. The energy of a moveable laser beam induces a phase change in a thin layer of a photosensitive fluid. The fluid becomes solid (polymerizes) where the beam hits the surface. A new layer is built on the solidified layer. The procedure is repeated until the last layer is finished.

The decision which alternative should be used depends on the purpose for which the prototype is intended. Stereolithography, for instance, results in very smooth surfaces, but is expensive. A combination of starch powder and wax can be used to build a model for investment casting. The model is burned by the hot molten metal with nearly no remainders. A part built of plaster powder infiltrated by cyanoacrylate can be finished like wood.

2.3 Color

The visual variable *color* is essential in cartography and for the visualization of GIS objects and maps. Until recently it was not possible to integrate the coloring into the assembling process using rapid prototyping. The raw models had to be colored manually, for example by using an airbrush. In 2001, ZCorporation introduced the 3D printer Z406 with integrated coloring. The device applies three different adhesives containing pigments in the subtractive base colors cyan, magenta and yellow to fuse the powder. The result is a multicolored part.

The Z406 and the new Z810 (with a larger build space) are until now the only devices on the market providing multicoloured parts. The capability to integrate color opens some new application fields for rapid prototyping besides cartography and GIS, such as multicolor models of molecules, buildings or plants, or the large field of medical visualization based on tomography data.

3. PRODUCTION OF THE MODELS

3.1 Outsourcing

Generally devices for rapid prototyping are rather expensive. For a small to midsize production volume the most economic way to build prototypes is outsourcing to a specialized firm (4Dconcepts in this case, http://www.4dconcepts.de/). The numerical description of the part is transmitted in a file, for example as an attachment to an e-mail. The part is assembled, infiltrated with a fluid, if required, and expedited to the customer by a parcel service. The

Rapid Prototyping Homepage at the University of Utah contains numerous references, also for outsourcing (http://www.cc.utah.edu/~asn8200/rapid.html).

3.2 File format

To facilitate the transmission of the part description a general, non-proprietary file format should be used. The numerical representation in the system of the customer is converted into the commands and data formats that the specific prototyping device needs to build the model. In the STL format (the name is derived from its first application in stereolithography) the part, or better its surface, is described by a set of triangles (vertices and triangle normals in 3D). Two versions are in use, one with the triangle descriptions as plain text, the other in a binary format resulting in a smaller file size.

The STL file format is not able to transmit color information. The scene description language VRML (from *Virtual Reality Markup Language*) can be used instead to define the triangles and the associated color, either for each triangle or for the whole model or parts of the model. A description of the latest version of the VRML and related documents can been downloaded from the website http://www.vrml.org/.

The triangles in the model are defined by pointers to a set of vertices. The vertices are stored only once, whereas in the STL format the same vertices must be repeated for each triangle, resulting in larger files. The following VRML script defines a tetrahedron with different colors for each triangle.

```
#VRML V2.0 utf8
#Tetrahedron
Shape{
geometry IndexedFaceSet {
colorPerVertex FALSE
color Color { color[0 0 1,0 1 0,1 0 0,0 1 1]}
coord Coordinate { point[1 1 1,-1 1 -1,1 -1 -1,
-1 1 -1,-1 -1 1] }
coordIndex[2,1,0,-1,2,4,1,-1,4,2,0,-1,1,4,0]
colorIndex[0,1,2,3] } }
```

The VRML files of the examples in chapter 4 were produced by a software package for cartographic applications written by the author.

3.3 Limitations of the 3D plotter

The maximal build space for parts produced by the 3D plotter Z406 is 20 by 25 by 20 cm. The thickness of each layer can be varied from 0.076 to 0.254 cm, dependent on the powder material used and the resolution required in the z direction. The build time is proportional to the number of layers. In color mode two layers per minute can be produced, in monochrome mode six layers. The powder consists of either starch or plaster. It is recommend to infiltrate the raw model to enhance the mechanical and thermal stability, and to lower the sensitivity against humidity. The infiltrant can be wax (in combination with starch), or different resins based on cyanoacrylate. After infiltration with the latter the model can be sanded like wood, colored or electroplated to imitate the appearance of metal. The newer model Z810 uses the same technical principles as the Z406, but has a larger build volume of 50 by 60 by 40 cm.

The software of the 3D plotter accepts only triangles (VRML node IndexedFaceSet). No other geometric objects possible in VRML (nodes) are recognized, such as extrusion bodies, text strings or heightfields. Each object must be represented by a set of triangles,

even lines, which can inflate the number of triangles and the size of the file considerably. The need for triangles and the resolution of the 3D plotter restricts the use of text objects. The letter size must be large enough to be recognized, which usually requires too much space on the model. The rear side of the model can be used to imprint, for example, a logo or a copyright notice.

4. EXAMPLES

4.1 3D choropleth map of land prices in Germany

Several models of 3D choropleth maps and conceptual surfaces were built using the 3D plotter Z406. The model in fig. 1 is a three-dimensional choropleth map visualizing the average cost of land in the counties and cities of Germany in the year 2000 (BBR 2001). The height of the prisms is proportional to the average price of land in Euro per m². In contrast to a 2D choropleth map depicting value classes, the absolute differences in height can be perceived immediately. To facilitate the comparison the tops and the walls of the prisms bear the colors associated with the value classes. The phone card (credit card size) in the photograph serves as a standard of comparison.
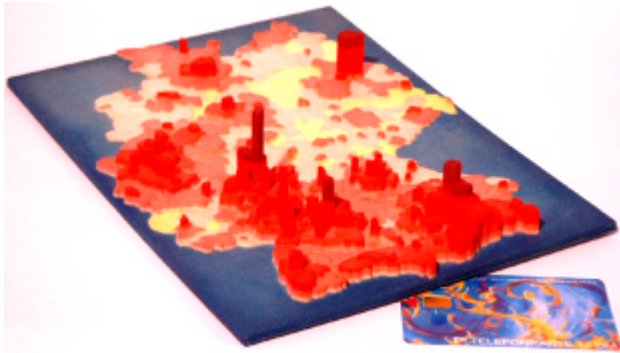

Fig. 1   3D choropleth map representing the price of land per km² in the year 2000

The powder material is plaster. The layers have a thickness of 0.01 cm. The production in the 3D printer took approximately 3.5 hours. After assembly the model was infiltrated with epoxy resin. The overall production cost including preparation of the files, infiltration and shipment were about 400 Euro.

4.2 Continuous surface of land prices

Fig. 2 depicts a continuous surface derived from the same data using the pycnophylactic interpolation procedure. A smooth surface is interpolated from polygon-based data ensuring the conservation of volume above the polygon (Tobler 1979, Rase 2001). The perception of height is facilitated by different colors representing the range between two adjacent contour levels. The state boundaries in Germany, the boundaries of the neighboring countries and the larger water surfaces (North Sea, Baltic Sea, Lake Constance) were added to provide better topographical cues for users less familiar with the locations.

The model was infiltrated with cyanoacrylate, which results in an enhanced mechanical stability. Due to the more expensive fluid the overall cost was slightly higher than for the previous model. At a closer look some dark spots in the low areas around Berlin can be identified. At these locations the distance between the surface (yellow) and the base (dark blue) did not suffice to deposit a layer of yellow material thick enough to cover the blue underground completely, as intended.
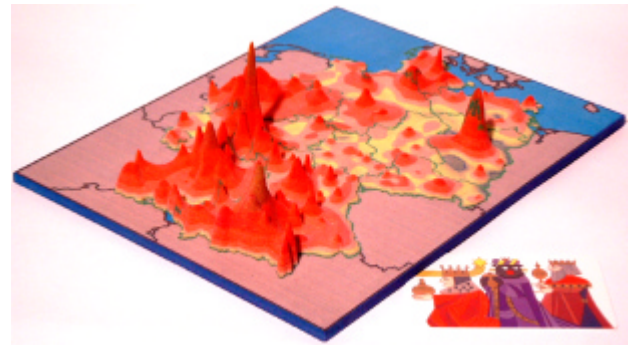

Fig. 2   Continuous surface interpolated from the data in fig. 1 by the pycnophylactic interpolation method

4.3 4D choropleth map with population data

Fig. 3 is a photograph of a 3D choropleth map representing the population in Germany. Units of reference are the so-called "planning regions" used for spatial monitoring in Germany. The volume of the prisms is proportional to the number of inhabitants in each unit. The height of the prisms is proportional to the population density expressed as inhabitants per km². To achieve a better perception, the colors associated with the value (height) classes and the class boundaries are depicted on the prism walls. The differences in population and density between the more rural regions and the densely populated cities of Berlin, Hamburg and Bremen are clearly visible. On the other hand the comparison of the less populated areas is more difficult due to the smaller differences in height.
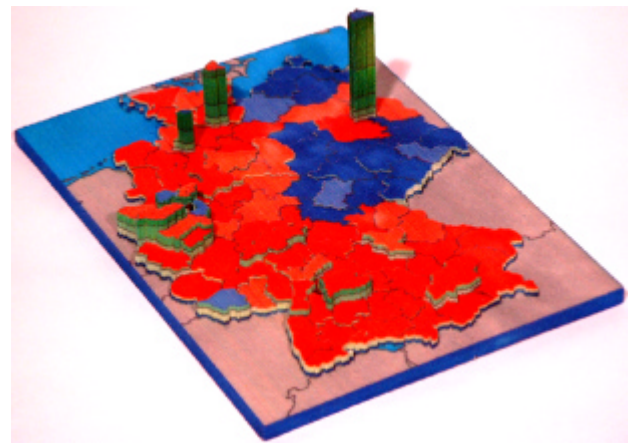

Fig. 3   3D choropleth map representing inhabitants and population density

A second variable, the change in population between 1990 and 2000, is represented by the color of the prism caps. Blue caps express two classes of population loss, red caps two classes of population gain. The 4D map – the two dimensions of the plane, the height proportional to the population density, and the cap colors representing classes of change rate – transmits additional information, but is more difficult to conceive than a 3D map with redundant visual variables. Theoretically additional visual variables could be used to encode even more dimensions, but the limits of usability seem to be reached with a 4D map.

4.4 Continuous surface of population density

The continuous surface in fig. 4 was interpolated from the population values and the polygons of the cities and counties, again with the pycnophylactic interpolation procedure. The black isolines separate the colored regions representing height classes. The state boundaries (green) are intended to provide topographical cues. The peculiar lines at the slope of the "mountain" in the east (left) are the boundary of the city of Berlin, projected onto the slope (also visible in fig. 2).
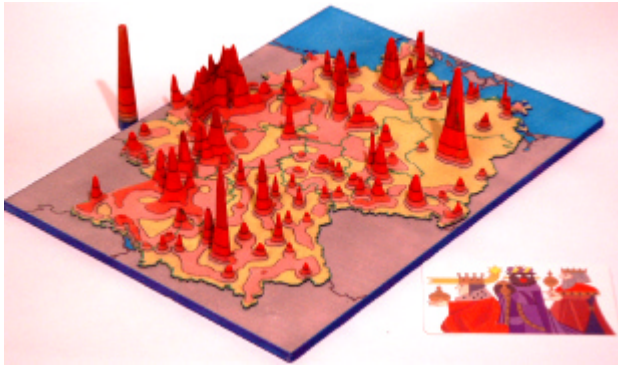

Fig. 4   Smooth surface depicting population density based on county data. The moveable cone at the left serves as a legend to estimate the height.

5. PROS AND CONS OF REAL MODELS

The few real models of GIS objects produced so far have revealed the technical possibilities and limitations in hardware and software, the approximate production costs, and the benefits and problems of outsourcing the production. But what are the advantages of physical models in comparison to conventional maps, perspective drawings, or VR techniques?

On "normal" maps the third dimension is encoded by visual or graphic variables (size, lightness, color, texture, shape, orientation). The reader of the map must be able to decode the visual variables to achieve a mental reconstruction of the third dimension, assisted by a legend. Some of the recipients have problems to decode the visual variables of maps because they do not have the necessary training or experience. In this case the message in the map fails to reach the addressee.

Humans have a life-long training to interpret 3D objects or pictures thereof and to construct a mental model in 3D (which, of course, can go wrong in certain cases, called optical illusions). Especially for decision-makers with limited experience in map reading the real 3D model transmits the cartographic message much better and faster than a two-dimensional map.

The 3D effect can be achieved by a perspective drawing of the object as well. Physical models have the advantage over 2D drawings that slight movements of the head or body suffice to look at parts of the model covered by obstacles in the line of sight, for example high prisms or mountains in the foreground. In this case a second or third drawing must be provided to present all parts of the surface.

Humans are able to estimate distances in a 3D scene by stereopsis and minor changes of the eye point due to lifelong training and experience in evaluating 3D scenes. Thus it is easier to compare the heights in a model than in a drawing. Optical irritations and

illusions which might occur in perspective drawings are solved for real models by a slight change of the viewpoint.

Probably the most important disadvantage of the physical models shown here is the lack of textual information necessary for legends and topography. The 3D maps shown here are not self-explanatory. To understand the content of the models either a verbal description or additional legends on paper are required.

The nearest competitors for real models are the techniques of virtual reality (VR). As mentioned in the introduction with respect to buildings, VR can provide functions that are not possible with real models, such as immediate response to interactions of the user, visualization of the time dimension in animation sequences etc. Stereoscopic images can be generated with the help of shutter glasses, monitors with lenticular lenses, or head-mounted displays, for example. In situations where several persons have to look at a 3D scene simultaneously VR is still quite expensive. It depends on the specific purpose and situation whether VR or physical models are the appropriate solution in terms of perception and economics.

6. CONCLUSION

The first experiences concerning the reception of the models by researchers in my agency were very encouraging. And surprising: nearly everybody tried to touch the models with his hands, *to get a feeling* in the literal sense. The use of the haptic channel, to touch and feel something, is a basic sensual capability. Although it is less important than the optical and acoustical senses, it has been necessary for the development of mankind, to invent and use fine tools, for example. Besides the possibility to provide maps for blind and visually impaired persons, the haptic experience could be utilized as an additional stimulus for transmitting a cartographic message and to induce insight.

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