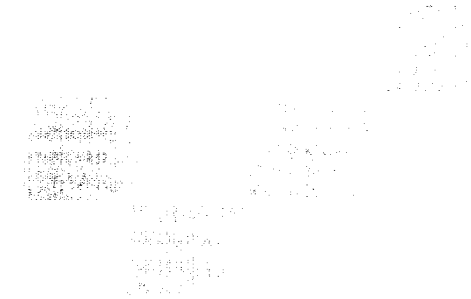
Voxel-Based Modeling for Layered Manufacturing



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Layered manufacturing technologies have revolutionized the prototyping of complex geometric designs, but still employ traditional CAD tools. A voxel-based approach is under development in a modeling tool called G-WoRP.

Several manufacturing technologies that support rapid prototyping have recently become available both in research laboratories and in the commercial marketplace. These technologies—variously called layered manufacturing, additive manufacturing, and stereolithography—allow a part, prototype, or tool to be built by laying down material in a gradual, controlled way. By contrast, traditional manufacturing methods depend on removing material (as in milling and turning) or deforming it (as in casting and molding). In this article, we use the term layered manufacturing (LM) to denote any of the technologies that support the fast-developing field of rapid prototyping.[1,2]

Software efforts in this area have focused so far on ensuring compatibility between existing CAD tools and the new manufacturing process. Because existing CAD tools are geared toward the design of parts manufactured by traditional methods, they do not help designers exploit the expanded design space offered by LM technologies. We are not aware of any work attempting to redefine the role of CAD tools in the new context. Project Maxwell[3] does try to finesse the CAD-tool-based design phase by using shape optimization techniques to go automatically from the functional specification to geometric representation. This approach obviously depends on the ability of LM technologies to manufacture arbitrary shapes.

We believe that a voxel-based approach to geometric modeling has several features that make it close to ideal for exploiting the new technologies of layered manufacturing.

Voxel-based geometric modeling

A voxel represents a volume element in volume graphics, just as a pixel denotes a picture element in raster graphics. *Voxelization* is the process of converting a geometrically represented 3D object into a voxel model. Kaufman[4] proposed that graphics is ready to shift paradigms from 2D raster graphics to 3D volume graphics with implications similar to those of the earlier shift from vector to raster graphics. Volume graphics, voxelization, and volume rendering have attracted considerable research in recent years. All of this work, however, has been directed at the informative display of volume data. We propose a voxel-based approach to geometric modeling for the new LM technologies.

The current range of rapid prototyping machines can be broadly classified based on the way they add material to an object under fabrication:

- Sequential/vector-based systems create layers by the sequential formation (by solidification or deposition) of the contours in the object's cross sections. Solid interiors are obtained with a hatching or filling-in operation.
- Parallel/image-based systems use masks to create successive layers of the component. Either a light source solidifies a photopolymer or a sprayer deposits a material on surfaces exposed by the mask. The advantage of this approach is that geometric complexity does not affect the time it takes to complete a layer. Each mask is simply a slice of the object—essentially, the image of the object's cross section.

Though the current installed base of sequential/vector-based systems far exceeds that of parallel/image-based systems, we believe the latter will dominate over the long term. A voxel-based approach is well suited to parallel systems, and the remainder of this section briefly sketches aspects of geometric modeling that can benefit from adopting this approach.

Visual correspondence

The volume-rendered image of a voxel model has direct visual correspondence to the object fabricated using LM equipment. Figure 1 shows an object voxelized using three different resolutions along the z-axis. (We obtained these and other images in this article using Bob and VolVis, two public-domain volume-rendering pack-

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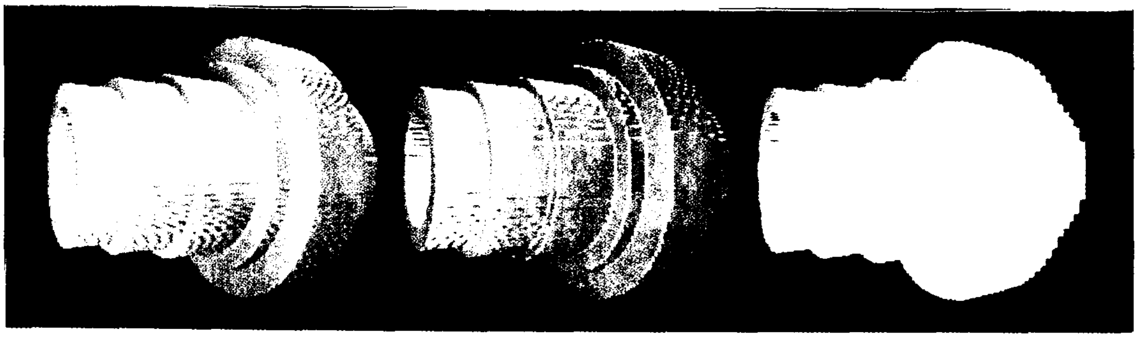
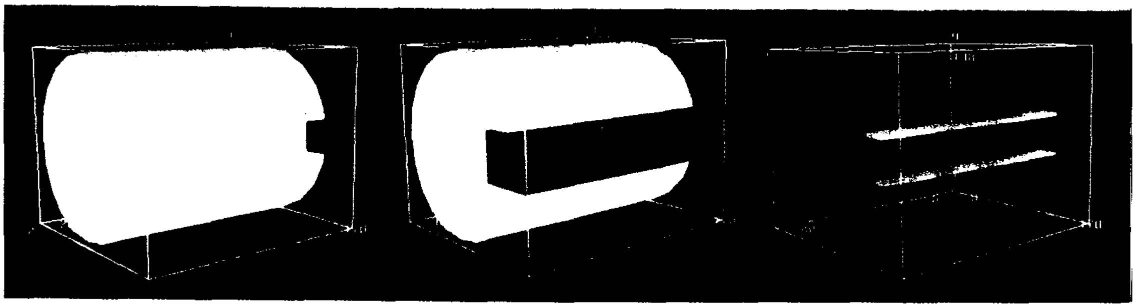
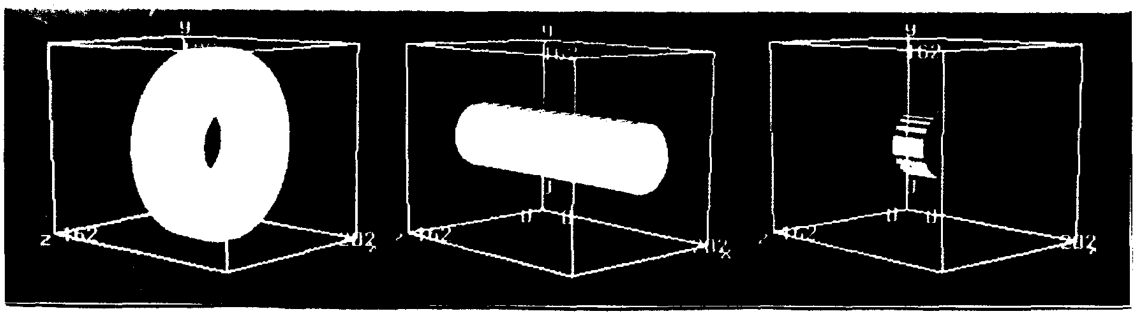


1 Object voxelized using three different resolutions along the z-axis.



2 Interference in a cylinder and key assembly detected by the difference volume.



3 Tolerance variations in washer and peg assembly visible in the interference volume.

ages that employ direct volume rendering.)

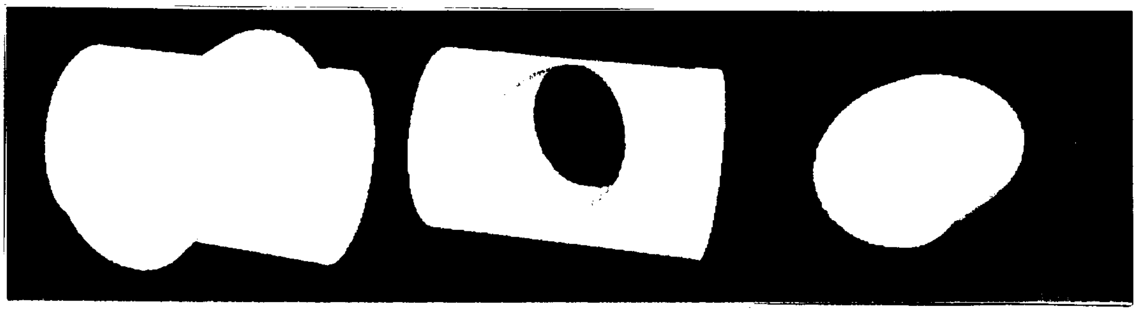
If we assume that the z-axis corresponds to the vertical axis in the LM equipment, then the z-axis step size corresponds to the layer thickness. In Figure 1, the step size or layer thickness on the left is half that in the middle, which is half that on the right. The images show the surface finish as it would appear in the actual object fabricated from the voxel models. Thus, a voxel-based system naturally provides a WYSIWYG interface, whereas a traditional geometry-based modeler displays a smooth, shaded object that gives the designer no feedback on the actual surface finish of the object after fabrication.

Estimating mass properties

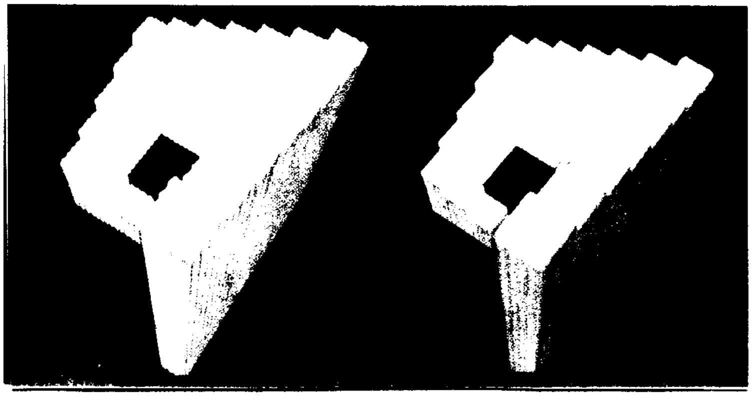
The voxel model lets designers evaluate the mass properties of the modeled object. For instance, the total material volume can be obtained as a simple sum of all the nonzero voxels of the volume buffer, suitably scaled by the parameters of the LM technology (layer thickness, horizontal resolutions, and so forth). This measure is a reasonably accurate estimate of the actual volume of the object, since each voxel translates to a precisely quantifiable unit of material deposited during fabrication. This measure can be applied independent of the object's topology. Prakash and Manohar[5] present a set of volume measures that enable the designer to easily estimate various physical properties of the modeled object. Here we outline two simple applications of these volume measures.

Interference detection. Detecting interference among the components of an assembly is a major problem in computer-aided design of mechanical parts. Analytical methods for computing such interference have been proposed,[6] but they are complicated and do not easily generalize to arbitrary geometries. A volume-error measure—the intersection volume of the two voxel volumes A and B—gives a direct and simple quantification of the interference. Figure 2 displays the interference between a cylinder and sliding key. The complete assembly displayed in the middle does not indicate any problem, but the difference volume on the right clearly shows the extent and location of the interference. This measure can be applied irrespective of the assembly's complexity and is another advantage of a voxel model.

Tolerancing. Tolerancing is an important aspect of mechanical design (for example, see ElMaraghy et al.[6]). In a voxel-based modeler, the intersection of two objects due to variations in tolerance can be visualized as a 3D interference volume itself. Figure 3 shows this in a wash-



4 Voxel-based CSG modeling of union, set difference, and intersection.



5 Staircase voxelized at 1 sample per voxel (left) and 64 samples per voxel (right).

er and peg with tolerance variations in size (diameter of the peg) and in position (axis of the peg). The interference volume due to these tolerance variations is shown on the far right. Tarbox and Gottschlich[7] provide an excellent treatment of the use of voxel models for automated visual inspection, addressing issues of registration and the use of volumetric set operations.

CSG modeling

The suitability of a voxel-based approach to constructive solid geometry (CSG) operations is well documented (for example, see Kaufman[4]). Figure 4 shows three CSG objects rendered using this approach. The union of two off-axis cylinders appears on the left; the set difference is in the middle and their intersection is on the right. Computation of the Boolean operations reduces to voxel-by-voxel logical operations.

Determining layer thickness

The fabrication time for image-based LM technologies depends primarily on the number of layers. As seen with reference to Figure 1, the number of layers determines the smoothness of the surface as well as the fidelity between the modeled and fabricated objects. Reducing the number of layers in fabricating a given model exactly parallels the aliasing problem in 2D graphics. Thus, you can apply antialiased voxelization algorithms when converting the geometric description of an object to a voxel model.

We have developed an antialiasing algorithm[5] that is a simple extension of the accumulation buffer algorithm for 2D polygons. Figure 5 shows a staircase voxelized with one sample per voxel on the left and 64 samples per voxel on the right. In both cases the resolution of the volume buffer is the same.

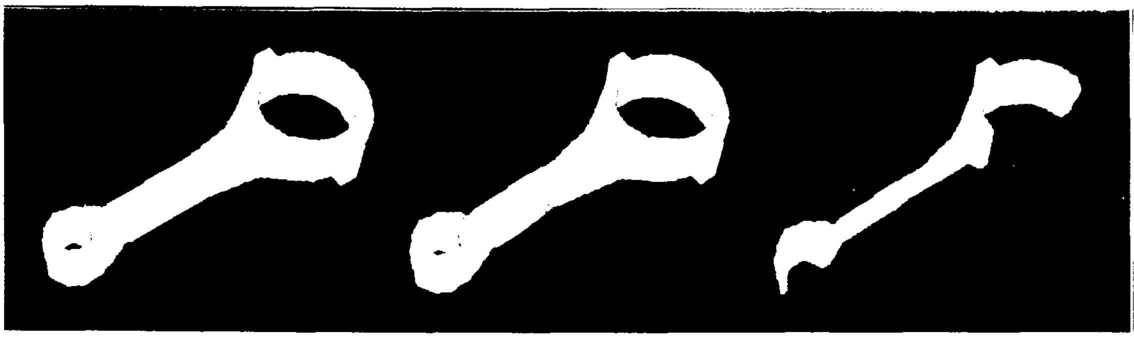
Voxel-level analysis

Figure 6 shows the volume-rendered image of a connecting rod modeled as a voxel array of dimension $200 \times 80 \times 30$. The image in the middle shows the results of free-body vibrational analysis on the model, and a cross section of this image appears on the right. Each voxel has information about the three components of the vibration. By visualizing the analysis results at the voxel level, it is possible to determine critical regions where the vibrations might exceed a specified threshold.

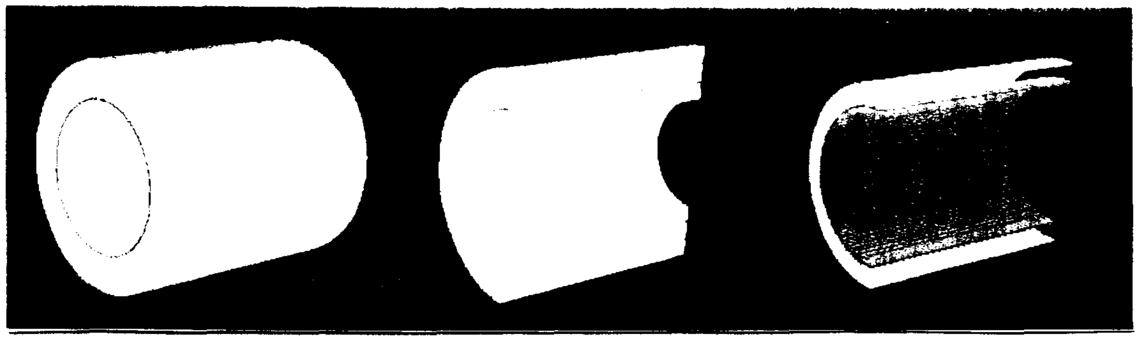
Such analyses and visualizations are not exclusive to voxel-based design tools. In fact, we obtained the connecting rod data in Figure 6 by voxelizing a polyhedral model of the object and the analysis data by applying finite-element analysis on the polyhedral model. The powerful aspect of voxel-based modeling is that the designer can selectively modify individual voxels so that the resulting object meets the design specifications. Conventional modeling does not support this capability. Achieving it in voxel-based modeling, however, requires solutions to two problems: computational analysis of voxel-based models and interactive volume sculpting (discussed later under "Research issues in voxel-based modeling").

The conventional design and analysis cycle does not consider whether a component is intended for fabrication using LM equipment. Consequently, the component is designed using any one of the widely available mechanical CAD packages. The component is modeled, then analyzed using a finite-element analysis module. The results are displayed, the design is iterated to account for analysis results, and the model is output in the .STL format for fabrication. The LM equipment takes the .STL file and generates a set of slices by orienting the object based on constraints and process parameters unique to that LM equipment. The component designer has no information about the choices made during the slicing step. Because of the discretization inherent to LM, the resulting component could have properties different from what the CAD analysis predicted.

A voxel-based approach, in contrast, eliminates the need for an intermediate format as well as for a postprocessing step beyond the designer's control. Thus, the results of a voxel-based analysis enable the designer to modify the model appropriately.



6 Variational analysis of a connecting rod.



7 Voxel model of a composite object.

Designing composites

Given solutions to voxel-level computational analysis and interactive sculpting, the voxel-based approach can exploit a major capability of LM equipment: the fabrication of composite objects. The range of materials that current commercial LM systems handle is limited but growing. It is very likely that in the near future, LM technology will mature to fabricate a single component from multiple materials. Conventional design tools are not oriented to the design of composite objects. Specialized tools are used in areas like the aircraft industry where composite materials play a major role. However, advances in LM technologies promise to bring composites into the domain of the average mechanical component. Figure 7 shows a simple composite object created using a voxel model. There are two layers of a different material (blue and red in the figures) reinforcing the bulk material (in yellow).

A voxel-based modeler can ultimately provide the capability to design a composite object with materials selectively placed at individual voxels. There is no need to compute the complex geometries of the interleaved materials because each slice of the voxel buffer can be directly read out during fabrication and several masks per layer can be created to deposit the different materials. Such capabilities will be indispensable as the technology of microelectromechanical systems matures. A voxel will then be of molecular dimensions.

Estimating surface properties

Estimating the surface properties of objects from a voxel model poses another challenge. A solution is feasible because of the direct relationship between a voxel and the basic additive resolution of the LM equipment. This relationship implies that the surface area of the resulting object can be estimated by identifying the exposed voxels in the model, adding the area contributed by the voxel faces on the boundary, and using suitable filters to simulate the effects of merging and coagulation behaviors in the real material. Properties such as friction coefficients, surface roughness, and contact area between interacting parts to be estimated.

Generating slices

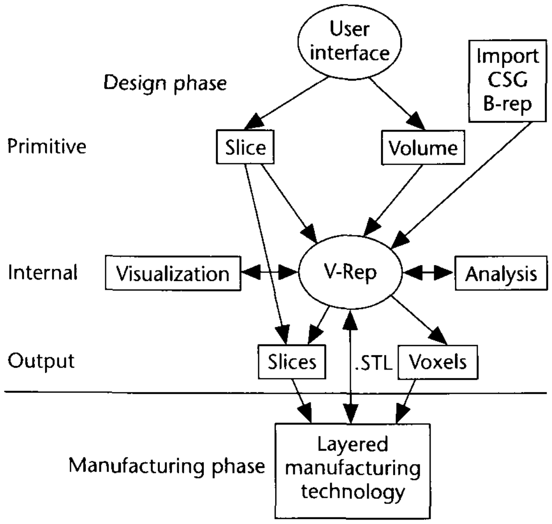
As pointed out earlier, image-based LM systems do not require a slicing step with the voxel-based approach, since the slices in three orthogonal directions are directly available from the voxel volume. However, vector-based LM equipment requires a translation step to extract contours and enclosed regions from the image data of each slice. The obvious drawback is the size of the data, but image compression techniques can mitigate this problem.

Reverse engineering

The combination of LM technologies and volume scanning devices (like CT and MRI) is a powerful reverse-engineering platform. A voxel-based modeling package can import the scanned volume data, perform voxel-level modifications, and then directly fabricate the object, or its tooling, using LM equipment. Custom prostheses, replicas of archaeological artifacts, and retooling for components where a sample is available but the design information is lost are some areas that greatly benefit from this combination.

Research issues in voxel-based modeling

Several bottlenecks, some computational and some algorithmic, must be overcome to realize the potential offered by voxel-based geometric design. We briefly sketch them here and indicate current research and development efforts aimed at their elimination.



8 G-WoRP architecture.

Memory

The memory requirements of voxel models are enormous. To store a model of reasonable resolution, say $400 \times 400 \times 400$, in raw form (that is, just as a 3D array of voxels) requires 64 megabytes of space. You can trade computation time for storage space by one of the following means:

- Store the voxel array in compressed form and use algorithms that will operate directly on the compressed data.
- Convert the voxel array into a more compact representation and reconvert into voxels when required. There are several candidate representations: octrees, wavelets, shells, alpha-shapes, and spheres (see Ranjan and Fournier[8] and the references therein).
- Retain the original geometric representation and use voxelization algorithms when necessary. This is especially valuable, since engineering design has a large library of components that can be imported into the voxel-based modeler.

Rendering complexity

To be an effective design tool, a voxel-based system should be able to update the display at interactive rates. Current graphics rendering systems cannot provide rendering performance levels on voxel models comparable to their polygon-rendering performance. This situation, however, will likely change in the near future as current research focused on parallel algorithms and hardware support for volume rendering resolves the problems.

Interactive volume sculpting

One premise underlying a voxel-based modeling and design system is the availability of a powerful interaction paradigm that gives a designer freedom to realize arbitrary shapes. Without this capability, called *interactive sculpting*, most of the advantages of a voxel-based design for rapid prototyping are nullified. Interactive sculpting is currently a highly active research area.[9] Voxel-based sculpting, however, has not received much attention. In a pioneering paper, Galyean and Hughes[10] presented a detailed vision of a voxel-based sculpting system that is a logical extension of a 2D paint program. They described the system as a coarse modeling/sculpting tool and, due to the limited volume resolutions, not a precision modeling tool. No follow-up work on the system has been reported, but our current research platform, described in the next section, extends this approach with a specific focus on layered manufacturing.

Other issues

We have discussed the importance of computational analysis of voxel-based models (see earlier section, "Voxel-level analysis." Efficient algorithms for LM process planning is another challenging research issue, which we address in the next section.

G-WoRP

G-WoRP, a *geometric workbench for rapid prototyping*, is a work in progress to create modeling software tuned toward fabrication with LM equipment. We briefly outline it here and describe it in detail elsewhere.[11]

Figure 8 presents an overview of the G-WoRP architecture. The user interacts with the workbench through an input layer that provides two major primitives—the *slice* and the *voxel*—and the operations that support them. An import facility also permits designs from other CAD systems.

Central to the internal layer is *V-Rep*, a new representation scheme that provides an efficient interface among the various G-WoRP modules. The output layer gives the part description in a form suitable to the actual LM technology employed. It also supports a process description for manufacturing the part using traditional processes.

The design and manufacturing phases do not require an explicit process-planning step because the design description of the part closely resembles the input description needed by the LM equipment. In most LM technologies, the process-planning steps reduce to the following:

- Proper orientation of the workpiece with respect to the machine, based on factors such as production time (which depends on the number of layers), accuracy, and avoidance of overhangs and trapped liquid.
- Modification of the model to compensate for shrinkage, warpage, and so on.
- Possible design of support structures for overhanging parts in some LM technologies. (Others may create the support structure automatically as part of the manufacturing process.)

G-WoRP integrates these process-planning steps in the design phase itself. Since the design develops in terms of slices or voxels, the designer can get immediate feedback about manufacturability. Further, the choice of primitives in G-WoRP obviates the requirement for a slicing processor. The manufacturing process information is made available to the internal layer to enforce constraints on the design as well as to assist in the process-planning steps.

The G-WoRP modeling paradigms based on the slice primitive are closely related to the sweep representations of geometric modeling, which have been thoroughly addressed in the literature. It is the voxel primitive that sets G-WoRP apart from traditional geometric modeling software. Clearly, building up a complex part (or even a simple part) one voxel at a time is tedious, if not totally impractical. We therefore provide several operations that let the designer work with a large chunk of voxels. However, the designer can still choose to modify a few voxels, one at a time if necessary.

The workbench is being implemented in C++ and OpenGL. We have completed the following modules: the slice primitive and its operations, the import facility for CSG models, a new voxelization algorithm with antialiasing for polyhedrally defined objects, and volume measures and their visualization. Our current focus is on voxel operations that include generalized sculpting tools; creation, manipulation, and copying of subvolumes; conversion between representations; and operations on individual layers of a volume. We are also exploring the use of virtual reality interfaces for sculpting.

Conclusion

The voxel-based approach for geometric modeling offers a powerful methodology for the new rapid prototyping technologies. It has several advantages over conventional modeling methods, stemming chiefly from the close resemblance between a voxel model of an object and the object fabricated using an LM technology. G-WoRP is our research vehicle, currently under development, for tackling the several challenging problems that remain to be solved. The design of an interactive environment for voxel sculpting is the critical factor that will bring out the full power of the voxel-based approach to geometric modeling and is the focus of our current efforts. ■

Acknowledgment

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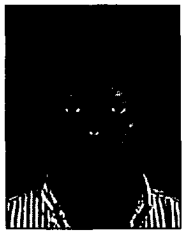

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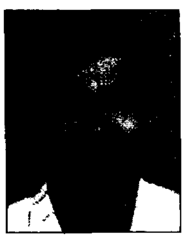

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