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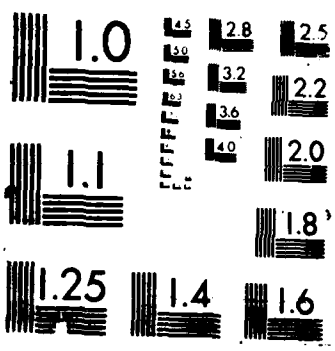
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FINAL REPORT on N00014-82-K-0351

Computer Aided Geometric Design

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All opinions, findings, conclusions or recommendations expressed in this document are those of the author and do not necessarily reflect the views of the sponsoring agency.

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The purpose of this contract was to develop and apply subdivision techniques to Computer Aided Geometric Design, using the conceptual key based on the theory of discrete splines and the "Oslo" Algorithm computational engine.

The basic validity of the theory and algorithms were established by the development of new modeling, graphical, and interactive schemes based on them and also the use of many of these ideas by othr researchers and the use of the published results by industry. Related new theory and algorithms were developed; the mathematical model was extended. New styles of modeling were proposed and theory and algorithms for graphics and modeling of nonrectangular surface generalizations were developed. The role of graphics in design and modeling as a tool has been considered.

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1. Technical Description of Project and Results

The problems that this grant attacked were taken from the original proposal, with several generalizations as they became appropriate. We cite from the abstract of the proposal.

> ... funding is sought for continued research in the development and application of subdivision techniques in the area of Computer Aided Geometric Design (CAGD). ... The conceptual key to this work is some recent advances in the theory of discrete splines and the new "Oslo" algorithm which can provide the necessary means to bring together the geometrical design and graphical display of curved surface objects to form the basis of an integrated approach.

The proposed research had the following main points:

- Continue to extend the mathematical model of discrete splines and the Oslo Algorithm which computes them to the domain of CAGD.
- Have a goal of designing, implementing, and experimenting with discrete splines and the Oslo algorithm in order to significantly advance the present state of affairs in CAGD.
- Use subdivision and refinement as the philosophy of approach and the Oslo Algorithm as the main computational tool.
- Study and develop modeling operations
- Address nonrectangular surface generalizations

The purpose of this grant was to develop and apply subdivision techniques to Computer Aided Geometric Design, using the conceptual key based on the theory of discrete splines and the "Oslo Algorithm" computational engine. A major theme was to design, implement, and experiment with discrete splines and the Oslo algorithm in order to advance the state of affairs in CAGD.

The basic validity of the theory and algorithms were established by the development of new modelling, graphical, and interactive schemes based on them and also the use of many of these ideas by other researchers and the use of the published results by industry. Related new theory and algorithms were developed, the mathematical model was extended. New styles of modelling were proposed and theory and algorithms for graphics and modelling of nonrectangular surface generalizations were developed. Since good computer aided design requires realistic image making capabilities for the models, some work was devoted to developing new algorithms and software for that area, including those based on line drawings, image composition and modification. The role of graphics in design and modelling as a tool has been considered.

We considered an integrated approach so that one branch of the research could rely on the other. The research fell into several main groupings, with significant overlap. These areas include theoretical results, algorithms based on theory, ab initio modelling operators and and a posteriori data fitting, graphics to visualize models, systems issues in Unix, and model based vision.

1. Nonrectangular Surface Domains: Initial investigations of multivariate spline theory with T. Lyche resulted in [5] where we introduced "discrete box splines", which serve as a theoretical framework for refinement theory of continuous box splines. The proofs and algorithms developed investigating the relationships between discrete and continuous box splines opened the door for investigation of other properties of continuous box splines and for the first time made it feasible to consider computation, modeling, and rendering with them.
2. Theory and Algorithms: In [3, 4] we developed theory and algorithms, based on discrete

B-splines for degree raising of general spline curves. These results were immediately useful to in research performed on developing new 3-D modelling techniques for computer aided design.

3. Modelling Operations:

Boolean Operations: Performing boolean operations on spline based boundary models is theoretically straightforward, but the implementation in floating point causes many practical difficulties. In [18, 17], a general method was presented for performing Boolean set operations on solids represented by a sculptured surface boundary model. The method is developed first for solids with closed boundary surfaces. It is then shown to apply also to "partially bounded" solids, which have incompletely specified bounding surfaces.

Primitive Modelling: In [13] simple solid primitives were incorporated into a spline based boundary representation. In the course it was noticed that most primitives really used in modelling do not have sharp edges, but are rounded, so new "Rounded Edge Primitves" were developed.

Shape Operators: The notion of shaping operators within the framework of a unified representation was developed in [2]. High level operators which accomplish many tasks have been proposed as samples within this framework.

Approximation: Parts were modelled a posteriori and several techniques that are useful for modellers to have were discussed in [6, 7].

4. Graphics:

Understanding, proposing and developing graphical cues as useful aides to understand shape as part of the design process was the theme of [12]. Applying hidden line renderings as an aid to surface visualization was done in [8]. Ray tracing of B-splines has been investigated [19], and [16] extends ray tracing to include dispersive refraction.

The Utah Raster Toolkit was developed. The Utah Raster Toolkit is a set of programs for manipulating and composing raster images. These tools are based on the Unix concepts of pipes and filters, and operate on images in much the same way as the standard Unix tools operate on textual data. The Toolkit uses a special run length encoding (RLE) format for storing images and interfacing between the various programs. This reduces the disk space requirements for picture storage and provides a standard header containing descriptive information about an image. Some of the tools are able to work directly with the compressed picture data, increasing their efficiency. A library of C routines is provided for reading and writing the RLE image format, making the toolkit easy to extend.

5. Other: Spline based modelling has been a subject for much study, since it is the premise upon which many of our algorithms and modelling operators are based [10]. The Unix operating system has influenced many choices [14], and workstation technology is changing the importance of many computational issues [15].

2. Publication Citations

All papers appearing in this section cite this research grant for partial support. The supported theses also are listed in this section.

1. Bhanu, B., Henderson, T., and Thomas, S., "3-D Model Building Using CAGD Techniques," *Proceedings of CVPR 85*, 1985.

2. Cobb, Elizabeth Susan, "Design of Sculptured Surfaces Using the B-spline Representation," Ph.D. dissertation, University of Utah, June 1984.

3. Cohen, E., Lyche, T., and Schumaker, L.L., "Algorithms for Degree-Raising of Splines," *ACM Transactions on Graphics*, Vol. 4, No. 3, July 1985, pp. 171-181.

4. Cohen, E., Lyche, T.,Schumaker, L.L., "Degree Raising for Splines," *Journal of Approximation Theory*, Vol. 46, No. 2, February 1986, pp. 170-181.

5. Cohen, Elaine, Lyche, Tom, and Riesenfeld, Richard, "Discrete Box Splines and Refinement Algorithms," *Computer Aided Geometric Design*, Vol. 1, No. 2, 1984, pp. 131-148.

6. Cohen, E., "Some Mathematical Tools for a Modeller's Workbench," *NASA Symposium on Computer Aided Geometry Modelling*, 1983.

7. Cohen, E., "Some Mathematical Tools for a Modeller's Workbench," *Computer Graphics and Applications*, October 1983.

8. Fuson, Vanessa Taphouse, "Applications of a Hidden Line Algorithm to Surface Visualization," Master's thesis, University of Utah, August 1984.

9. Peterson, John W., Bogart, Rod G., Thomas, Spencer W., "The Utah Raster Toolkit," *Proceedings of the Third Workshop on Computer Graphics*, Lou Katz, ed., Usenix, November 1986.

10. Riesenfeld, Richard F., "A View Of Spline-Based Solid Modelling," *Proceedings of AutoFact-5*, 1983.

11. Riesenfeld, Richard F., "Computer Aided (Geometric) Design Education in the CS Department," *Proceedings of Conf on University Programs in Computer Aided Engineering, Design, and Manufacturing*, BYU, Provo, Utah, 1983, Presented to the BYU conference, April 1983

12. Schweitzer, D., "Artificial Texturing: An Aid to Surface Visualization," *Proceedings of Siggraph '83*, July 1983, pp. 23-31.

13. Stay, Paul Randal, "Rounded Edge Primitives and Their Use in Computer Aided Geometric Design," Master's thesis, University of Utah, August 1984.

14. Thomas, S. W., "The Alpha_1 Computer-Aided Geometric Design System in the Unix Environment," *Proceedings of the Computer Graphics and Unix Workshop*, Lou Katz, ed., USENIX Organization, Dec. 1984.

15. Thomas, Spencer W., "A Low Cost Graphics Workstation," *Proceedings of the 1986 USENIX Computer Graphics Workshop*, Reidar Bornholdt, ed., USENIX Assoc., Dec. 1985.

16. Thomas, S. W., "Dispersive Refraction in Ray Tracing," *The Visual Computer*, January 1986.

17. Thomas, S. W., "Set Operations on Sculptured Solids," Tech. report UUCS-87-004, Dept of Computer Science, University of Utah, February 1987.

18. Thomas, Spencer Woodlief, "Modelling Volumes Bounded by B-spline Surfaces," Ph.D. dissertation, University of Utah, June 1984, Also Technical Report UUCS-84-009

19. Warren, Lloyd Van, "Geometric Hashing for Processing Complex Scenes," Master's thesis, University of Utah, August 1985.

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