Rapid Prototyping from 3D Scanned Data through Automatic Surface and Solid Generation

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Abstract

With the introduction of solid free form fabrication techniques there has been significant interest in producing prototypes from design representations. Although free form fabrication processes require solid modeling information, the representations available in the design stage might often be of lower order dimensions. In certain cases, the design information is presented as a set of sampled points scanned from 3D objects. In this paper, we describe an implementation where scanned data is automatically converted to surface -and solid representations successively using a non-manifold geometric modeling system, NOODLES. After defining valid solid models, prototypes are fabricated with streolithography. The stereolithography process is planned within NOODLES by transforming solid representations into planar slice descriptions using the non-regular set operations provided by NOODLES.

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1 Introduction

SoUd-freeform-fabrication (SFF) processes are a relatively new class of fabrication technologies **which build** three-dimensional shapes by incremental material buildup of thin layers. These processes include, selective laser sintering [2], laminated object manufacturing [4], ballistic particle manufacturing [7], three-dimensional printing [8], and stereolithography [3]. SFF processes can make geometrically complex parts with little difficulty and are particularly suited for rapidly producing physical prototypes from design representations. They are also useful for reproducing models of arbitrary shaped physical objects using representations obtained from scanned measurement data.

The focus of this article is on the construction of surface and solid representations of physical objects from the sensor data and converting the three dimensional representation into the contoured planar surfaces required for planning the SFF process. In addition to the three-dimensional represenation's use in SFF, these representations are also important for graphic displays, for computing geometric properties, and for computer models for various engineering analysis.

The method of constructing surface and solid representations will depend on the type of the data. This article describes an approach to construct surface and solid representations of objects from the data gathered by three dimensional coordinate measuring machines(CMM). A non-manifold geometric modeling environment is used in this application for representing the various intermediate modeling stages.

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In the current implementation, only *21D* objects such as sheet metal parts are considered. It is also assumed that the objects are projectable in *x-y* plane without overlap. Thus, the z-directional component of a local surface normal at any location on the same side of a surface has the same sign, either positive or negative. An automobile hood is used as an example throughout this article.

The type of the input data is briefly described here since the surface generation techniques strongly depend on the type of input data. The input data is given in the form of a group of sampled points in the *x* and *y* directions and along the boundary of an object. Each group *ot* points forms a continuous curve (e.g. interpolating spline) in the *x* direction, in the *y* direction, or along the boundary. Scan lines in *x* and *y* directions or along the boundary consists of several disconnected curve segments. The spacing between sampled points in one scan line and spacing between two adjacent scan lines in the same direction is assumed to be arbitrary. It is also assumed that there is no explicit information in the data regarding direction, order, or connectivity of the curve segments. Therefore, the input data represents a group of curves without any relational information between curves. The goal is to form a smooth curved surface from this data.

The basic strategy for this solving problem is to build a fully connected wireframe model and then transform it into a surface model. However, a set of curves given as an input data is not sufficient, even for a complete wireframe model. In the initial data, curves on the boundary, and curves on *x* and *y* scans are not topologically connected with each other [see Figure 1]. Therefore, the topological connectivity at the points where the curves cross each other must be obtained only from the geometry. Once a valid solid representation is obtained it is further processed for planning the stereolithography operations. The strategy is to reduce the 3-D data to a set of *2½D* cross-sections by intersecting the solid with a stack of planes.

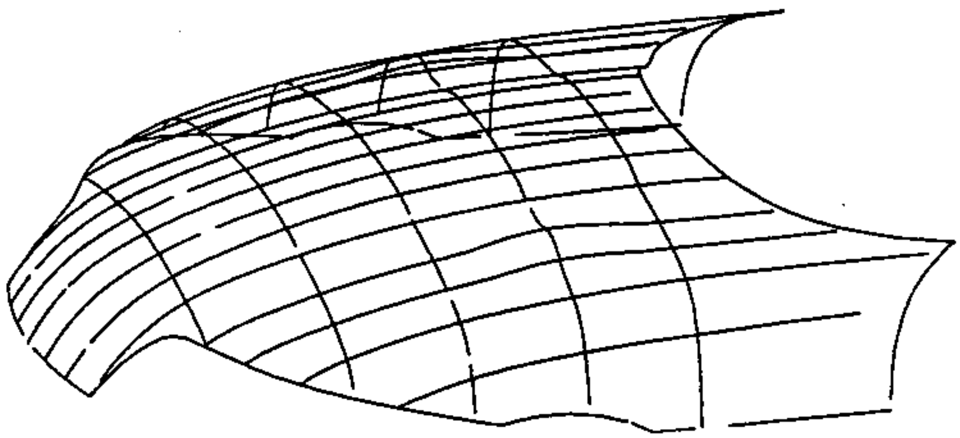

Figure 1: A Set of Interpolated Curves from Sampled Data Points

2 Modeling with Scanned Data

A non-manifold geometric modeling environment is the natural choice for the required representations, because it can handle non-homogeneous dimensions within a uniform data structure. Furthermore, the transitions from a wireframe model to a surface model, then from a surface model to a solid model, and finally from a solid to a set of cross-sections can be handled easily in a non-manifold modeling system rather than using separate systems for surface and solid representations.

The B-rep non-manifold geometric modeling system *NOODLES*[2] [1, 5] was chosen for the

[2]The non-manifold geometric modeling system *NOODLES* was developed at Carnegie Mellon University

implementation of the work described in this article. The current *NOODLES* **geometry supports only straight lines, polygons, and polyhedra, although the extension into the curved** geometry is in **progress. Therefore, currently, we use only linear approximations to** represent curved **geometric entities.**

2.1 Wireframe Model

The input data contains a number of unstructured curves that are interpolated curves from the sampled points by a CMM. A vertex is created at each data point and two adjacent vertices are connected by a straight edge. Through this process, the input curves are mapped onto a wireframe model that is a set of disconnected curves. Each of the curves is composed of several edges connected together.

Following this, the disconnected curves are organized for the construction of a network structure. Each of the curves is classified into one of the three categories, i.e., ^-direction curves, ^-direction curves, and boundary curves. This classification is achieved by using the tangential component of the curves in *x-y* plane and the proximity of the curves. Then, the curves in each category are ordered in each direction using the position of the curves. Boundary curves are ordered in clockwise or counterclockwise direction to form a closed loop. Curves running in *x* and *y* directions are classified into several scan lines. Each of these scan lines consists of several ordered curves. The scan lines themselves are also ordered in each direction. There are 15 scan lines in *x* direction, and 5 scan lines in *y* direction in the example of Figure 2.

Disconnected curves on the boundary, and in each *x, y* scan lines, are topologically connected by making edges between two close end vertices of the two adjacent curves. Also, the first and the last curves in each scan line are topologically connected to the boundary curves by extrapolating the scan lines. This is accomplished by finding the two points on the boundary curves which intersect with each scan line on *x-y* plane.

At this point, the wireframe model is topQlogically fully connected along the boundary. The final step in completing the wireframe model is to find out all the internal crossing points, and to connect a pair of crossing curves at each point. For each pair of scan lines, one from *x* direction and the other from the *y* direction, it is possible to obtain **a** pair of intersecting curves on *x-y* plane. Although these two curves intersect on the *x-y* plane, they actually do not pass the same point in 3D space due to the error from the CMM measurement and the interpolation. Therefore, we need to decide where the actual crossing point should be located. It can be located midway through the two positions on the curves that give closest distance between those two curves, or it can be located on one of the two crossing curves. Then the two curves are topologically merged at the adjusted crossing point. However, the introduction of the crossing point may cause the sudden change of the local curvature on the final surface representation. To minimize the effect of the sudden curvature change, it is necessary to propagate the position displacement at the crossing point over the neighbour interpolating points on the curve. This issue will be further discussed in the following section. By connecting all the intersecting curves at crossing points, a

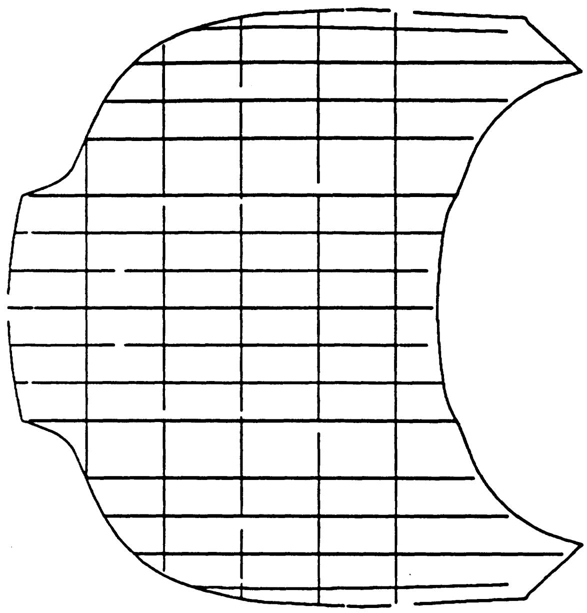

Figure 2: Top View of Raw Scanned Data: Interpolated Curves

wireframe model with a complete network structure is prepared for the next surfacing step [Figure 3].

2.2 Surface Model

One of the important problems that must be addressed for the smooth curved surface fitting is the adjustment of two curves at the crossing point. Although this problem should have been handled in the wireframe modeling stage, it is discussed here since its effect can be observed very clearly when the curved surface fitting is attempted.

Because of the nature of the scanning method with CMM and the curve interpolation, two curves, which are supposed to cross at a point in 3D space, do not actually cross. Therefore, we need to adjust the pair of the near crossing curves by introducing an additional data point and moving neighbour data points for the smooth transition of curvatures. In Figure 4 solid lines are the original curves which are interpolated curves with given data points. In this example, the crossing point is decided at the middle of two positions on the curves that give closest distance between those. A method *B*, in which the positions of neighbour points are adjusted appropriately, will result in smoother surface than method *A*. The method of propagating the displacement for the best result in curved surface fitting is an another research issue. But, the

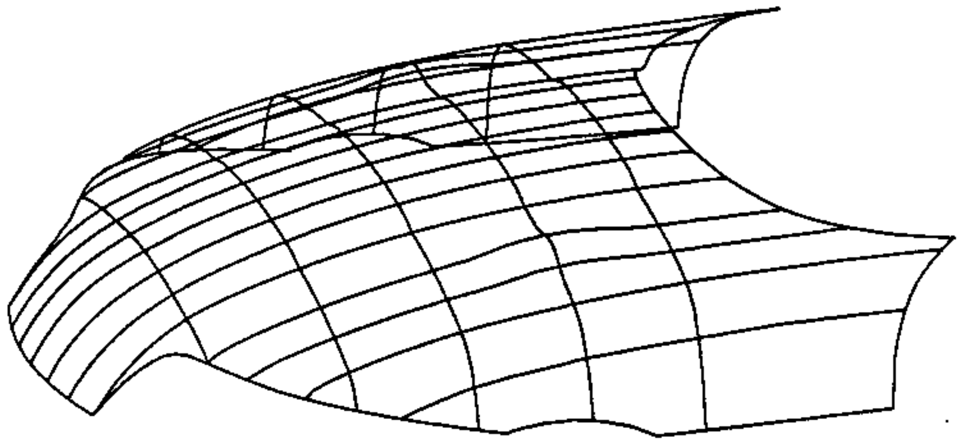

Figure 3: Completed Wireframe Model

propagation of the displacement may again introduce a undesirable effect on the other crossing points nearby. This effect must be also taken into account for smoothing the wireframe grid.

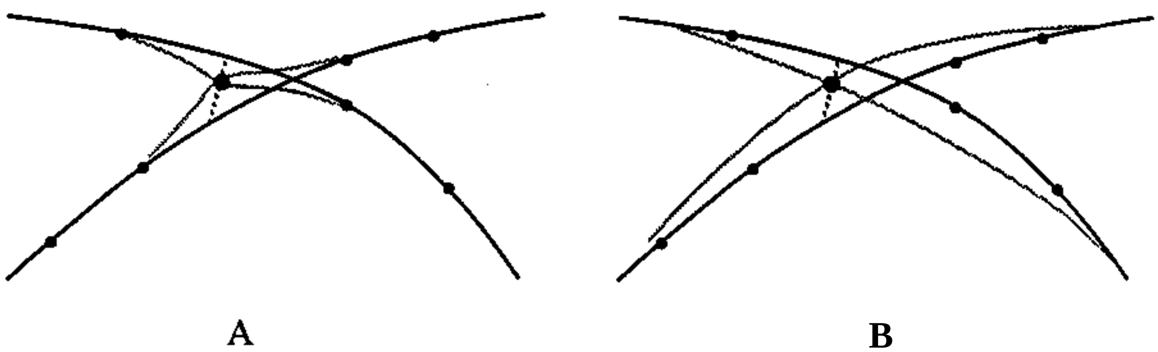

Figure 4: Adjustment of Two Curves at a Crossing Point
Method A: Interpolating Points Are Not Disturbed
Method B: Displacement is Propagated over Interpolating Points

A smooth curved surface with the desired shape is the ultimate goal of the surface fitting onto a wireframe model. Currently, however, only the polygonal approximation of the surface has been accomplished as an initial attempt. It is also assumed that the entire surface does not have sharp ridges or grooves. If sharp ridges or grooves are desired in the surface, the information must be incorporated in the data during the scanning.

It is first necessary to identify each grid that forms a closed loop in the wireframe model [Figure 5]. Edmonds' embedding technique [9] is used to form valid loops in the wireframe model. This is possible because of the assumption that the wireframe model is projectable onto *x-y* plane without overlap. Boundary curves are used only once, and internal curves are used twice in both directions to form all the valid loops. More detailed description of the algorithm can be found in [6].

Then, the loop is filled with triangular patches. The triangular patches can be formed by connecting appropriate three boundary vertices on the loop. Or, a vertex can be created inside the loop for the apex of all the triangular patches, each of which uses a segment of the loop as the foot. The method of creating triangular patches may affect the smoothness of the approximated surface. Although this is only an approximation of a curved surface, it could be useful in several aspects including $2\frac{1}{2}D$ finite element mesh generation for plate-like objects directly from the scanned data.

2.3 Solid Model

In the non-manifold environment, a solid can be created by simply closing an open surface. If the proper tools and algorithms for constructing an arbitrary surface from the scanned data are provided, a solid will be automatically obtained when the surface is closed by the last surface patch. However, in the particular application described in this paper, only non-volume trie $2\frac{1}{2}D$ objects are of interest. Thus, a thin solid is created by sweeping the surface along the z direction for the physical realization of the object. The photo in Figure 6 shows the object fabricated by stereolithography using this solid model. The quality of the surface approximated with polygons may be improved by sampling more data points. However, surface fitting with composite curved surfaces on the network of interpolated curves is our ultimate goal.

3 Generation of Representation for SFF

The fundamental nature of SFF processes is to incrementally build-up objects in layers. Therefore, the geometric aspect of the process planning involves decomposition of the objects into successive cross-sections. In terms of representation, it is necessary to first have a valid solid model in order to generate cross-sections that are not merely contours, but rather plane-portions with inside-outside information. This requirement introduces an interesting transition in the choice of an appropriate representation for the process planning phase. As described in the previous section, a conversion from lower to higher dimensionality of representation had to be performed in order to build solid models of the objects to be fabricated. In the process planning

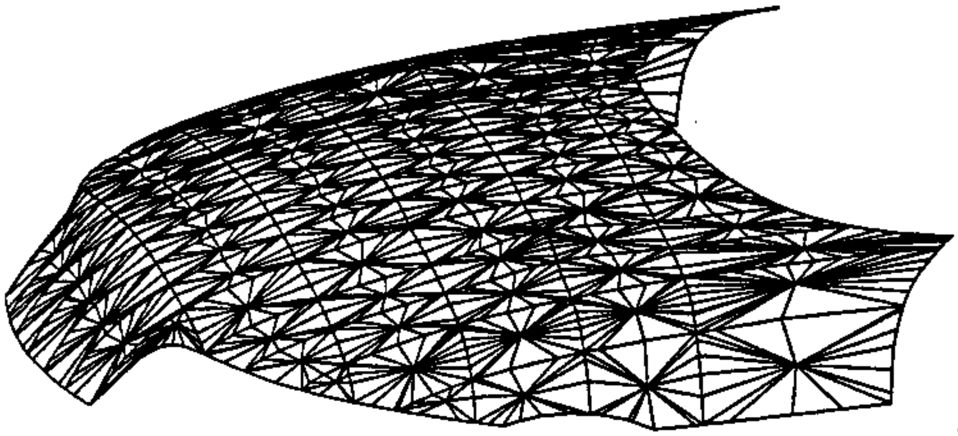

Figure 5: Polygonal Approximation of the Surface

phase however, a decomposition back into lower dimensions has to be performed in order to generate the appropriate geometric information. This situation makes it very advantageous to use a geometric modeling environment that represents objects of varying dimensionality in a uniform fashion. Another significant aspect is the requirement for operators that can perform these dimensional transitions in a formalized fashion.

NOODLES performs boolean operations between objects of non-homogeneous dimensions on the set-theoretical basis. Hence, boolean operations on non-homogeneous entities produce perfectly meaningful results. This allows the cross-sections to be conceived as intersections between solids and planes. For the specific case of stereolithography, we generate a geometric model composed of a stack of planes that are spaced according to the desired slice resolution. The cross-sections are obtained as the boolean intersection of the object with this model. The plane portions are further processed to extract the oriented contour information. This constitutes a lower level input to the stereolithography process which usually takes some form of outer shell description.

Conceptually, the decomposition can be taken one step further to generate raster information to drive the laser. This transition can be achieved within the same representational and operational formalism. Currently, this level of input is not supported by the stereolithographic system that is being used. However, significant advantages may be gained by propagating the properties of the

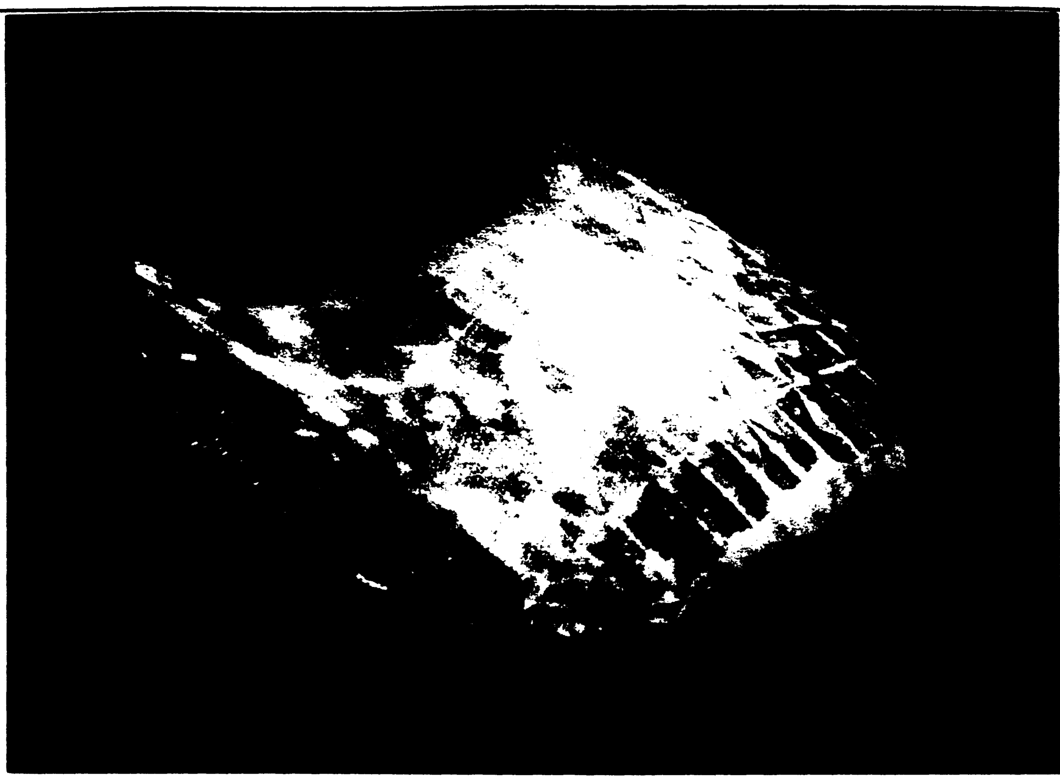

Figure 6: A Surface Duplicated from a Physical Object through Scanned Data

object's surface all the way down to the raster level. With the appropriate inheritance, such issues can be addressed to improve the precision of the fabrication.

4 Conclusion

This article described our preliminary work on converting scanned data to surface and solid models, and eventually prototyping the objects with the stereolithography process. First, a wireframe model was created from the scanned data. Then a surface model was constructed by patching each grid with polygons. Finally a solid model was created by sweeping the surface. This solid model was used to build a physical object, with arbitrary scale, using the stereolithography process. The unifying modeling environment NOODLES was used for both the multi-dimensional geometric representations and for process planning. A unified data structure for all the levels of representation seems to provide easier transition from one level of representation to the next.

Although several assumptions have been imposed in the current work, our result shows an example of 3D duplication directly from a physical 3D object within a short period of time with minimal human intervention. Future work includes the model reconstruction of arbitrary volumetric 3D objects from various types of data including cross-sections such as CAT scan data. Current representation with straight lines and planar polygons must be also replaced by the

one with free form curves and surfaces in the future.

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