Geodesic and Semi-Geodesic Line Algorithms for Cutting Pattern Generation of Architectural Textile Structures

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Abstract

The general field of stressed membrane surface structures is first introduced. The design processes typically involved in the design of such membranes, namely *Form-finding*, *Statical Load Analysis* and *Cutting Pattern Generation*, are next described. Specific consideration of *Geodesic Line Generation* and the requirements for a practical solution strategy are then given. A novel procedure for addressing the complex problem of generating *Semi-Geodesic* lines is next presented. All the line generation tools implemented in the widespread lightweight structure design system, Easy, including *Geodesic* and *Semi-Geodesic* are then described. Finally, these tools are demonstrated using a typical example surface. Due to the general importance of good quality seam line generation, the strategy described is applicable for all cutting pattern generation systems.

Introduction

This paper is concerned with the design of architectural membrane surface structures fabricated from planar strips of either textile fabric or plastic film. Originally this problem was addressed through the construction of physical models for both *Formfinding* and C*utting Pattern Generation*. After several decades of continual development, sophisticated software systems are now routinely used during the design process. These are based on either simultaneous patterning/form-finding; surface cutting/flattening; or planar sub-surface growth. Today, the main focus for system enhancement lies in the creation of interactive tools to facilitate design optimisation, particularly the control of cutting pattern seam layout.

The Membrane Structure Design Process

The three main processes involved in the design of membranes for architectural structures are; *Form-finding*, *Statical Load Analysis* and *Cutting Pattern Generation*. *Form-finding* is the name given to the problem of determining a structural form, in most cases a surface, which is in force equilibrium and satisfies additional design constraints. *Statical Load Analysis* must typically be performed using geometrically non-linear structural analysis software in order to check that the form-found surface satisfies ultimate and serviceability constraints. Finally, the formfound

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surface must be converted into a set of planar cloths for fabrication, this is termed *Cutting Pattern Generation*. Detailed examination of these processes can be found in the literature [4-10]. Consideration of *Cutting Pattern Generation*, however, usually deals exclusively with the problems of defining cloth subdivisions of large surfaces, and ensuring that these sub-surfaces are two-dimensionally developable. The specification of the actual layout itself is handled, at best, by interactive input from the design engineer. This layout optimisation problem, together with a systematic approach for dealing with it is considered in [12]. Fig. 1 shows a typical high point surface as formfound, while Fig. 2 shows the locations of the inter-cloth seams during the subsequent cutting pattern generation procedure.

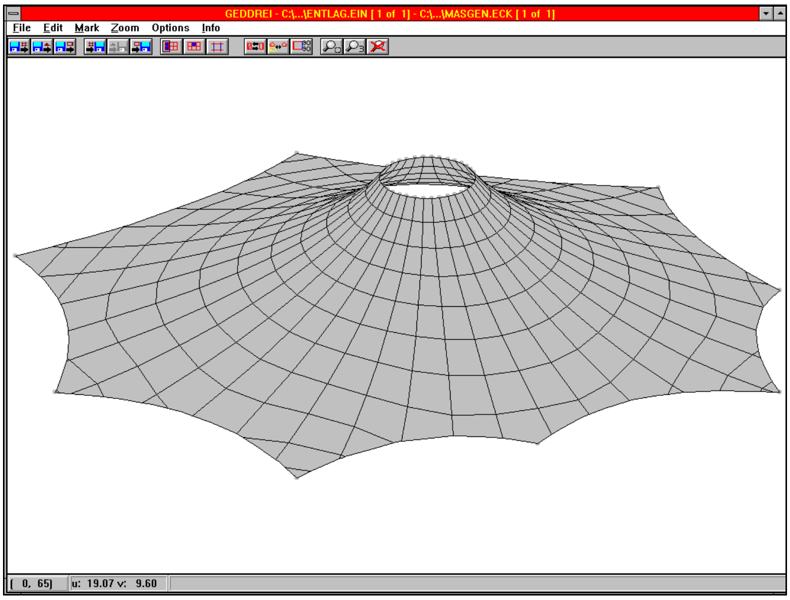

Fig. 1: Typical high point surface structure.

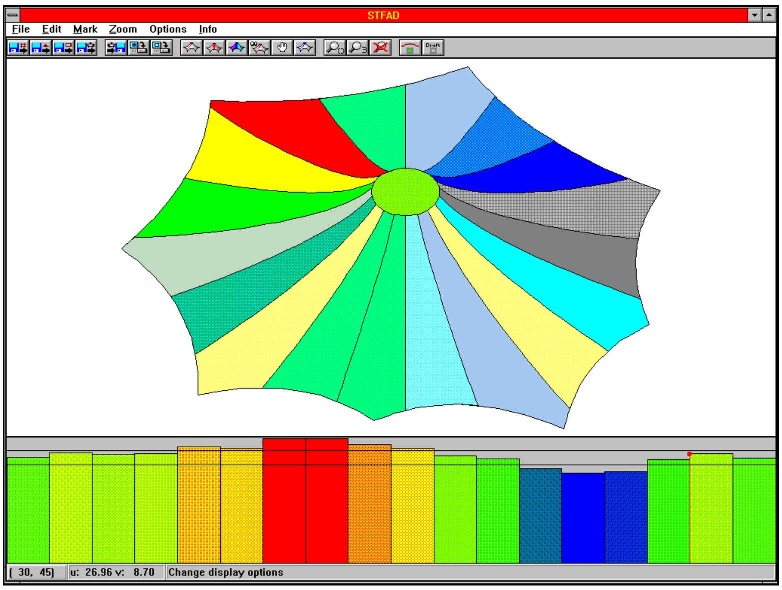

Fig. 2: Screen dump of the Easy system's STfad patterning tool showing a cutting pattern layout for the high point surface shown in Fig. 1 with graph of cloth widths.

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Surface line generation

A major aspect of all cutting pattern generation systems is the manner of seam line creation. The quality of the seam geometry greatly affects both the technical and aesthetic performance of textile roofs. The most important seam parameters are the *Line type*; *End point location*; and *Discretisation* level. The problems of efficiently specifying and varying *End point location* and *Discretisation* are dealt with in [12]. In the following, specific attention is given to the strategies used for the generation of intermediate line nodes.

Line types

We define the following types of surface lines: *Geodesic, Planar Section, Irregular,* and *Semi-Geodesic*.

Geodesic

Geodesic lines have the property that as they pass over a surface, they do not curve in the tangential plane. Consequently, a surface properly patterned on the basis of geodesic lines can have cloths which minimise cloth usage as well as the angles between textile weave and surface principle stresses.

Planar Section

Some patterning systems exclusively use lines defined by the intersection of the structural surface and simple planes. The deficiency of such a strategy compared to a geodesic approach has been long established. For example, in Figs. 4 and 5 two patterns are shown for the simple saddle surface shown in Fig. 3. In Fig. 4, vertical planar cut patterning was used. The characteristic 'banana' cloths may be compared to those derived from a geodesic patterning which are shown in Fig. 5.

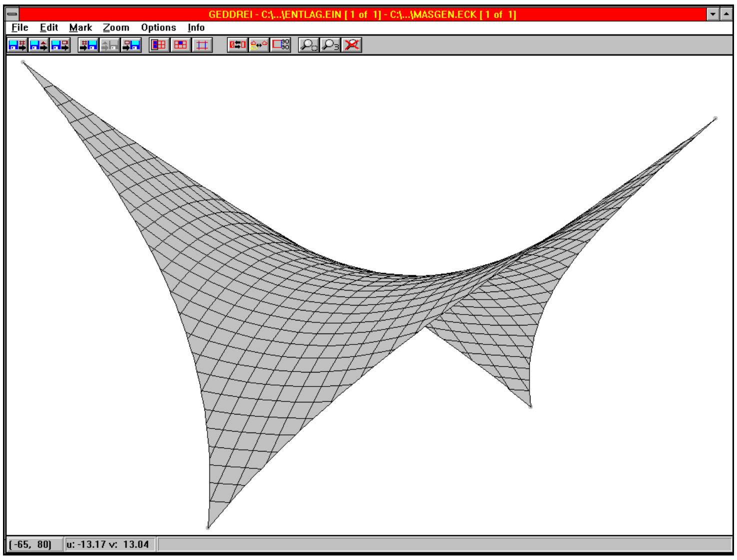

Fig. 3: Simple saddle surface.

There are, however, some situations where a planar section is the most appropriate line type. For example, in symmetrical surfaces a vertical cut may be the best choice for the seams, or cloth centres, running along the symmetry axes. Similarly, where roofs must connect to rectilinear supports, in some cases it is better to cut the formfound surface with planar sections, rather than formfinding with rectilinear boundaries.

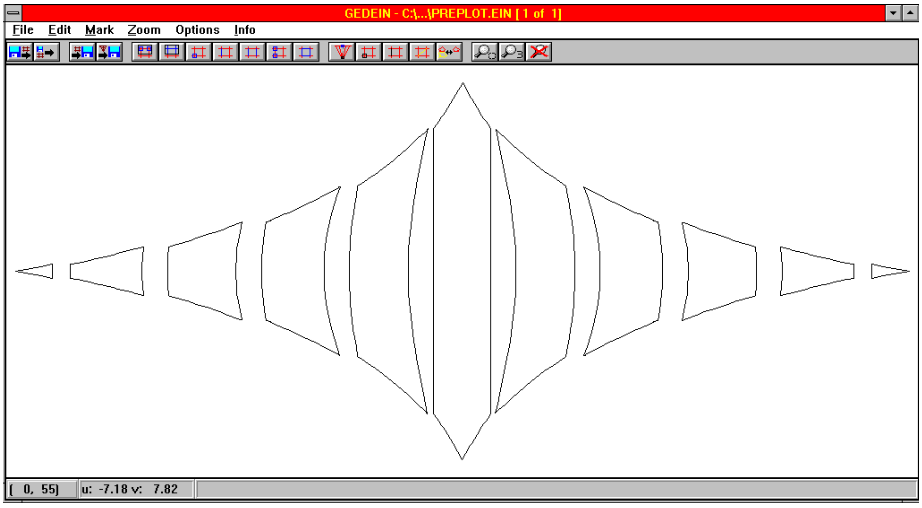

Fig. 4: Vertical planar cut patterning of saddle shown in Fig. 3.

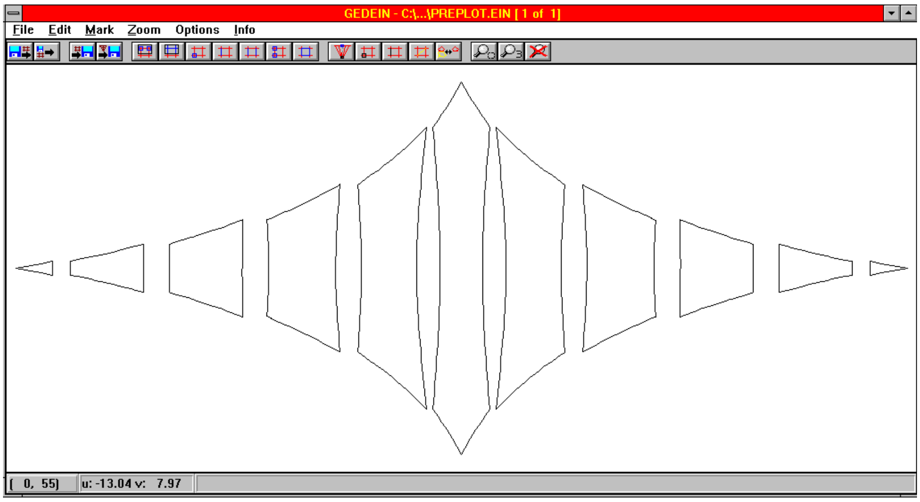

Fig. 5: Geodesic patterning of saddle shown in Fig. 3.

Irregular

In some cases it is necessary to be able to generate cloths with very detailed boundary shapes, such as with boundary cable scalloping. If the level of detail is much finer than the basic surface mesh, it is necessary to be able to generate geometric boundaries and thence project these irregular lines onto the basic surface.

Semi-Geodesic

Whatever their basis, most high quality cutting pattern systems exploit in some way the benefits of *Geodesic* seam line generation. As illustrated above, since *Geodesic* lines have the property of being locally straight relative to their surface of generation, cloths patterned with *Geodesic* seams will tend to have good economic and mechanical performance. In a small number of situations, however, *Geodesic* lines will not be the most suitable choice. This is particularly the case when patterning surfaces whose curvature does not strongly constrain the *Geodesic*. For example the ends of some airhalls can approach spherical shapes. In such situations it can be difficult to keep cloth centre widths controlled. A pure geodesic line is usually defined in terms of only its end point positions. For better user control, it would be useful to be able to constrain the generated lines to additionally pass through specific interior surface points. Unless such constraining points lie on the pure *Geodesic* path, then the generated line will not be straight relative to the surface. Accordingly the term *Semi-Geodesic* is used to distinguish such lines.

Geodesic and Semi-Geodesic Line Generation Strategies

It is extremely common for geodesics to be defined as ‘The line of shortest distance between two points on a surface, passing over that surface.’ This definition is false, though it is certainly true that any line satisfying the condition will be geodesic. The problem with the definition is that in certain situations there may be more than one geodesic lines between the two points. For example, consider the simple cylinder where there are an infinite number of geodesics, only one of which is shortest; or the poles of a sphere which are connected by an infinite number of geodesics, all of equal length. It is unfortunate that this incorrect definition has become so popular, in that it emphasises the length aspect rather than the angular nature of the geodesic property. It is the fact that a geodesic is straight which leads to its excellent suitability for seam generation in textile architectural applications.

As with the theoretical definition, the techniques used for the computational generation of geodesic lines can be broadly divided between *Length* and *Angular* based approaches. With the former the position of the intermediate points are adjusted such that the total length of the line is minimised. This can be achieved in a number of ways. Seam links with very high tension may be introduced into the formfinding mesh and used to pull the seams into geodesic paths. Clearly, so as not to affect the formfound surface too much, the out of plane components of these high string tensions must be suppressed together with the end point reactions. Alternatively, such strings may be slid about over a fixed surface using a length minimisation cost function.

One simplistic approach to the creation of geodesics over triangulated surfaces is based on the propagation of line/triangle intersections from facet to facet. Although effective in many situations, the drawback with such an approach is that numerical errors accumulate across the surface. The purest approach is to use an algorithm which adjusts the position of the nodes according to observations on the normal plane angles themselves. In such an approach the surface tangential planes in the neighbourhood of each line point are determined in order to define multiple local coordinate systems. By constraining the line nodes to lie on these planes, it is possible to develop linear adjustment problems with observations on the angles and single degrees of freedom for each point. After solving each linear problem, the nodes need to dropped back onto the surface and the process repeated until convergence is achieved. If desired, the spacing between the intermediate nodes can be modified by re-discretisation along the generated line.

Proponents of the shortest length definition argue that for all practical cutting pattern generation situations, the desired geodesic will always be the shortest. This is indeed usually true, but there are exceptions. Accordingly, geodesic line generation strategies based on length minimisation can sometimes prove inflexible compared to algorithms which adjust normal plane curvature.

It should be clear that when we decide to generate a semi-geodesic line through the introduction of a single additional inner constraint, the resulting line can have constant in-plane curvature. When more than one inner node is constrained translationally, or angular constraints are also prescribed, this need not be the case. It is theoretically feasible for an iterative adjustment problem to be formulated to deal with this comprehensive case. In the present work only constant curvature cases have been implemented. The justification for such a partial solution lies in the fact that semi-geodesic lines are only occasionally better than pure geodesics, and when required a single extra constraint node provides more than adequate flexibility. As may be expected the limitation to constant curvature permits the exploitation of a number of efficient strategies. In particular it is possible to apply distributed fictitious loading in the plane of the surface to deflect the curve the required amount.

Surface Line Generation in the EASY Membrane Design System

STfad is the fundamental cutting pattern seam generator in the Easy surface structure design system [11]. When executed it reads the geometric and topological description of a surface to be patterned from standard datafiles. The specification of the desired seam lines may additionally be read from input files. The surface is plotted together with a representation of the location of any exiting lines. The user is then able to interactively edit the location or attributes of existing lines, or create completely new lines. Mouse dragging of end points in the *x*,*y* screen directions are converted to global *x*,*y*,*z* values.

Each seam control point can be manipulated using any of four modes. These are *Cartesian*; *Two Node Parametric*; *One Node Parametric*; or *Angular*. Each end node's parameters can be displayed while the user is dragging its location. Parameters for all modes are shown simultaneously, but only the currently active mode values are editable. Conversion between all modes is freely permitted.

In most ordinary situations the creation of a new line takes the following form:

1. The position of the starting point of the line is selected by clicking on the boundary curve with the mouse. While holding down the mouse button, the end point of the desired line is selected, whereupon the button is released. The position of both end points are snapped to the nearest points on the boundary curves.

2. If necessary the end point positions may be modified by using the mouse to drag them, or by numerically altering their positional parameters using a dialog box.

3. When the end point positions are satisfactory, the intermediate points may be calculated according to the specified line generation type.

The starting positions of the intermediate nodes are determined using a nearest point on surface algorithm. Consequently, when only the two end nodes are specified, a unique geodesic will result. In order to be able to generate alternative geodesics, such as non-shortest length lines, it is necessary to be able to provide extra information concerning the desired path of the line. This is achieved by converting one or more intermediate nodes to be inner control points, and then dragging them over the surface to their appropriate position. The positions of these nodes on the surface are subsequently saved as part of the line generation parameters. Starting intermediate node positions are then determined which are closer to the target geodesic, resulting in convergence to the correct line.

As currently implemented, one inner control point per line may be fixed at its specified position on the surface, resulting in the generation of a semi-geodesic line.

Example

Fig. 6 shows a typical doubly-curved surface as formfound using the Easy Membrane Structure Design System. In Fig. 7 the path of a pure geodesic line between the two specified end points is shown. The series of lines shown in Fig. 8 were generated between the same end points used for the pure geodesic shown in Fig. 7, but were additionally constrained to pass through the nodes shown highlighted.

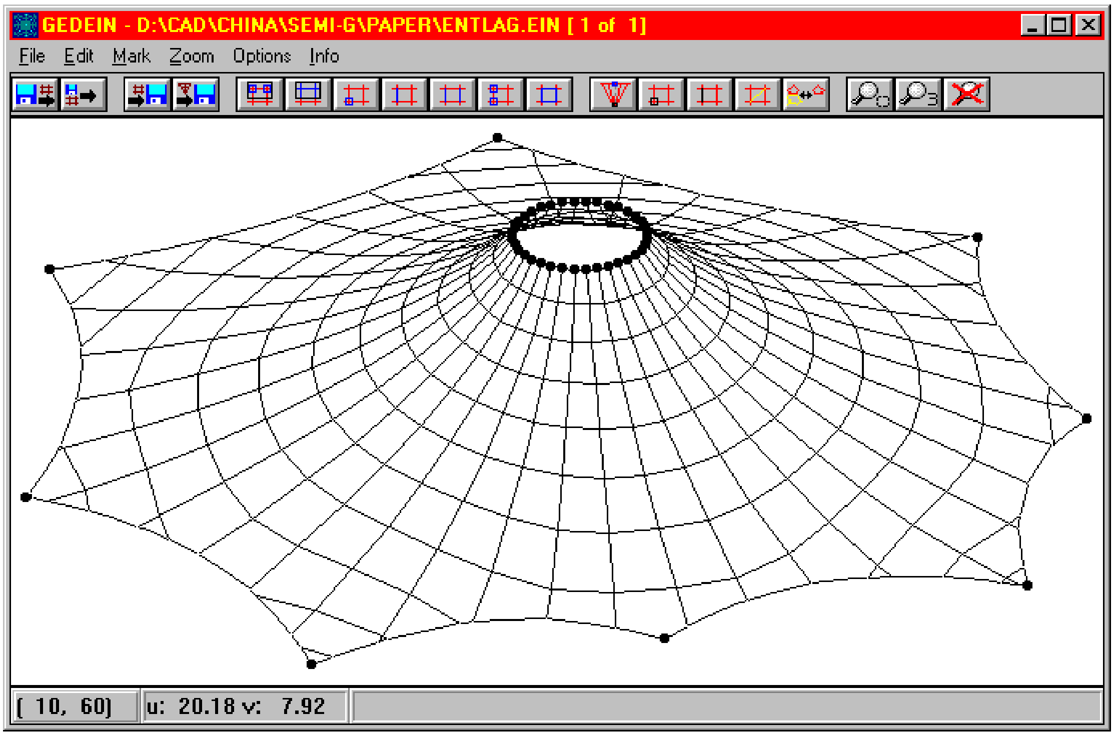

Fig. 6: Example surface.

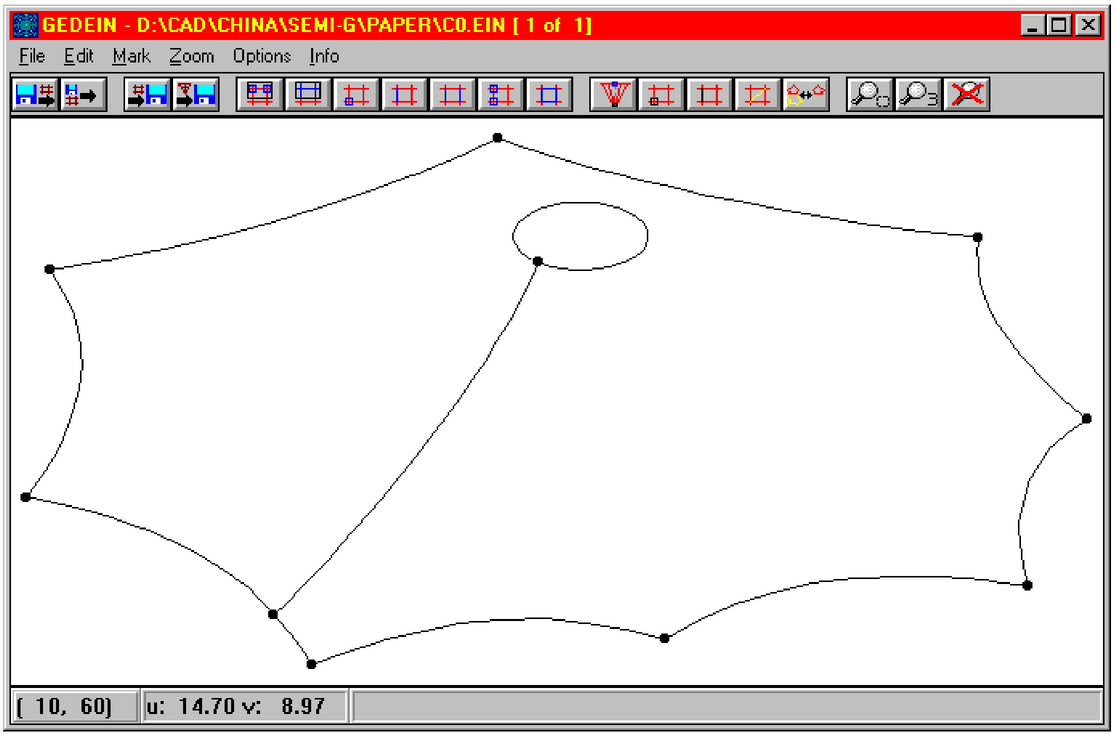

Fig. 7: Pure Geodesic line.

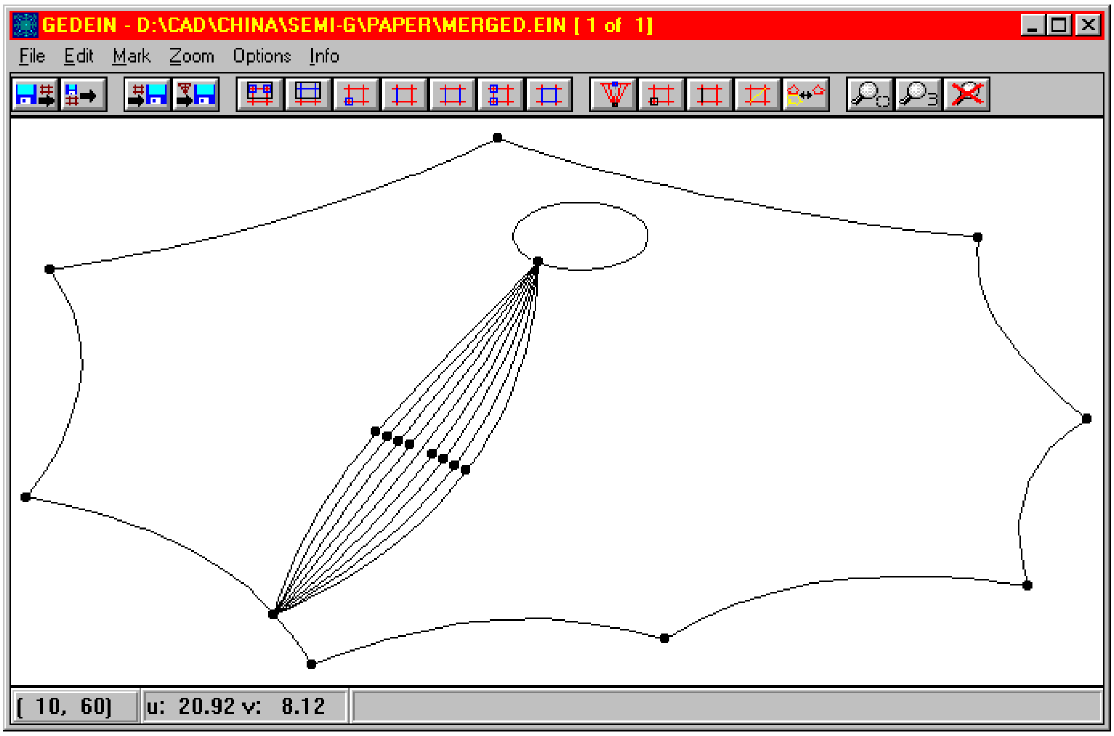

Fig. 8: Series of Semi-Geodesic lines.

Conclusions

In the field of architectural membrane structures, the particular kind of practical problem which requires the semi-geodesic solution strategy presented here is quite rare. As such it has, quite understandably, been given less importance by the developers of surface structure design systems. Now that the fundamental elements of such design systems are well established, attention is being paid to specific problems like this. As implemented within the Easy system, the semi-geodesic line solution strategy described herein, complements the existing geodesic and other line types very well. The resulting line generation capability is now extremely comprehensive, and capable of dealing with problems of much greater complexity than just architecural membranes.

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