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SIMULATION OF BURIED POWER TRANSMISSION SYSTEMS: SOME COMPUTER GRAPHICS OPTIONS

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Abstract—This paper discusses some computer graphics options useful for both computation and display of three-dimensional motions within buried high-voltage power transmission lines as they undergo temperature changes (load cycling).

1. INTRODUCTION

This paper is motivated by the problem of thermo-mechanical bending (TMB) which can occur in certain types† of buried, high-voltage, power transmission systems[1-3]. These systems typically consist of three 4" dia. cables within a 10" dia. pipe (see Fig. 1). Problems arise in these systems due primarily to thermal effects and the manner in which the cables themselves are manufactured.

A typical cable might have a copper or aluminum conductor of about 1 3/4" dia. enclosed within a hundred or so layers of paper tape insulation which are impregnated with dielectric oil. As the electrical load cycles in these cables so does the temperature. The primary mechanical effect of this temperature change is a "snaking" of the cables within their conduit. Under certain circumstances, this "snaking" leads to flexural fatigue which degrades the insulation, forming what are called "soft spots", and to eventual electrical failure. Problems of TMB have occurred in both New York City and adjacent power transmission systems in New Jersey and are of some general concern within the electric power transmission community.

For several reasons, TMB is relatively complex. It is a hybrid phenomenon in which mechanical actions produce electrical failure. Apart from the electro-mechanical interaction, the cables themselves are complex mechanical systems: at the very lowest level they are highly nonlinear beams due to both material non-linearities of the conductor and intertape slip within the insulation, both of which are inherent in the construction of these cables.

†Technically, pipe-type cable.

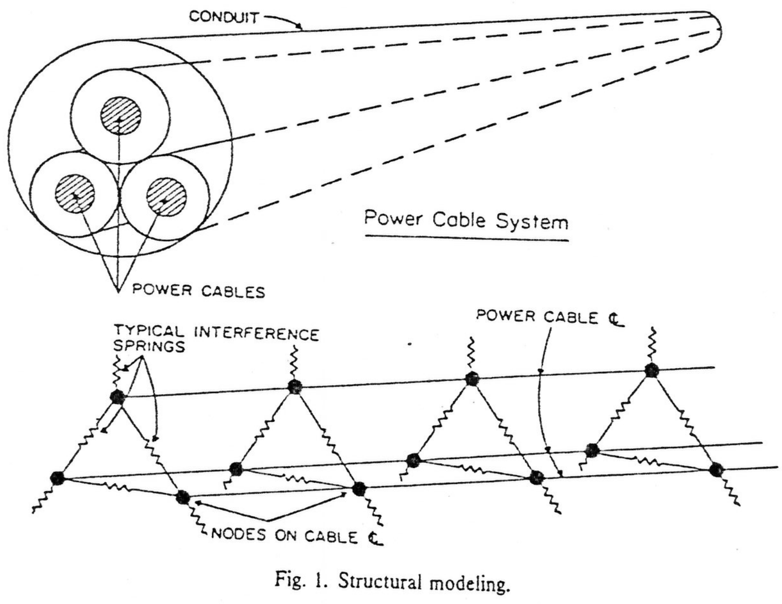

Fig. 1. Structural modeling.

More to the point, very little is know about the *in situ* mechanical response of these cable systems to load cycling. Certainly, parameters such as the cable curvatures at failure (which are basic to the cable response as a beam) are virtually unknown. They are almost impossible to measure under electrical load and have never been simulated carefully in the laboratory for many reasons. The obvious step then is to attempt to simulate TMB behavior numerically using a digital computer.

This paper is not concerned with the simulation of TMB *per se* but with the associated computer graphics options. It is concerned with a classic vein of computer graphics in which the understanding of a complex phenomenon (simulation) requires three-dimensional graphic display of computer generated output. In the application discussed in this paper computer graphics is required on two levels. First of all there is the structural analysis. The three cables within their conduit are modeled using points along the centerline of each cable together with nonlinear (initially) straight beam segments between these points; "interference springs" are invoked when a cable contacts other cables or the pipe wall (Fig. 1). As discussed below, the interference problem is sufficiently complex that a graphic display is required if a high level of confidence is to be achieved with respect to the algorithms programmed to simulate this interference. The second level of computer graphics deals with the ultimate user of the system. The type of graphics needed by the structural analyst is not appropriate to the ultimate user who is concerned with the phenomenon of TMB not the details of the analysis. He needs graphic output which is as close as possible to real life.

Within the context of TMB and buried power cable transmission systems, the paper explores the computer graphics options now available using general purpose computer systems and displays. First of all, the analysis problem is discussed briefly in an attempt to set the stage for both levels of graphics described above. For the case of the graphics used to assist the structural analyst, "stick" representations are inexpensive and quite adequate. For the ultimate user a broad range of options is explored from high quality color graphics to "stick" representations. As a final choice, a special purpose algorithm developed by Franklin[4] for spheres appears to have extraordinary potential.

2. THE STRUCTURAL ANALYSIS PROBLEM

The simulation of a buried power transmission system of the type shown in Fig. 1 is first of all a problem of structural analysis. On the most elementary level, the electro-mechanical interaction is reduced to a thermal stress problem[5] in which the electrical load simply heats the cable. With regard to boundary conditions, each cable is fixed at its ends (at manholes) and must satisfy "interference" conditions with respect to the other cables and the pipe conduit.

As suggested in the introduction, it is common in cases such as this to replace the continuous system of three cables by a discrete system represented by points at regular intervals along the cable centerlines. The cables themselves are modeled as three-dimensional bilinear beams; the interference problems are dealt with using "interference springs" which are (a) very stiff in compression when activated and are (b) removed when tension develops.

The algorithm used to deal with the nonlinearities (material and interference) simply applies the incremental stiffness approach. That is, the load—in this case the temperature change—is applied in small increments. For each increment the stiffness from the state-of-stress computed at the preceding increment is used to compute the response for the next step of load. No iterations are made to go back to check or revise a step in view of the new computed state-of-stress.

The simulation itself starts with a program for 3-dimensional frames[5]. In this system, there are 6 "displacement" quantities (3 displacements and 3 rotations) associated with each node and 6 "force" quantities (1 thrust, 1 torque and 4 bending moments) associated with each member. As a result, the number of simultaneous equations to be solved at each step is 6 times the number of movable nodes. Of course, sparse system technology must be used and changing geometries must be accounted for.

In implementing such a structural analysis system, the programmer is faced with the problem of devising sufficient checks to develop a high level of confidence in the eventual system output. This is furthermore an area in which the results are for the most part not *obviously* either right or wrong since there have been no earlier attempts at this type of simulation. Because of these arguments and the difficulty of following the interference springs as they enter and leave the system, it was felt that the system could not be properly developed without some graphics output for the programmer.

With respect to the structural analysis of this simulation, it was decided that a "stick" type representation—showing the interference springs—would be adequate for the requirements of the programmer who is, of course, a relatively sophisticated system user. Typical output produced is shown in Fig. 2 using Hardware Configuration 1 of Appendix 1. This step in the development of the simulation is thought to be highly successful.

With regard to the details of the computations associated with Fig. 2, it is first of all necessary to perturb the system since the cables will otherwise remain straight under uniform thermal load. The initial perturbation can be seen near the center of the farthest away lower cable in the first stage of Fig. 2. In this case, the perturbation activates interference springs with both the pipe conduit and the upper cable. Next, the center perturbations cause the adjacent areas to "lock up" and begin to move. Eventually, the center rotates, the lower cables spread out and the upper cable attempts to move down through the other two cables. (It cannot do so because of the geometry inherent in this configuration.)

Using the hardware described in Appendix 1, each of the drawings shown in Fig. 2 can be displayed as it is computed in a convenient manner allowing the pro-

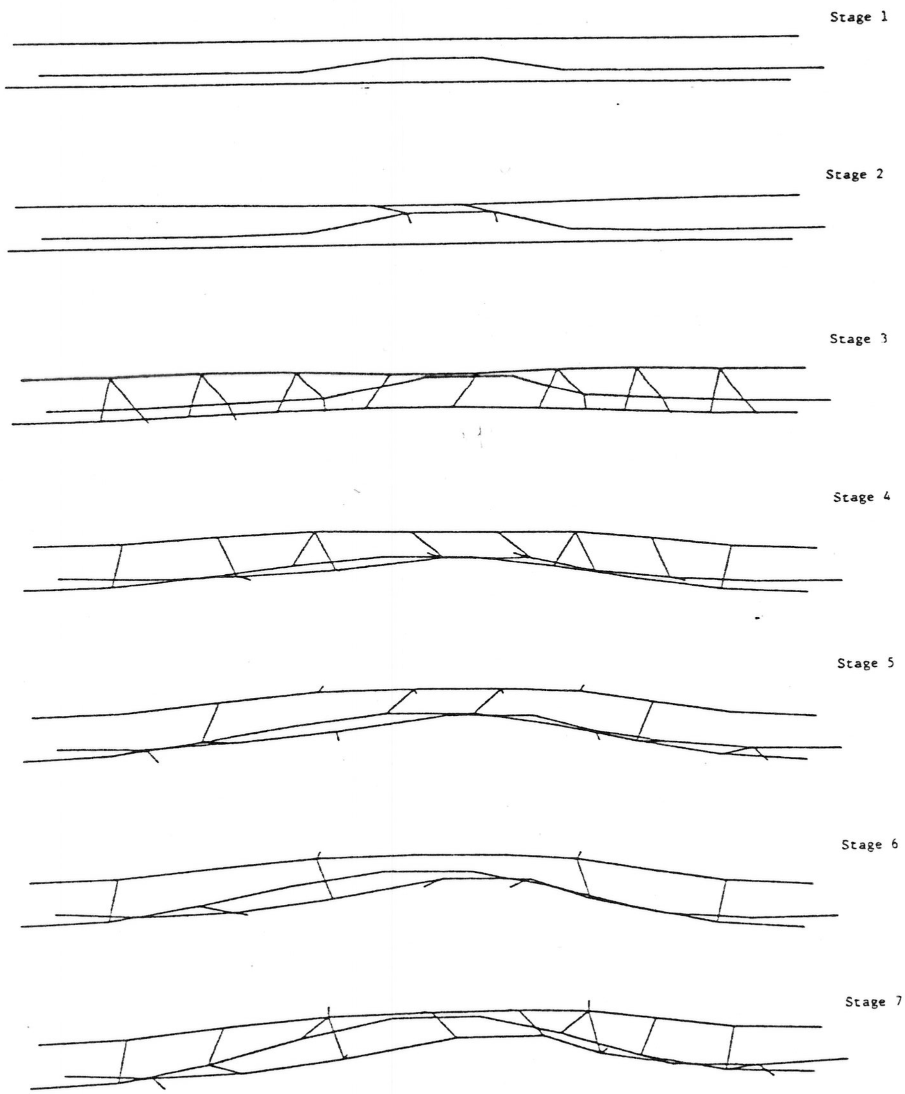

Fig. 2. Graphic output for the programmer.

grammer to debug or modify his program efficiently. Furthermore, the cost of the displays or their hard copy is negligible (less than $1 per Calcomp drawing) in terms of the cost of developing the simulation.

3. GRAPHICS FOR THE ULTIMATE USER

As in many other simulations, it is of primary importance to the ultimate user that the (graphics) output approximate real life as closely as possible. In view of the technology available today—both in hardware and software—it is actually possible to get as close to real life as you like. The question then is not how close you can get to real life but how close you can afford to get to real life.

This section examines 3 options for graphics output (discarding "stick" representations such as those used in Section 2 as inadequate): high quality color graphics, a lower quality monochrome graphics representing curved surfaces, for example, by flat facets, and monochrome graphics using a special purpose algorithm developed by Franklin. It will be concluded that for this type of application which involves hundreds of points along the cables and perhaps hundreds of views, Franklin's algorithm is the only viable option for reasons of time and cost.

In spite of 15–20 yr of work in this area, the problems graphics users of this type must deal with all go back to hidden line or surface removal. Hidden line removal remains a time consuming and expensive process which obviates the most straight-forward approach to three-dimensional displays for the simulation in question. Without the algorithm of Franklin, it would have been impossible in this case to go beyond "stick" type representations for practical situations.

3.1 *High quality color graphics*

The proximity of the Image Processing Laboratory (IPL) (see Appendix 1 for the hardware configuration) at

RPI makes it a relatively easy matter to try high quality color graphics as a means of displaying the simulated motion of the power cables under thermal load. In order to gain some experience with this system and its software, a simplified problem was set up using four nodes along each cable. On the basis of this example, it was concluded below that this type of graphics is too expensive for the application considered.

The IPL software requires as data the coordinates of all the surface nodes together with a description of the surface topology at each node. Since the output of the structural analysis provides the node coordinates along the cable centerline, it is necessary first to define a plane at each cable node which is normal to the average cable centerline and then the points in this plane which are to be used to define the cable *surface* (see Fig. 3). This requires a post-processor for the structural analysis program which then serves as a pre-precessor to the IPL software.

Figure 4 shows typical color photo of the IPL system output. The system has smoothed the data, performed hidden surface removal, and shaded the display. The resulting quality is excellent but something like 4 1/2 hr of computer time is required to produce the image shown. In view of the fact that this display does not yet represent a practical application (only 4 nodes are used along each cable rather than, say, 100) and that it is necessary to generate many pictures as the cable moves under many different geometrical constraints, high quality color graphics does not seem to be a viable option at this time.

3.2 *Vector graphics displays of medium quality*

Backing down somewhat from high-quality raster graphics, there is a vector graphics package available under the MTS system[6] supported by RPI's Computing Center (see hardware configuration in Appendix 1). Using this package the cable surfaces are defined by triangular facets (see Fig. 3) which again requires a post-processing of the structural analysis program output as did the color graphics package of IPL.

Figure 5 shows some typical output from the MTS package: Note first of all that this type of output is rather standard for medium quality computer graphics today and that at this level there is no attempt made to shade or smooth surfaces. The resulting drawings are recognizable as deformed cylinders but the triangular facets detract somewhat from the presentation. More to the point are questions of size and cost. These simple drawings made using only 4 sections are somewhere near the limits of the systems as it now runs under the MTS package at RPI. Each of the drawings took about 10 sec of computer time to generate at an internal cost of about $2.

The conclusions concerning this package are similar to those concerning the IPL package: It is possible to obtain excellent results within the constraints of the system and algorithm used, but cost and size problems obviate the use of this package here for any real simulation.

3.3 *Franklin's special purpose algorithm*

What has been learned to this point is that the state-of-the art of hidden line/surface removal hardware and software technologies obviate the direct treatment of the graphics associated with the present simulation. For practical situations of over a hundred nodes along each cable and with the intention of making many drawings (perhaps even a movie), conventional approaches described above are simply prohibitive in cost. Largely out of desperation, attention then turned to special purpose algorithms. Fortunately, an algorithm of Franklin, which deals only with spheres, is available. It produces high quality (for the present application) figures in a highly efficient manner (see Fig. 6).

The basic idea comes from Franklin's paper[4] in which he uses lines of spheres to create letters with

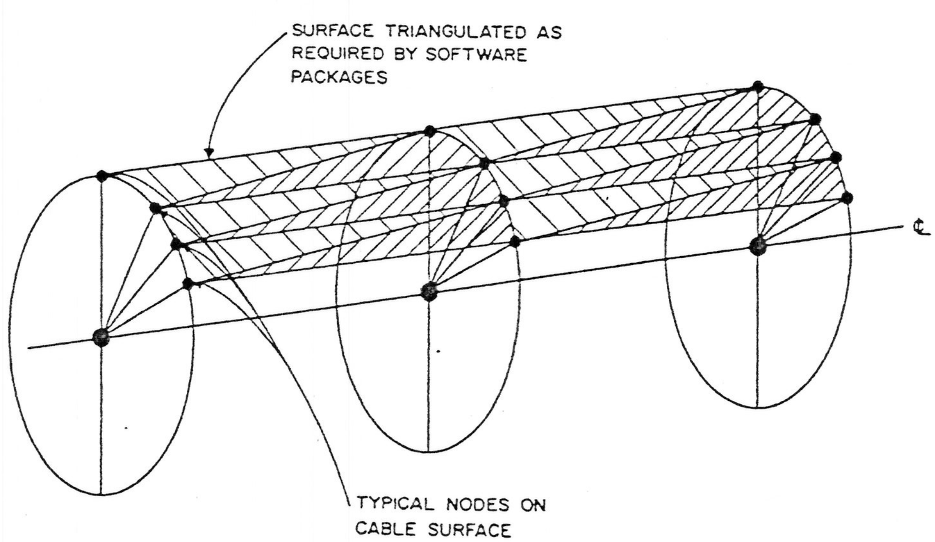

Fig. 3. Cable surface description.

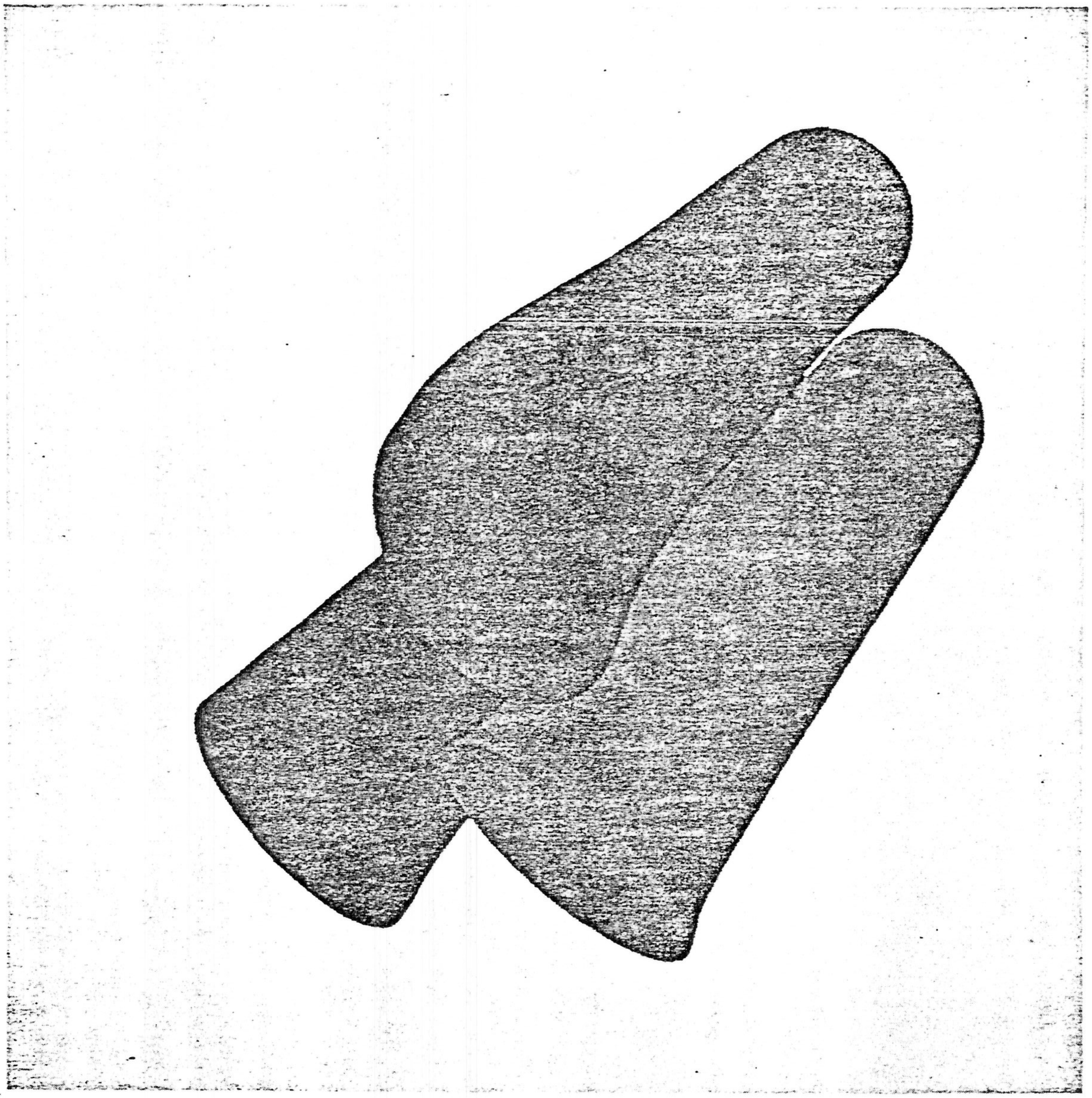

Fig. 4. Monochrome reproduction of a high quality color graphics display.

depth in perspective: Clearly spheres can be used to give the impression of a long, solid cylinder! Beyond that the spheres offer an unexpected payoff in that the outlines of the individual spheres are reminiscent of the helical skid wires which are found around the outside of power transmission cables. The overall effect is excellent.

The reader is referred to Franklin's paper for a discussion of his algorithm. It will simply be noted here that (a) the description of a cable surface as a series of spheres is relatively simple compared to the surface descriptions used above, (b) since the intersection of two spheres is a circle, the hidden surface removal problem simplifies considerably, and (c) Franklin conducts his searches cleverly in a manner which is linear in the number of faces to be drawn.

The results are, in any case, quite encouraging. The simulation shown in Fig. 6 which is close to a real—if somewhat small—cable configuration ran about 15 sec per stage at an internal cost of $0.50 per picture on hardware configuration 3 (see Appendix 1). In order to deal with the large sets of simultaneous equations associated with this simulation, it will probably be necessary to move this system from the Prime to the IBM 370/3033 at RPI. If the conversion factor between these systems is, say, 10, the 15 sec per frame cited above would reduce to 1.5 sec which is excellent. Of course, the more complex simulations will run longer.

4. CONCLUDING REMARKS

The problem of simulating buried power transmission systems under thermal loads has been used as a vehicle to take something of a worm's eye view of the state-of-the-art of computer graphics. As it turns out, quality is not a problem. But in spite of developing software and

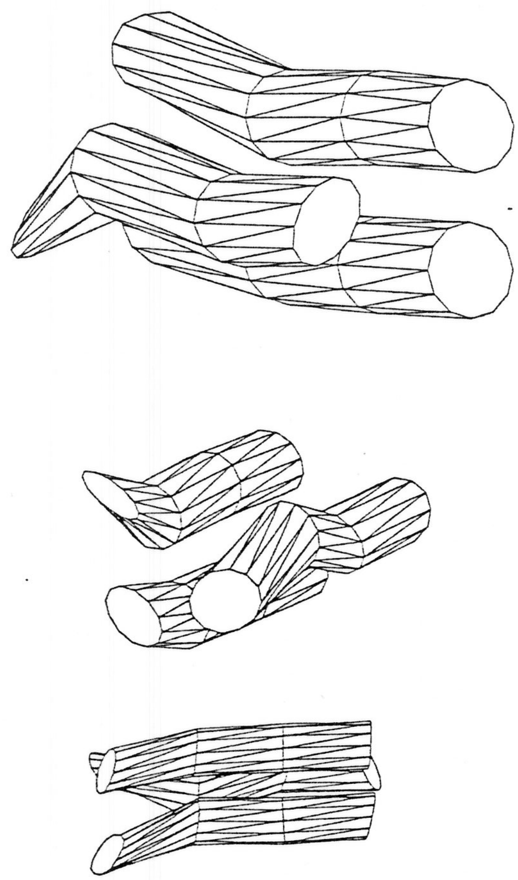

Fig. 5. Vector graphics display.

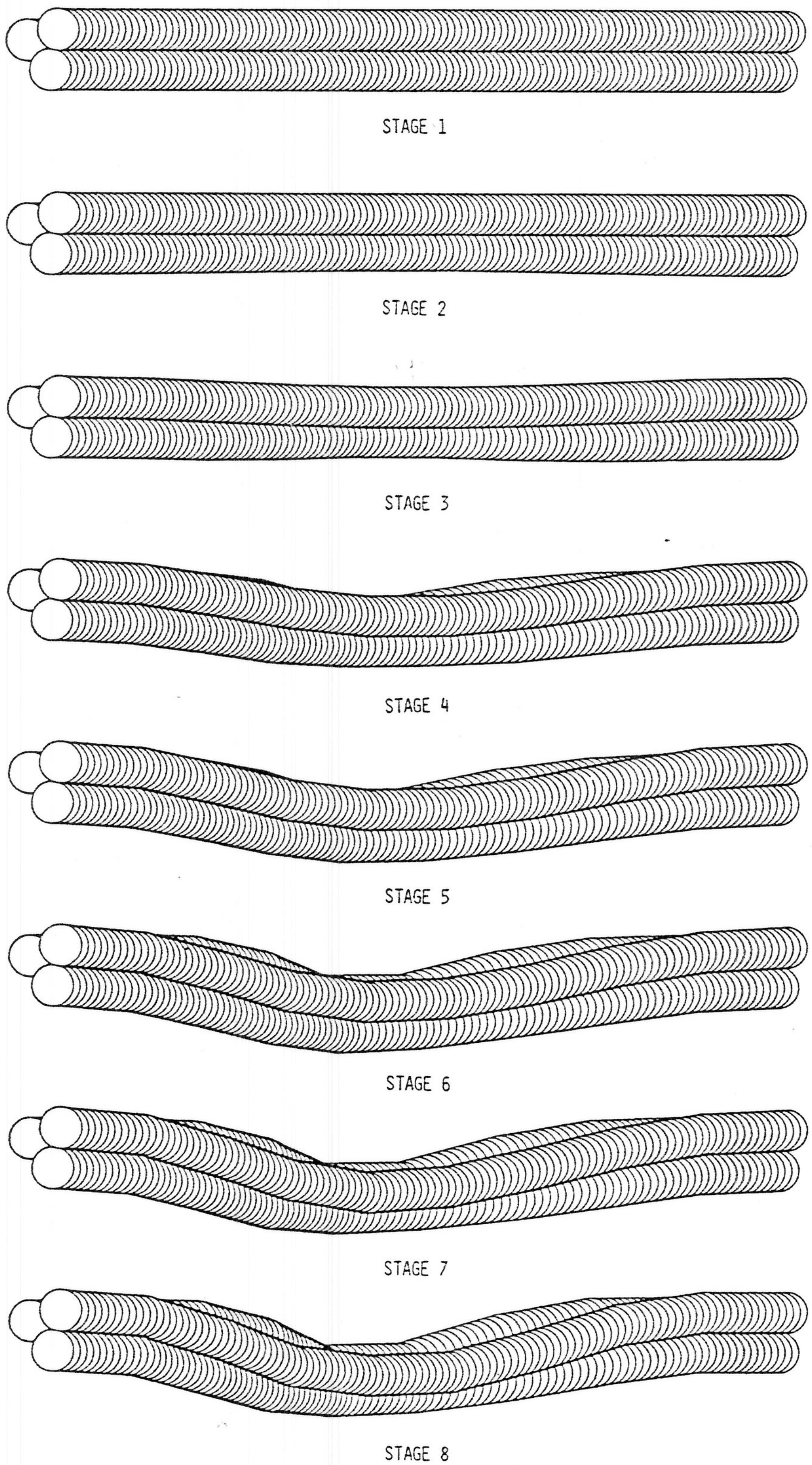

Fig. 6. Display using Franklin's algorithm.

hardware technologies, hidden line/surface removal remain a time consuming and expensive proposition. This particular application has been saved by using a surprisingly effective special purpose algorithm.

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APPENDIX 1.

Hardware configurations (all at Rensselaer Polytechnic Institute)

(1) Vorhees Computing Center
IBM 370/3033 (8 megabytes main storage)
Wide variety of peripherals
Plots made using:
(a) IBM 3270-GA terminal
(b) Tektronix 4025 plot-previewing terminal
(c) Cal Comp 1051 drum plotter
Supports Michigan Terminal system.

(2) Image Processing Laboratory
Prime 750 (0.75 megabytes main storage)
Wide variety of peripherals
DeAnza terminal
Dunn camera.

(3) Interactive Computer Graphics Center
2 Prime 750's (1.5 megabytes main storage each)
Wide variety of peripherals
Imlac terminals
Versatec Plotter.