

## The COMPUTER SIMULATION OF META STRUCTURES

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### ABSTRACT

This paper outlines the results of a research project dealing with a dynamic prediction system for space oriented architecture in Meta Structures using interactive computer graphics techniques. Meta Structures in architecture are variable, space-enclosing, support systems that allow maximum dimensional changes with minimum effort and/or adjustment. Examples of Meta Structures range from the simple umbrella to the complex, variable support system of Skylab II. The use of real time computer graphics has been investigated to improve the design of structures which until now could only be visualized through expensive scaled models.

This investigation has initiated the development of a computing model which allows the user to interactively define a Meta Structure via linguistic and analog control and to simulate the real time motion of structures that are considered to be part of the indeterminate set.

The user may deploy a designed structure in real time observing the transformations on the Vector General 3DR graphics display which is controlled by a PDP11/45 using the GRASS language developed by Dr. Thomas A. Defanti at the University of Illinois, Chicago Circle. This observation can be compared to watching an automobile convertible top being automatically deployed from its stored position to its unfolded position.

**Keywords:** Interactive, Metastructure, Kinetic, Antennae, Macro, Transformation, 3D, Real Time, Deployment, Modelling, Meta Module, Pantograph

### COMPUTER SIMULATION OF META STRUCTURES

The research outlined in this paper is an outgrowth of the exploration work done by NASA on large deployable space structures. The formulation of the mathematical model was itself the subject of my doctoral thesis (1).

There are three basic structural approaches to the large space systems used by NASA, namely deployed, erectable and space fabricated (2,3,4,5,6,7,8,9,10,11,12,13)

This paper presents a timely solution to many of the design problems of the Deployable(4,8,14,15,16) and Erectable Concepts (17).

The graphics system outlined in this paper was used to solve a problem pertaining to large deployable space structures given by the NASA Langley Research Center. A video tape showing in real time the complexity of the actual folding and deployment of the structure was produced. This project is described in the second part of this paper.

## The Use of Computer Graphics

Meta Structure complexes are sometimes difficult to visualize and describe (see Figure 1). Even structural models are at times inadequate since they give little or no indication as to where cross-members may overlap in the course of a transformation. This paper has successfully attacked this problem with the aid of interactive graphics and has provided a unique tool for the study of Meta Structures (1,18,19) in theoretical and practical contexts. The complex visual changes occurring within Meta Structures are displayed virtually instantaneously on a refresh CRT so that the user can watch the transformation of a particular Meta Structure in real time, control its speed, stop or reverse the transformation, and rotate the Meta Structure about any axis to enhance in depth viewing. All the transformations are controlled interactively with function switches, dials, and an alphanumeric keyboard. The user may also list the Meta Structure transformation equations that produce the real time graphics on the CRT. Along with the changes in selected parameters, one may even insert new parameters in the equations without destroying the originals. Thus, visual feedback and interaction are important tools in learning and exploring the possibilities of Architectural Meta Structures and similar transformation patterns.

This research was developed using a Vector General (VG) cathode ray tube (CRT) interfaced with a PDP11/45 mini-computer with 64K x 16 bits of memory. The real time interactive software routines (MACROs) were written in GRASS, a high level graphics language developed by Dr. Thomas A. DeFanti. (19) This system had the advantage of being able to support both the three-D graphics display on the CRT screen and the immediate visual feedback that real time interactive design requires. It proved extremely important in the development of this work.

In accordance with the convention used in this system, assume for all of the following discussion that the X and Y coordinates are horizontal and vertical respectively across the CRT, and the Z coordinate is perpendicular to its face (20). The positive values for X, Y, and Z, are assumed to be to the right, up, and towards the viewer, respectively. One must solve for the X, Y, and Z coordinates to determine the end points of vectors.

## Meta Structure Theory of Regular Polygons

In developing the Meta-language to control the basic primitive functions used in describing Meta Structures, it was decided to begin with operations on subcomponents which when combined

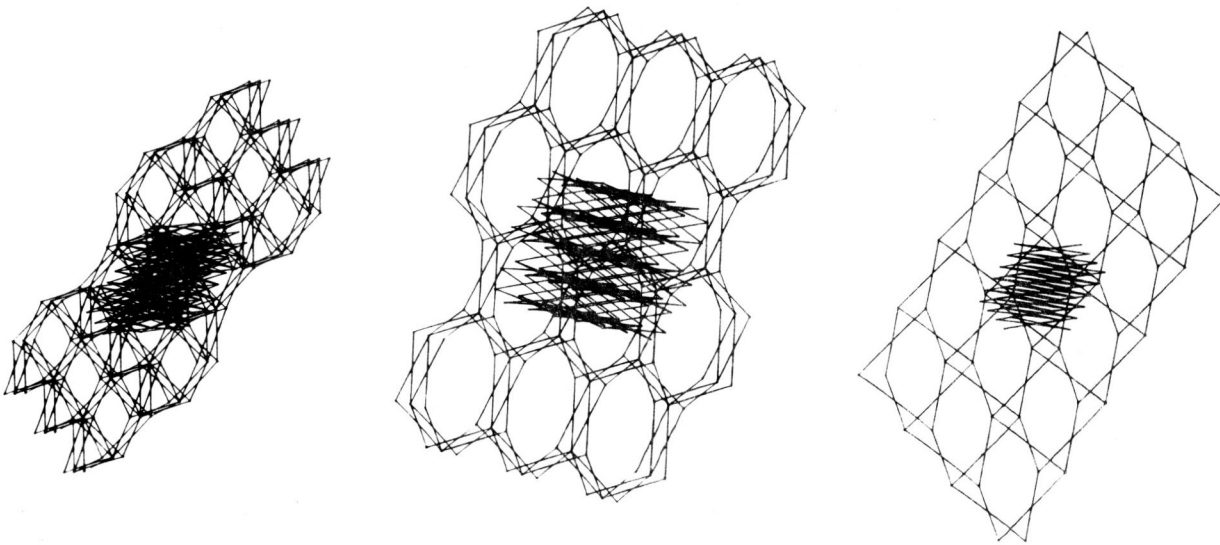


Figure 1. Meta Structure Complexes

make up Meta Structure modules and complexes. For purposes of simplicity, a line segment was selected to represent a structural element moving about the joint (one degree of freedom). An interactive program (MACRO) was produced in the GRASS (19) language to achieve the desired interactive motion control using dials and function switches.

Motion is imparted to the Meta Structure elements by joining the two end points on opposite sides of a center joint with a hypothetical tensioning member (see Figure 2). By tightening this tensioning member the same way a hand might grasp a pair of scissors, (simulated with the turn of a dial) the joined elements can be made to close vertically while maintaining true element lengths. The user can now establish a height parameter and a rate of change within the MACRO by interacting with the keyboard. This MACRO (META1.MAC) produces the centrally joined elements which are the basic building blocks for the simulation of all modular 3D-space Meta Structures.

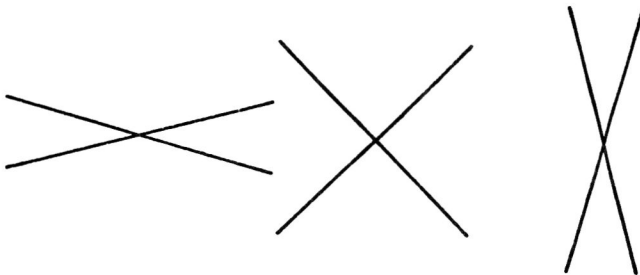


Figure 2. Simple Meta Structure

A second MACRO (META2.MAC) was written to produce joined elements in a polygonal plan where the number of joined elements is determined by the number of sides in the polygonal plan (Figure 3). Implicit within the MACRO is the possibility of displaying a large number of polygonal prisms (triangular, square, pentagonal, etc.) (21,22) the only limitation being the amount of available computer storage.

This MACRO introduces the third dimension and also the real time rotation of the structure. The first seventeen lines of code set up the input parameters for the structure. They are as follows: the picture name (\$A), element length (FA), structure height (FB), and the scale factor (FS). This MACRO introduces an additional input variable, namely the number of modules (FD) which corresponds to the number of sides in the regular polygon. In other words, the primary components of the regular polygon plan are the Meta Modules (composed of scissors elements) defined by the previous MACRO.

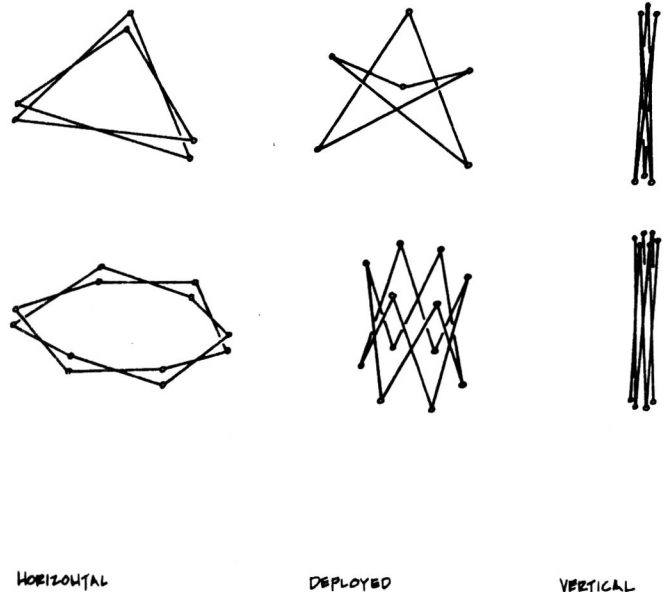


Figure 3. Basic Prism Modules

Line 190 prompts the user for input of this number and line 200 assigns the value input for (FD) to memory.

```
190  PROM "INPUT NUMBER OF MODULES"
200  INPUT FD
```

These input values are used in the equations for the Meta Structure Prism Modules (see Figure 3). The next line assigns the picture file to dials for real time rotation.

```
210  ROT/D $A,X,D0,D1,D2,D3,D4
220  FA=FA/2;FC=0;FE=0;M=0;N=0
```

In line 220, the hinge is placed in the center of the Meta Module (FA) and the increment angle (FC) for the polygon plan is set to zero. The plan view will be in the X-Z plane. Line 230 calculates the interior angle (FF) used to determine the end point coordinates in the X-Z plane (see Figure 4).

```
230  FF=(360/FD)*0.0174532
250  FH=(180.-360./FD)/2.*0.0174532
```

In line 250 the angle (FH) used to calculate the Z coordinate is converted to radians (see Figure 4 for variable descriptions).

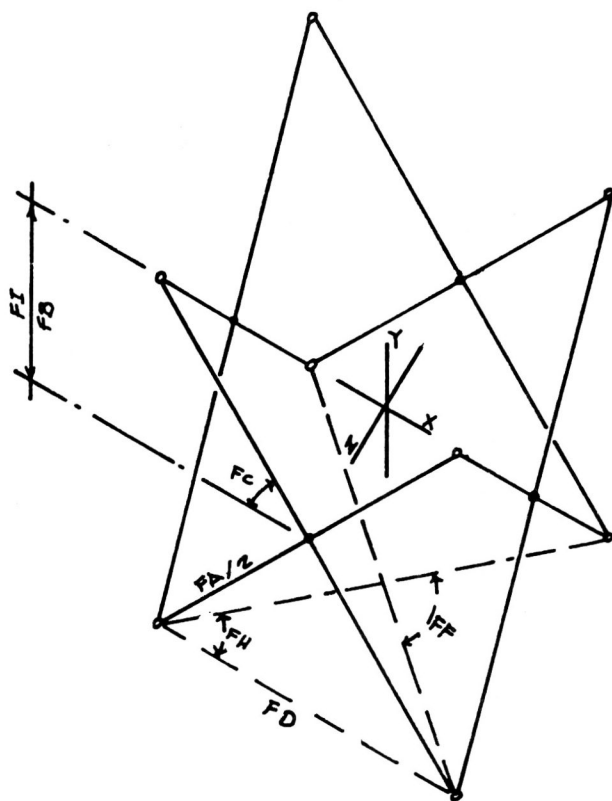


Figure 4. Variables for META2.MAC

The limiting parameter (FI) for the maximum structure height is calculated in line 260 and its value later compared with the Y coordinate. Since the structure is symmetrical, this value is equal to one-half of the scaled structure height. The maximum number of points (FJ) in the prism structure can be determined by multiplying the number of modules by three and adding one.

```
260  FI=FB*FS/2.;FJ=FD*3.+1
270  PROM "PUSH FUNCTION
      SWITCH 1 TO STOP"
```

Line 270 is a prompt statement which reminds the user to stop the growth of the structure before it reaches maximum height. The following twenty three lines form the iteration loops where the value of the incrementing angles (FC) is calculated in radians and then used in the equations for the X and Y coordinates. These coordinates are replicated symmetrically to plot the first Meta Module, which forms one of the sides of the prism. The Y coordinate will stay the same until the internal loop is completed

closing the prism. Tests are made to see if the maximum parameters have been reached, if not, the scissors angle (FC) is incremented and the procedure is reiterated using the new angle. This angle is used to calculate the new Y coordinate.

```
280  FL=FC*0.0174532
290  FX=-FA*COS(FL)*FS;FM*FX;
      FO=ABS(2.*FX)
300  FZ=FX*(SIN(FH)/COS(FH));FN=FZ
310  FY=FA*SIN(FL)*FS
320  PUTPOI FX,-FY,FZ,1
```

Line 280 calculates the value of the scissors angle (FC) to radians. In line 290, the X coordinate of the first point within the iteration is calculated and its value is saved for point three in (FM), and the variable (FO) is set equal to the side length of the polygon plan. Line 300 calculates the Z coordinate (in META1.MAC this value was set to zero). This value is also saved in (FN) for point three. Line 310 calculates the Y coordinate by multiplying one-half the structural element length by the sine of the changing angle (FL) and the scale factor (FS). In line 320 the coordinates for point number one of the iteration are plotted on the CRT with the PUTPOI command (19).

The following nine lines (330 to 410) plot the Meta Module, increment the angle (FE) by the polygon's interior angle (FF), and test to see if the polygon is complete. If it is not complete, the new X and Z coordinates are calculated with the new plan angle.

```
330  FK=FE
340  FX=FX+COS(FK)*FO
350  FZ=FZ+SIN(FK)*FO
360  PUTPOI FX,FY,FZ,0
370  PUTPOI FM,FY,FN,1
380  PUTPOI FX,-FY,FZ,0
390  FM=FX;FN=FZ
400  FE=FE+FF;N=N+1
410  IF N LT FD, SKIP -8
```

Line 330 begins the loop by setting the plan angle (FE) equal to FK, an angle used to calculate the X and Y coordinates (see Figure 5).

Lines 340 and 350 are used to calculate the X and Z coordinates for the second and fourth points to be plotted in line 360 and 380. The third point is plotted in line 370 from the saved values of (FM) and (FN). The X and Z coordinates are saved in line 390 for the next iteration or next side. In line 400, the radian value (FE) is incremented by (FF) and the side counter (N) is incremented by one. This value (N) is tested in line 410 to determine if the number of sides



plotted is less than the number of sides input (FD). Upon closure, which occurs when the side counter is equal to the input value, the counter is set to zero and the process continues with a new angle. The folding sequence is simulated by turning a dial: a clockwise turn increases the angle from zero to ninety degrees while a counter clockwise turn decreases the angle. By pressing a function switch, the execution of the MACRO can be stopped and the menu of other MACRO's is presented for additional work.

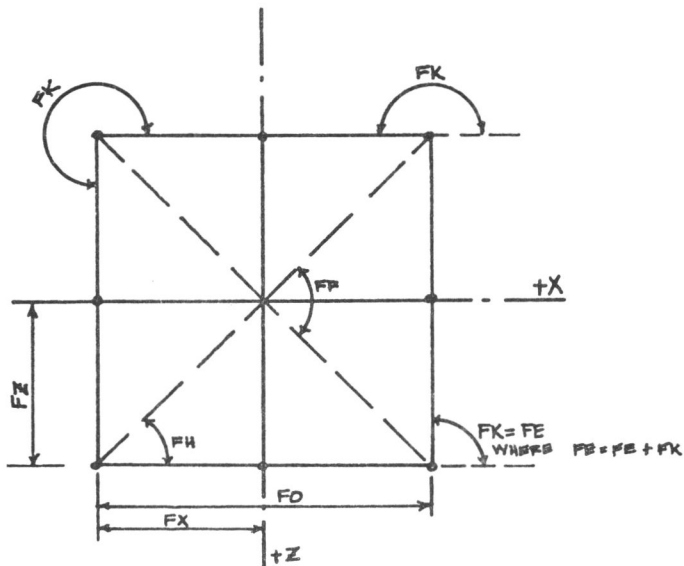


Figure 5. Plan View of Meta Prism Module

A third MACRO (META3.MAC) was developed to allow the user to change the location of the planar scissors joint above or below the halfway mark on the elements. The new location of the joint is expressed as the ratio of element lengths (e.g. ratios of 40/60, 30/70, 20/80). If one moves the point up (55/45, 60/40, 80/20), the prism-making MACRO (1,18) mentioned above produces pyramid-shaped Meta Structures. Inverted pyramidal Meta Structures are produced when the element joints are moved down (40/60, 30/70, 20/80, see Figure 6). If the user selects a hinge location of either zero or one hundred per cent, the graphics will simulate the opening and closing of an umbrella.

This MACRO has similar input to the previous MACROS. Dials, function switches and keyboard provide interactive control. Dial zero rotates the structure about the X axis. Dial six controls the scissors angle which in turn controls the structure's growth from horizontal to vertical packing. The function switch is used

to abort the execution of the MACRO at will and instantly recall the display of menu options.

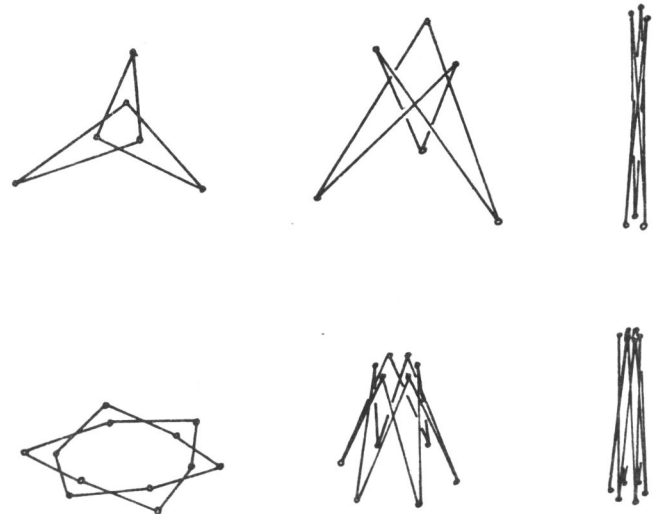


Figure 6. Pyramidal Module

The fourth MACRO deals with Meta Structures having an even number of sides such as squares, hexagons, octagons etc. (2-D polygon plans). The principle underlying the structural geometries of Meta Structures is that all flexibly joined polygons with an even number of sides (squares, hexagons, octagons etc.) can be folded into a compact linear bundle. In this type of structure the hinges are placed at the end of the structural element and alternating points (hinges) in the polygon plan change from 0 to 180 degrees and 180 to 360 degrees allowing the connected elements to move vertically in opposite directions as they collapse toward the central Y axis. As the dial corresponding to the vertical increment angle is turned from 0 to 180 degrees, alternate points within a common plane move up and toward the central axis, while the remaining points move down in a parallel plane toward the same axis. The resulting folding pattern evokes a circular accordion fold (see Figure 7).

The input is the same as for all the previously defined sets of input. The picture name (\$A), scale factor (FS), element length (FA), and the number of modules (FD) are all included in the code from line 10 through line 190. Line 200 through 300 are very similar to

those previously defined to calculate the angles that determine the first point. Lines 310 and 320 calculate the X and Z coordinates of the next point. The undulating pattern (zig-zag) characteristic of the accordion fold is created by alternating the sign value of the Y coordinate from one point to the next.

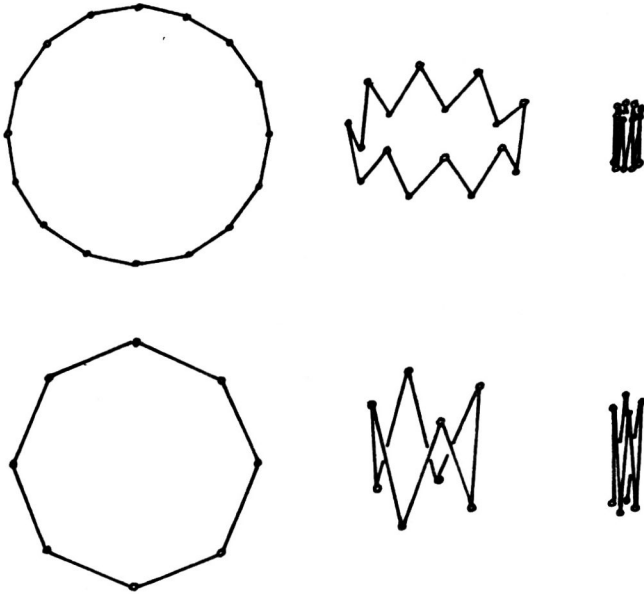


Figure 7. Accordion Fold Module

```

310    FX=FX+COS(FE)*FO
320    FZ=FZ+SIN(FE)*FO
330    PUTPOI FX,FY,FZ,0
340    FE=FE+FF;N=N+1;FY=-FY
350    IF N LT FD, SKIP -4
360    EXEC M4XXX

```

The plan angle (FE) is incremented to set up the next side of the polygon, the side counter (N) is incremented and the Y coordinate is inverted in line 340. Line 350 tests for closure of the polygon; if false, the next side is calculated and output by returning to line 310 and repeating the sequence. Once closure has occurred, the MACRO branches to the sub-MACRO which executes (EXEC command in line 360 19) the real time interaction of the accordion module. The vertical angle (FL) is assigned to dial six in line 10 of the sub-MACRO. The coordinates of the initial point are calculated in lines 20 to 40, erasing the previous ones, and the new point is output to the CRT by the ZAPP (zap point) (19) command in line 50.

```

010    FL=(D6+32768)/728*0.0174532
020    FX=-FA*COS(FL)*FS;
        FO=ABS(2.*FX)
030    FZ=FX*(SIN(FH)/COS(FH));J=2
040    FY=FA*SIN(FL)*FS
050    ZAPP $A,1,FX,-FY,FZ,1

```

The next point is calculated in lines 60 and 70 and output in 80. The plan angle (FE) and side counter (N) for the next side are incremented and the Y coordinate (FY) is inverted in line 90. In line 100, the point counter (J) which is used in the ZAPP (zap point) command is incremented and the side counter is tested to see if the polygon is complete.

```

060    FX=FX+COS(FE)*FO
070    FZ=FZ+SIN(FE)*FO
080    ZAPP $A,J,FX,FY,FZ,0
090    FE=FE+FF; N=N+1; FY=-FY
100    J=J+1; IF N LT FD, SKIP -4

```

In line 110, the side counter (N) and plan angle (FE) are set to zero and in line 120, the function switch is tested. If the switch is off, the MACRO skips back to line 10 for another iteration with the new angle read from the dial.

```

110    N=0; FE=0
120    IF FS1 EQ 1, SKIP 2
130    SKIP -12

```

The reader should be aware that the above sub-MACRO executes very fast and the user receives visual feedback as if the actual model were being folded. The structure responds directly to the turning of the dial; otherwise, it will not move. This is true for all the previously defined MACROS where dials are used. The user may also manipulate several dials simultaneously, turning dial one to rotate the structure while turning dial six to make the structure grow. The user may stop the execution of any MACRO by pushing the appropriate function switch. Control is then returned to the calling MACRO and the user is prompted to try another option, another structure, or stop and return to top level for machine commands.

The next section on planar types explains how the scissors hinge element can be developed into a pantograph beam (10,17,23) by attaching several planar Meta Modules together in a row. The row elements can also be joined to form planar arrays. The turning dial simulates the scissors angle and causes the total Pantograph Module to respond.

The Pantograph Module MACRO is similar to those discussed so far. Two additional variables, introduced in lines 160 to 190, are required to

create the repetitive structure of the Pantograph Meta Module. These two variables, number of columns (B) and number of rows (D), are used as limits for the two loops which create the graphics of the folding structure.

```

160     PROM "HOW MANY COLUMNS?"
170     INPUT B
180     PROM "HOW MANY ROWS?"
190     INPUT D

```

The element length (FA) is scaled in line 200 and the initial Y and Z coordinates are set to zero. The limit parameter for the X coordinate is calculated in line 210. There are eight points to be calculated in the simple structure shown in Figure 8.

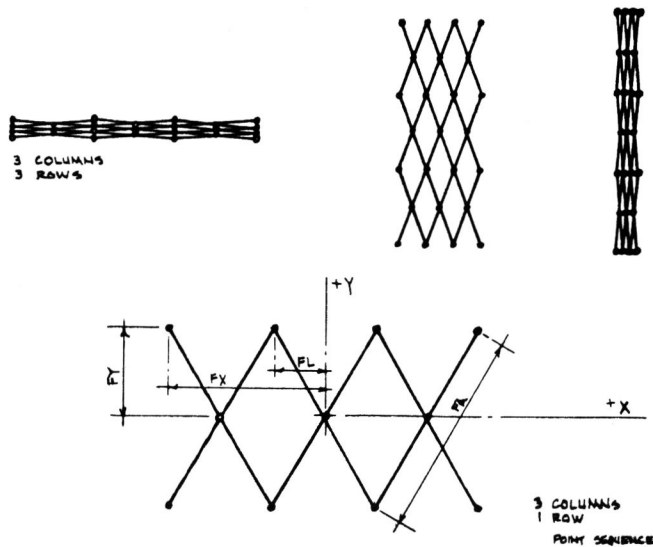


Figure 8. Pantograph Module Variables.

This MACRO repeats the same calculations for each point using the same formula as it progresses through the structure. Therefore the first point is found by using the equation in line 210 and output in line 220. Point two is found by moving two increments over (see FL in Fig.9). Since the structure is symmetrical about the X Y origin, the use of half the element length (FL) allows this number to be used as the multiplier for the extreme left and right limits as the number of columns (B). A constant of two (the Meta Module being symmetrical) may be added to this multiplier for each element to be drawn.

This constant is inverted to allow for the return of the calculated points. For example, the constant is positive for points two through four and negative for points six through eight in the simple structure illustrated. The Y coordinate is thus found in the exact same way, only the number of rows becomes its limiting factor.

```

200     FL=FA*FS; Y=0; Z=0
210     VB=-B; VD=0; FX=VB*FL
220     PUTP FX,Y,Z,1
230     VB=VB+2; FX=VB*FL
240     PUTP FX,Y,Z,0
250     IF VB LT B, SKIP -2

```

Once the first point is output in line 220, the MACRO loops from 230 to 250 until the column limit is satisfied. Line 260 plots the coordinates (see point five in Fig.9) for the return calculations. A similar loop is set up in lines 270 to 290 to perform the above iteration in reverse.

```

260     PUTP FX,Y,Z,1
270     VB=VB-2; FX=VB*FL
280     PUTP FX,Y,Z,0
290     IF VB GT -B, SKIP -2
300     VD=VD+1
310     IF VD EQ D, SKIP 2
320     SKIP -9
330     DO M6XXX

```

The row limit (FD) is tested in line 310. This value was incremented after finishing the output of the row in line 300. If the rows have been completed, all the points of the structure have been output to the picture file and control can be transferred to the sub-MACRO for real-time interaction with the structure. If the number of rows is not complete, the MACRO returns to line 230 and continues the next row. Once the data points are complete for the structure, control is transferred to sub-MACRO (M6XXX) in line 330.

In this sub-MACRO, the same logic is used to reproduce the coordinate points of the structure with the "ZAPP" point command. The scissors angle is read at each iteration and may be modified with the turn of a dial. Based on this angle, the new X and Y coordinates are calculated and symmetrically plotted in a logical sequence. Lines 10 through 50 are used to read this angle and calculate the coordinates for the first point. Next, in lines 60 through 90, points two, three and four of the simple structure are calculated. As soon as the limit factor (VB) is reached, the next set of calculations are performed in lines 110 to 130. Then lines 140 to 180 return plotted points five, six, seven, and eight of the simple structure shown. Line 190 tests to see if the number of rows requested has been satisfied. If not return to line 70 and

repeat for the next row. If it is complete, the function switch is checked in line 210 to see if the user wishes to stop or continue iterating by returning to line 10 for the next iteration with a new angle from dial two.

```

010  FD=(D2+32768.)*0.001373312;
      FC=FD*0.01745325556
020  FX=COS(FC)*FL; FY=SIN(FC)*FL
030  VB=-B; VD=D; VR=-2; I=1; FP=VB;
      FQ=VD; FR=-2.0
040  FM=FP*FX; FN=FQ*FY; X=FM; Y=FN
050  ZAPP $A,1,X,Y,Z,1
060  IF VB EQ B, SKIP 5
070  VD=VD+VR; VR=-VR; VB=VB+2;
      I=I+1; FP=FP+2;
      FQ=FQ+FR; FR=-FR
080  FM=FP*FX; FN=FQ*FY; X=FM; Y=FN
090  ZAPP $A,1,X,Y,Z,0
100  SKIP -4
110  VD=VD+VR; VR=-VR; I=I+1;
      FQ=FQ+FR; FR=-FR
120  FN=FQ*FY; Y=FN
130  ZAPP $A,1,X,Y,Z,1
140  IF VB EQ -B, SKIP 5
150  VD=VD+VR; VR=-VR; I=I+1; VB=VB-2
      FQ=FQ-2; FR=-FR; FP=FP-2
160  FM=FP*FX; FN=FQ*FY; X=FM; Y=FN
170  ZAPP $A,1,X,Y,Z,0
180  SKIP -4
190  IF VD EQ -D, SKIP 2
200  FR=-2.; VR=-2; SKIP -14
210  IF FS1 EQ 0, SKIP -20

```

If the function switch is on in 210, M6XXX returns control to META6.MAC at location 340 and the user is given the option to experiment with another pantograph or to stop.

```

340  PROM "DO YOU WANT TO TRY
      AGAIN(YES OR NO)"
350  INPUT $C
360  DELETE $A
370  IF $C EQ 'Y*', SKIP -28

```

When only one row and one column are input, this MACRO produces a single Meta Module (scissors element). It may also produce a Pantograph beam with the input of more than one column and only one row. A Pantograph gate may be formed when the inputs for both the column and row are greater than one. Barring the limits imposed by the computer memory capacity, the number of columns and rows that a user can specify is theoretically unrestricted.

This completes the discussion of planar Meta Structures. The next section will discuss the implementation of Meta Structure Complexes using the logic which has been developed up to this point.

## Theory of Meta Structure Complexes

If one can reproduce the Meta Module to form a Pantograph Module, then why not use the same logic with Meta Prism Modules to form three dimensional grids, square, hexagonal, and complex grids using a combination of squares and triangles (see figure 1). All these grids can be made up of the regular Prism Modules created with META2.MAC by simply specifying the number of layers or levels in addition to the number of rows and columns forming the lattice structure (see Figure 1).

This MACRO produces tessellations of Meta Structure Lattice grids. The graphics, which are controlled by turning dials, give a dynamic view of different positions of the transformations.

The input variables (see lines 10 through 80) for the tessellation grid types are selected from a menu. Once the grid type is selected in line 70, the user is prompted for the number of rows, columns, and layers which define the dimensions of the grid in lines 200 through 220.

```

010  PROM "MULTIPLE PICTURES OF THE
      FOLDING STRUCTURES"
020  PROM "A NAME IS NEEDED--PLEASE
      TYPE ONE"; INPUT $N
030  PROM "THESE ARE THE TESSALATIONS
      WE NOW HAVE"
040  PROM "1 SQUARE GRID"
050  PROM "2 HEXAGONAL GRID"
060  PROM "4 SQUARES AND TRIANGLES GRID"
070  PROM "PLEASE ENTER THE NUMBER OF
      YOUR CHOICE"; INPUT LA
080  PROM "READING FROM THE DISK.
      STAND BY"

```

The next seven lines call the correct sub-MACRO into core for the interactive control of the structures.

```

090  IF LA NE 2, SKIP 2
100  G TES1.MAC; G STES1.MAC; ER=1; EC=1;
      EY=0; EX=0; SK %GT
110  IF LA NE 2, SK 2
120  G TES2.MAC; G STES2.MAC; ER=1.5; EC=1.8;
      EY=.5; EX=.88; SK %GT
130  IF LA NE 4, SK 2
140  G TES4.MAC; G STES4.MAC; ER=1.88;
      EC=1; EY=.88; EX=.5; SK %GT
150  PROM "THE CORRECT NUMBER
      PLEASE"; SK %TE

```

The next three lines compile the sub-MACROS for execution and open the picture file for input.

```
%GT $T='TES' ,LA; $S='S', $T
170 PROM "COMPILATION"; COMP/F $T;
                                COMP/F $S
180 OPEN $N
```

The user is now prompted for the input of the number of columns, rows and layers (levels) for the grid selected.

```
%DM PROM "DIMENSIONS FOR GRIDS"
200 PROM "HOW MANY COLUMNS"; INPUT VC
210 PROM "HOW MANY ROWS"; INPUT VR
220 PROM "HOW MANY LAYERS TO BE
    STACKED"; INPUT VL
```

The next five lines of code set up the limiting values which ensure that the grid will fit on the CRT. The selected grid appears on the CRT in plan view for review.

```
230 EM=VC*EC+EX; EA=VR*ER+EY;
    IF EA GT EM, EM=EA
240 EA=VL; IF EA GT EM, EM=EA
250 FS=4000./EM
260 LL=VL; VL=VL*2
270 EXEC $T
```

The sub-MACRO in (\$T) above is executed, this will be TES1.MAC (for square grids), TES2.MAC (for hexagonal grids) or TES4.MAC (complex grid of squares and triangles) depending on the selection of the user. After reviewing the grid on the CRT, the user is given the opportunity to change the dimensions or select another grid in the lines that follow.

```
280 PROM VN,"ZAP POINTS WILL BE NEEDED
    FOR EACH STEP"
290 PROM "IF TOO BIG, TYPE R TO REDEMENSION
    OR P TO CHANGE É POS."
300 PROM "OTHERWISE HIT CR "; INPUT $A
310 IF $A EQ 'P', DEL $N; OPEN $N; SK -6
320 IF $A EQ 'R', DEL $N; OPEN $N; SK %DM
```

If the user hits the carriage return above, the picture file is closed in line 330. The structure may be rotated with dial 9 for the Z axis, dial 8 for the X axis, and dial 7 for the Y axis. The prompt messages given in lines 340 to 400 instruct the user on the MACRO commands.

```
330 CLOSE; ROT/D $N, Z D9; ROT/X $N, D8;
    ROT/Y $N, D7
340 PROM "FS1--STOPS MACRO FOR INPUT"
350 PROM "D6 --ADJUSTS SIZE OF STEP
    (BETWEEN -20 AND 20 DEGREES)"
360 PROM "IN S MODE SET FC=EB TO MAKE
    THE RANGE -5/5 DEG."
370 PROM " (SMOOTHER MOVEMENTS WITH
    SMALL STEPS)"
380 PROM " RESET RANGE WITH FC=EA"; VL=LL
390 EA=.1198458E-4; EB=.133162E-5; FC=EA
```

```
400 EXEC $S
```

In line 400, control is transferred to the sub-MACRO (\$S) which is the interactive simulation MACRO with dial control. One of the following MACROs is executed depending on the grid type selected: STES1.MAC (for square grids), STES2.MAC (for hexagonal grids), and STES4.MAC (for complex grids of squares and triangles). The interaction with the structure will carry on until the user pushes function switch one. If this occurs, control is transferred back to META7.MAC and the user is prompted to either continue with this shape, dimension another tiling, start anew, or save the present file and make another in lines 420 to 490.

```
410 IF FS NE 1, FB=FB+D6*FC; SK -1
420 PROM "ENTER C--CONTINUE FOLDING THIS
    SHAPE"
430 PROM " D--DIMENSION A NEW
    TILING OF THE SAME PATTERN"
440 PROM " R--RESTART AND TRY AGAIN"
450 PROM " S--SAVE THIS ONE AND
    MAKE ANOTHER"
460 FSOFF 1; IF $A EQ 'C', SK -6
470 IF $A EQ 'D', DEL $N; OPEN $N; SK %DM
480 IF $A EQ 'R', RESTART DO METVIDEO
490 IF $A EQ 'S', SK -99
```

This completes the discussion on the theory of the computer simulation of Meta Structures which focused on the techniques used to generate and manipulate regular polygons, and regular star fold polygons.

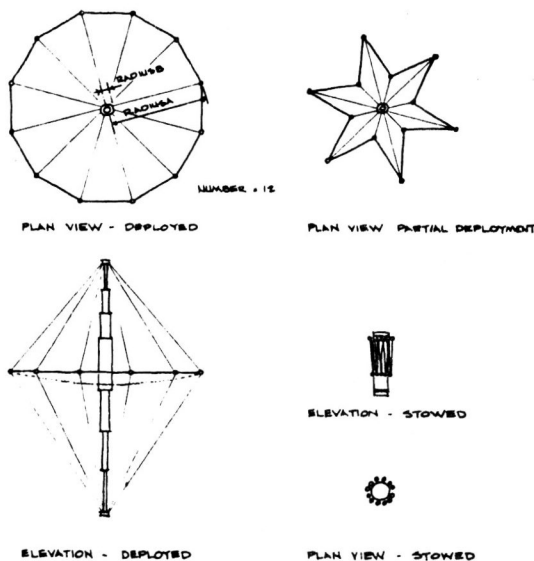
The next section will present some practical applications of Meta Structure Theory and give an example of its use in real time problem simulation.

### Applications in Space Research

The interactive computer graphics techniques used in the study of Meta Structures have produced a Dynamic Prediction System for Space Oriented Architecture (1). The mathematical model evolved allows the user to interactively construct Meta Structures using analog and linguistic controls. Real time motion can be simulated for structures which are considered to be part of the indeterminate set of possible outcomes. Real time interactions and dynamic simulations reinforce the user's decisions considerably and yet are absolutely unique to this medium. Furthermore, the programming language of the model, GRASS, (19) is both versatile and intelligible.

The capabilities of the modeling graphics have been demonstrated to several NASA professional groups well versed in the dynamics

behind the modeling of folding structures on the occasion of a special study requested by that organization (2,3,4,5,6,7,8,9,10,11,12,13). The problem posed by Thomas Campbell of NASA Langley Research Center dealt with large, self-deployed antennae. Of the several concepts and designs brought to the preliminary design stage and model tested for NASA by subcontractors, the Hoop and Column Concept of the Harris Corporation (see Figure 9) was the one chosen by NASA's Advanced Applications Flight Experiments of the Langley Research Center (4,8).



**Figure 9. Graphics Variables of Hoop and Column Concept**

The antenna structure is made up of an extendible central mast or column and a rigid hoop. The hoop and column in the deployed position, are connected together by control stringers. The hoop is made of rigid sections, each hinged to the adjoining section. Torsion springs are used in each joint to supply the energy required for deployment. The column contains the microwave components and the mechanisms controlling the stringers as they are payed out upon deployment.

The deployment sequence given by Campbell to put the graphics system to the test reads as follows:

- 1) The telescoping feed support and telescoping mast are extended (see Figures 10 and 11)
- 2) The hoop deployment begins by first allowing the (A) joints to move away from the column and down as they rotate about the position of the (B) joints until the hoop members lie in a plane perpendicular to the mast (see Figures 10 and 11)
- 3) The hoop deploys itself in the plane perpendicular to the mast as a result of the force generated by the torsion springs in each joint. The rate at which the stringers are payed out is kept constant and controls the speed of the deployment (see plan views Figures 10 and 11)

Only the following variables need be defined to generate the interactive real-time simulation of the Hoop and Column concept:

RADIUSA - radius of antenna  
 RADIUSB - radius of column or mast  
 NUMBER - number of elements in hoop  
 SCALE - scale factor for 2-D drawings

After interactively inputting the above data into the model building system, the real time deployment of the columns was assigned to one dial, the deployment of the hoop perpendicular to the column to a second dial, and the deployment of the hoop to its maximum radius to a third dial. Four lines of code were added to the existing MACRO (MSTAR.MAC) to allow the user to control the real time deployment of the hoop and column antenna. A complete solution describing the geometry of the structure and its deployment pattern was developed in less than ten hours of interactive connect time. A video tape showing the results was produced and delivered to NASA (See Figure 11).



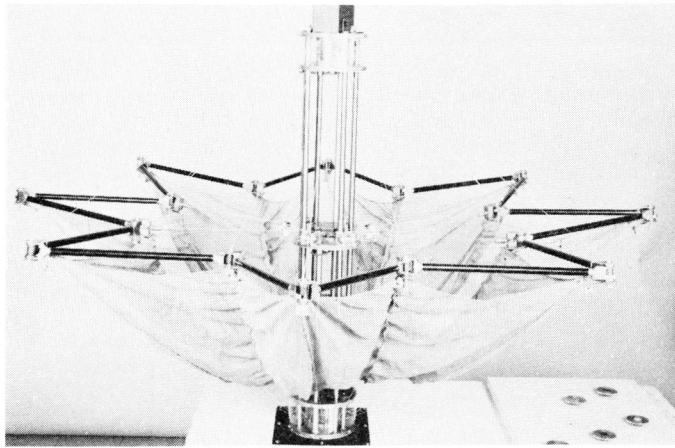


Figure 10. Hoop and Column Concept (Photograph Courtesy of NASA)

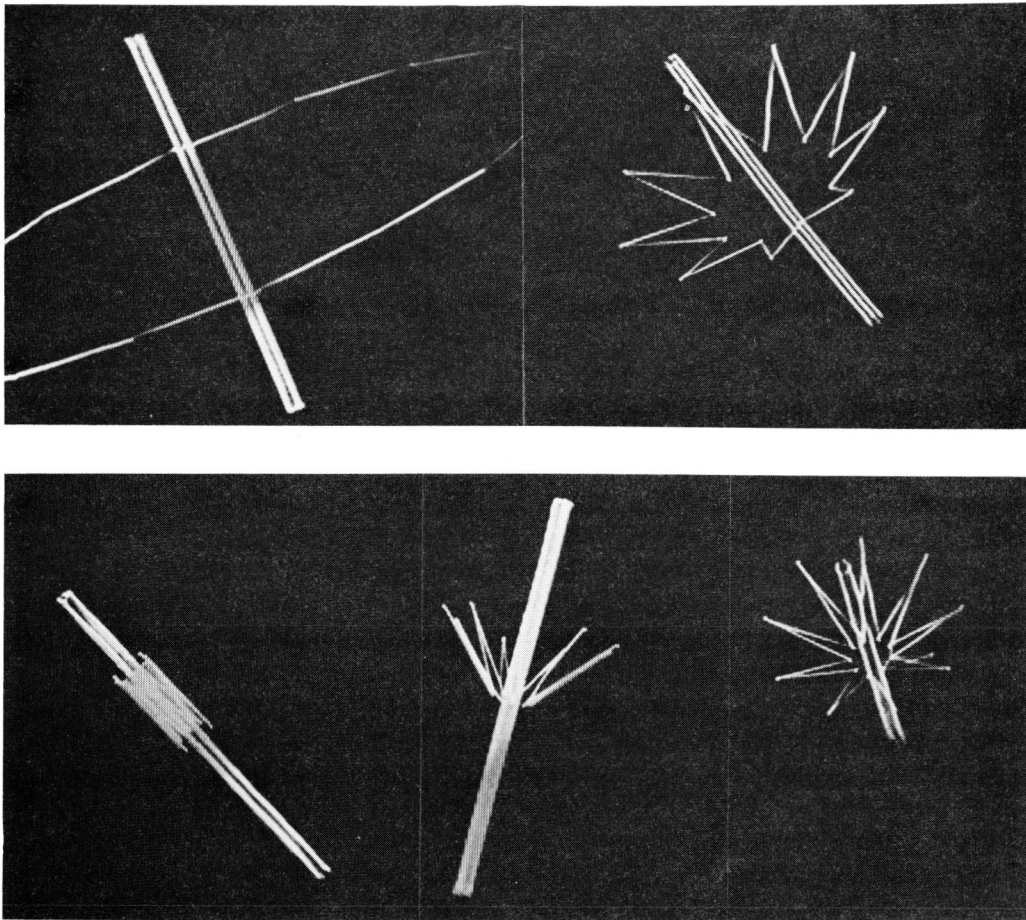


Figure 11. Computer Graphics Models

## Conclusion

The results of this test demonstrate the system's flexibility. It can be used and adapted to solve specific problems dealing with the real time transformations of folding structures using interactive graphics techniques. The author feels that the above solution dealt with a complex problem which could not have been solved in so short a time had it not been for the analysis and programming techniques outlined here. The graphics model of Meta Structures can become a powerful design tool for in the investigation of kinematic structures as well as kinetic structures.

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