THE DESIGN AND DEVELOPMENT OF
A TWO-DIMENSIONAL ADAPTIVE TRUSS STRUCTURE

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Abstract

The functional model of a two-dimensional adaptive truss structure which can purposefully change its geometrical configuration is introduced. The details of design and fabrication such as kinematic analysis, dynamic characteristics analysis and some test results are presented for the demonstration of this two-dimensional truss concept.

1. Introduction

An adaptive structure is a new type of space structure which can purposefully vary its geometric configuration and mechanical characteristics through geometric change of some component members in order to adapt to mission requirements and environmental conditions. This new structural concept appears to be applicable for use in many kinds of space structures; for example, in the control of geometry and vibration characteristics or for adjustment on orbit to compensate for the uncertainty in ground testing of large space structures.

One-dimensional adaptive truss-beam structures have already been studied (Refs. 1-3), and their application to space crane arms and to control of configuration and vibration characteristics has been proposed. They effectively use the properties of a statically determinate truss structure for their adaptivity.

In the near future two-dimensional truss structures will become important for planar space structures, such as large space antennas and space platforms. Various adaptive, two-dimensional truss structures have already been introduced and evaluated from the view point of both geometrical adaptivity and control of vibration characteristics (Ref. 5,6). In applications of space structures, some kinds of curved surfaces including paraboloids are important. There are two ways for obtaining a curved-surface, truss concept from a flat one. One is the bending concept in which the length of surface members is changed from that of the original flat structure, and the other is the shear concept in which the length of diagonal members is changed. The former is suitable for regular octahedral elements and the latter is suitable for cubic elements (Ref. 5).

The sheared deployable, cubic element, which is shown in Figure 1, displays the simple means of changing its configuration. In Figure 1, doubly-marked members change their length telescopically, while the members which are marked by a circle are folded when the cubic element is stowed. This sheared , deployable, cubic element can change its configuration by changing the length of the four diagonal members telescopically.

One example of a two-dimensional adaptive truss structure, which was introduced in Ref. 5 because of wide adaptivity for various configurations and ease of fabrication, is shown in Figure 2. The deployment stages are presented in Figure 2 (a)-(c). Figure 2(d) is a parabolic cylindrical surface. Figure 2(e) is a

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paraboloid , while Figure 2(f) is a hyperbolic paraboloid. In this example some of the cubic elements are modified by elimination of diagonal members to maintain a statically determinate truss structure (Ref. 7).

In this paper, the functional model of the two-dimensional adaptive truss structure, shown in Figure 2, is introduced. The details of design and fabrication of this model, kinematic analysis of various configurations, dynamic analysis, and test results are presented.

2. Kinematic analysis

Generally speaking, kinematic analysis is very important in the dsign and development of deployable structures, especially in determining the mechanical degrees of freedom and the offset position of hinges. Two types of kinematic analyses are performed to design the functional model.

First, a wire frame model which does not consider the diameter of members is studied. This analysis is very useful in understanding the kinematic behavior of the functional model while moving between the stowed and deployed configurations. There are two types of diagonal members which change their length telescopically. One is the so-called $\sqrt{2}$ diagonal member which changes its length in the range:

$\sqrt{2}a$: deployed configuration
$2a$: stowed configuration
where a : the length of the vertical member.

The other type is the so-called $\sqrt{3}$ diagonal member which changes its length in the range:

$\sqrt{3}a$: deployed configuration
a : stowed configuration.

The type of deployment under consideration is shown in Figure 2 (a)-(c).

Second, an analysis is performed on a solid model which includes the offset positions, the definition of kinematic degrees of freedom and the shape of the hinges. The analysis is performed using the Computer-Aided-Engineering (CAE) program GEOMOD. This method of design and analysis is very practical for obtaining highly efficient and reliable mechanism designs. In kinematic analysis, numerical problems in solving the simultaneous non-linear equations can occur, as the number of the independent kinematic loops increases. Therefore, precise kinematic analysis was performed only for typical elements of the functional model. The deployment of the configuration of Figure 1 (a)-(b) was analyzed by this method.

3. Shape control

The functional model, which depends on the shear concept, can form the following quadratic surfaces by changes in the length of the diagonal members telescopically.

Circular Cylindrical surface:

$$y^2 + z^2 = r^2$$

r : the length of radius

Parabolic Cylindrical surface:

$$z = y^2/2c$$

$$c \ : \ \text{the focal length}$$

Circular paraboloid:

$$z = (x^2 + y^2)/2c$$

Hyperbolic paraboloid:

$$z = (x^2 - y^2)/2c$$

To form the quadratic surface starting from the deployed planar truss, additional strokes of the diagonal members are necessary. As the actuator for the diagonal members of the functional model, a single ball-screw has been used (for reasons of simplicity, reliability, and cost), and the maximum possible stroke of the diagonal member is shorter than the length of the vertical member. Thus for the functional model, the stroke of the diagonal members limits the retrieval function, as described in section 6.

4. Dynamic characteristics control

A two-dimensional adaptive truss structure will be able to change its vibration characteristics by changing the configuration of the structure as shown in Figure 2. It is a very important charcteristic of the two-dimensional adaptive structure. To verify the change of vibration characteristics, finite element method (FEM) models, which have 337 grid points and 474 bar elements with the pin flag options for simulating hinges, have been made using NASTRAN for the configurations shown in Figure 2 (Case 1), namely plane, circular cylindrical surface, paraboloid and hyperbolic paraboloid. In these models, the focal length of the hyperbolic paraboloid is about four times as long as the vertical member length, 3000 mm; the radius of the circular cylindrical surface is three times as long as the vertical member length, 2100 mm; and the focal length of the paraboloid is about three times as long as the vertical member length, 2000 mm. Eigenvalue problems were solved by the modified Householder's method after reducing the original degrees of freedom to three translation degrees of freedom at every corner point, using the Guyan reduction method. The boundary condition is free-free.

The natural frequencies are listed in Table 1 and the first mode shape is shown in Figure 3. The first mode shape of the planar configuration is very similar to that of a free-free square plate, but the higher mode shapes are not similar. The natural frequencies of the lower modes for the curved configurations are slightly lower than those of the planar configuration.

For the configuration shown in Figure 2, to obtain the paraboloid surface, half of the $\sqrt{3}$ diagonal members are shortened and half of the $\sqrt{3}$ diagonal members are extended. With the configuration of Figure 4 (Case 2), two types of paraboloid can be formed. One is formed by shortening the $\sqrt{3}$ diagonal members and the other is formed by extending the $\sqrt{3}$ diagonal members.

From the point of view of vibration characteristics, it appears that the former paraboloid has higher natural frequencies than that of the latter. To verify this idea, natural frequency analysis was performed in the same manner as Case 1. The natural frequencies are listed in Table 2, and the first mode shape is shown in Figure 4.

In the planar configuration (Fig 4a), the first and the third natural frequencies are slightly lower than those of Case 1. But the paraboloid by shortening the diagonal members has higher natural frequencies than that of the paraboloid by extending the diagonal members. This is a very interesting characteristic of a two-dimensional adaptive truss structure. Both paraboloids have the same surface shape, but the vibration characteristics are different.

The arrangement of members in Case 2 was selected for the functional model.

5. Functional model

The dimensions of the functional model, which is shown in Figure 5, are approximately 3.5 m x 3.5 m x 0.7 m in the deployed configuration. The model consists of the truss structure and the actuator/control modules.

The truss structure consists of the following members:

       36 vertical members   :   diameter 20 mm
      120 lateral members :   diameter 10 mm
      36 diagonal members :   diameter 20 mm
      18 battern wires   :   diameter 2 mm

In the concept design phase wires have been used in place of diagonal members in the upper and lower surfaces of the model to reduce the weight of the truss. These members provide inplane shear stiffness.

The hinges consist of the following:

      184 pin-joints
      128 two degree-of-freedom hinges
       36 telescopic hinges.

Figure 6 shows one of major joints.

The truss has 36 actuators which change the length of those diagonal members with telescopic joints. The actuator consists of a ball-screw and a small DC servomotor with a speed reducer and encoder. The actuators are controlled by a micro-computer (INTEL 8086 equivalent) to change the configuration of the truss as shown in Figure 2. The functional block diagram of the actuator/control modules is shown in Figure 7. The micro-computer sends the reference values of the length and deployment rate of diagonal members to 36 drivers through GPIB (General Purpose Interface Bus). The drivers control the actuators in respect to both position and angular rate using feedback of the encoder signal.

6. Preliminary test results

The deployment/retrieval functional test was performed with a constant angular velocity of 0.5 deg/sec between the vertical member and the lateral member. The behavior of deployment/retrieval is very smooth on the floor with 18 casters. Figure 8 shows the "stowed" configuration at θ = 40 deg where θ is the angle between the vertical and lateral member; θ = 0 deg corresponds to a perfectly stowed configuration, while θ = 90 deg denotes the fully deployed configuration.

The functional model can actually be stowed up to θ - 25 deg. However, gravity effects in the ground test require support cables to compensate the gravity force when θ is smaller than 40 deg. The stowing functional test to θ = 25° will be performed with support cables.

The shape control test was performed on the floor also. The plane shape of the functional model was changed to the cylindrical surface configuration successfully. Figure 9 shows the cylindrical surface which is formed by the grid points of the upper surface. The shape control test for the paraboloid and the hyperbolic will also require support cables.

7. Concluding remarks

In early 1987, a modal survey for verification of vibration characteristics and the shape control tests for the paraboloid and the hyperbolic paraboloid with the support cables will be performed.

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Table 1. Natural Frequency (Case 1)

Mode	Natural frequency (Hz)			
	Plane configuration	Hyperbolic paraboloid	Cylindrical surface	Paraboloid configuration
1	19.45	18.48	16.03	16.19
2	22.19	19.45	20.26	20.89
3	27.96	25.69	20.43	20.92
4	28.03	25.69	27.80	23.39
5	28.65	27.62	30.99	27.14
6	41.06	36.03	36.13	30.17
7	41.76	37.53	37.59	35.85

Table 2. Natural Frequency (Case 2)

Mode	Natural frequency (Hz)		
	Plane configuration	Paraboloid configuration	
		$\sqrt{3}$ members extended	$\sqrt{3}$ members shortened
1	17.09	16.73	15.25
2	22.83	23.52	16.59
3	25.36	24.63	18.47
4	28.45	26.85	21.41
5	33.11	32.58	21.49
6	45.92	40.84	32.10
7	48.73	41.47	34.59
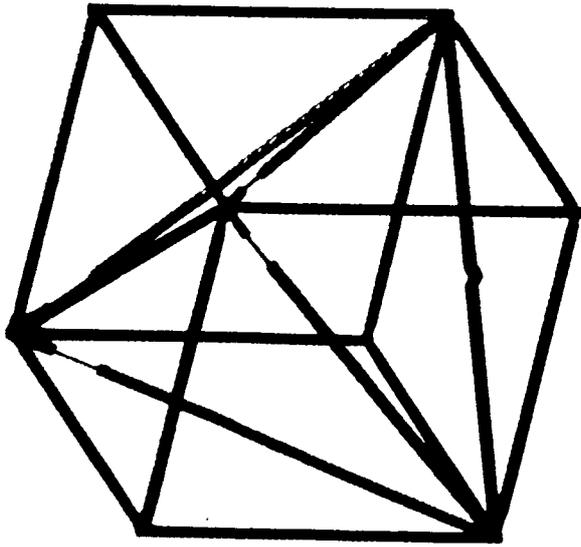
(a) Deployed Configuration
(Solid Model)
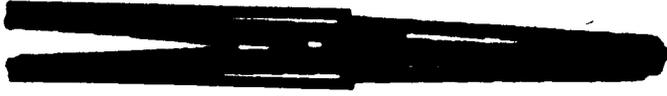
(b) Stowed Configuration
(Solid Model)
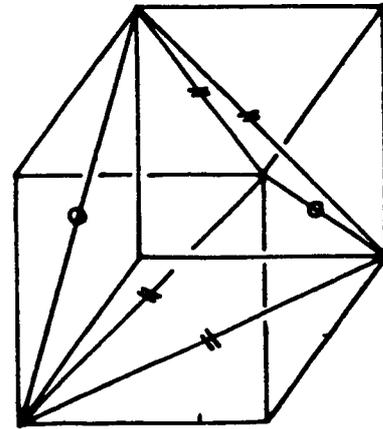
ll : Telescopic hinge

o : Folded hinge

(c) Arrangement of Hinges

Figure 1. Sheared Deployable Cubic Element

√3 Diagonal
Member

√2 Diagonal
Member

(a)

(b)

(c)

(d)

(e)

(f)

Paraboric surface
in one direction
or cylindrical surface

Paraboloid

Hyperbolic paraboloid
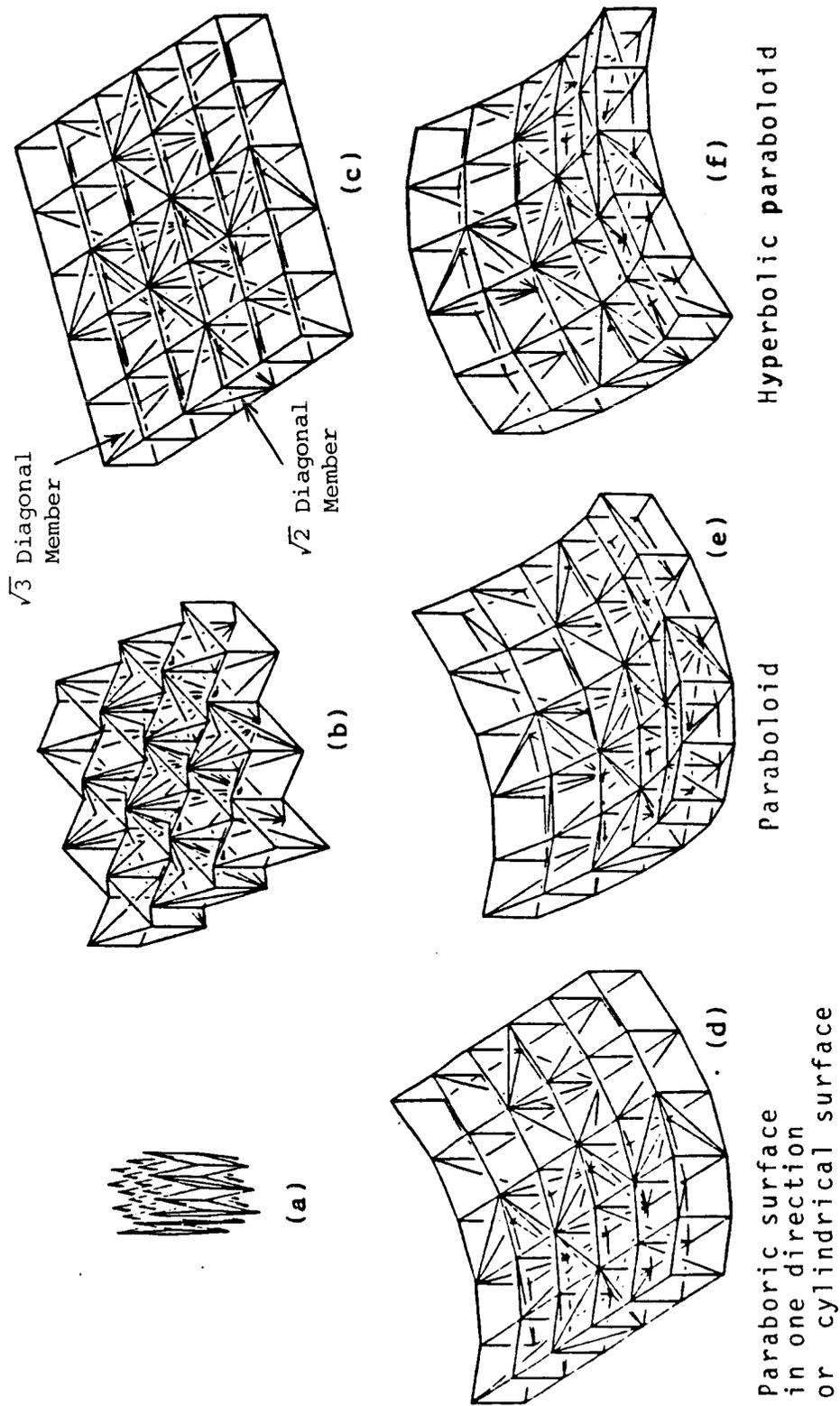
Figure 2. Two-Dimensional Adaptive Truss Structure (Functional Model)

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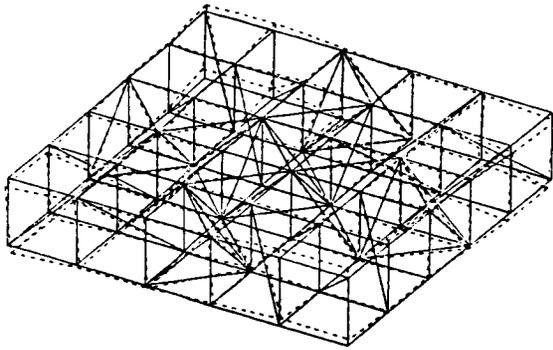
(a)   Plane Configuration
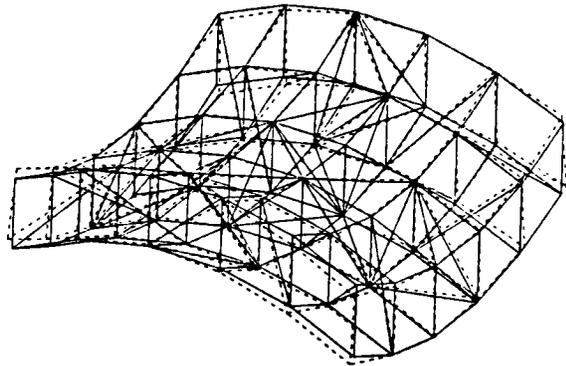
(b)   Hyperbolic Paraboloid
      Configuration
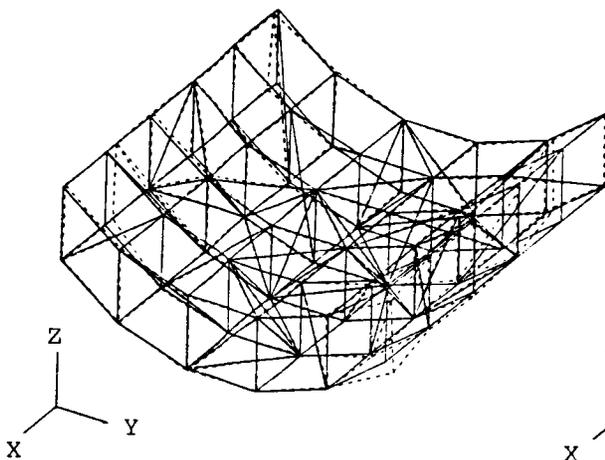
(c)   Cylindrical Surface
      Configuration
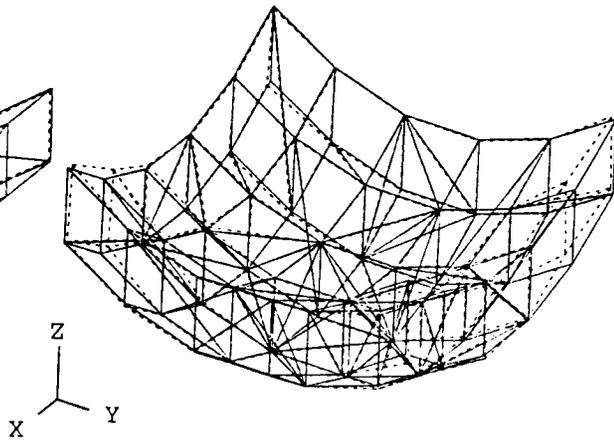
(d)   Paraboloid Configuration

Figure 3.   First Mode Shape (Case 1)

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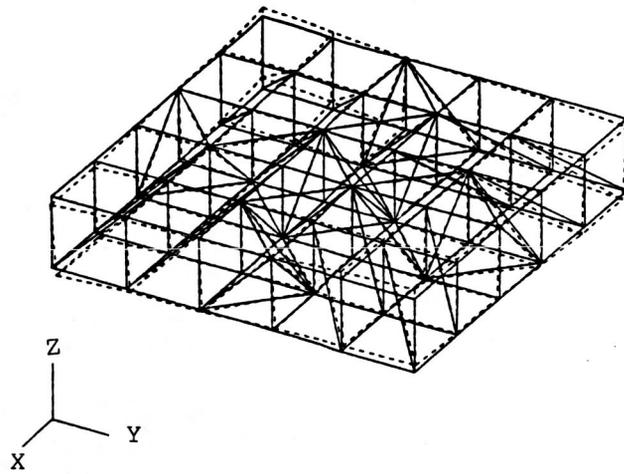
(a) Plane Configuration
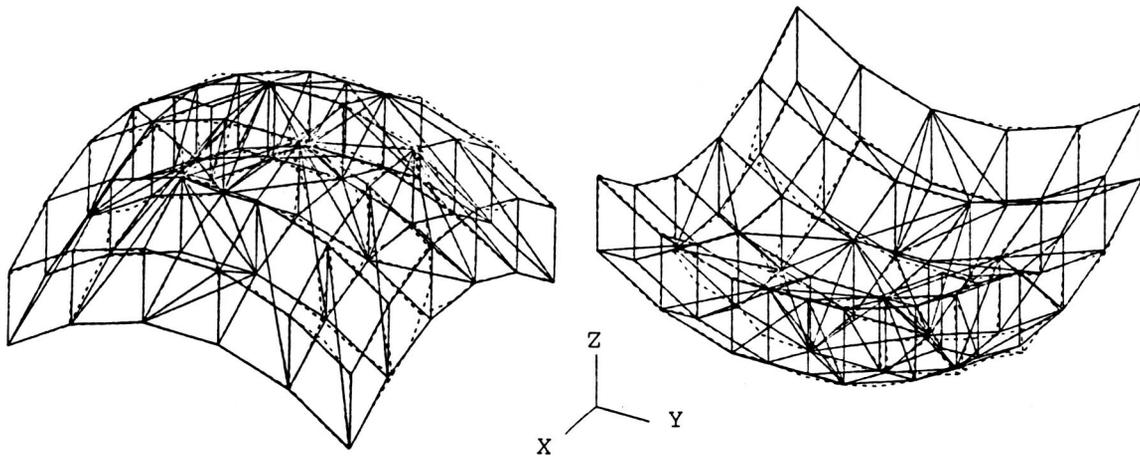
(b) Paraboloid Configuration
($\sqrt{3}$ Members Extended)

(c) Paraboloid Configuration
($\sqrt{3}$ Members Shortened)

Figure 4. First Mode Shape (Case 2)

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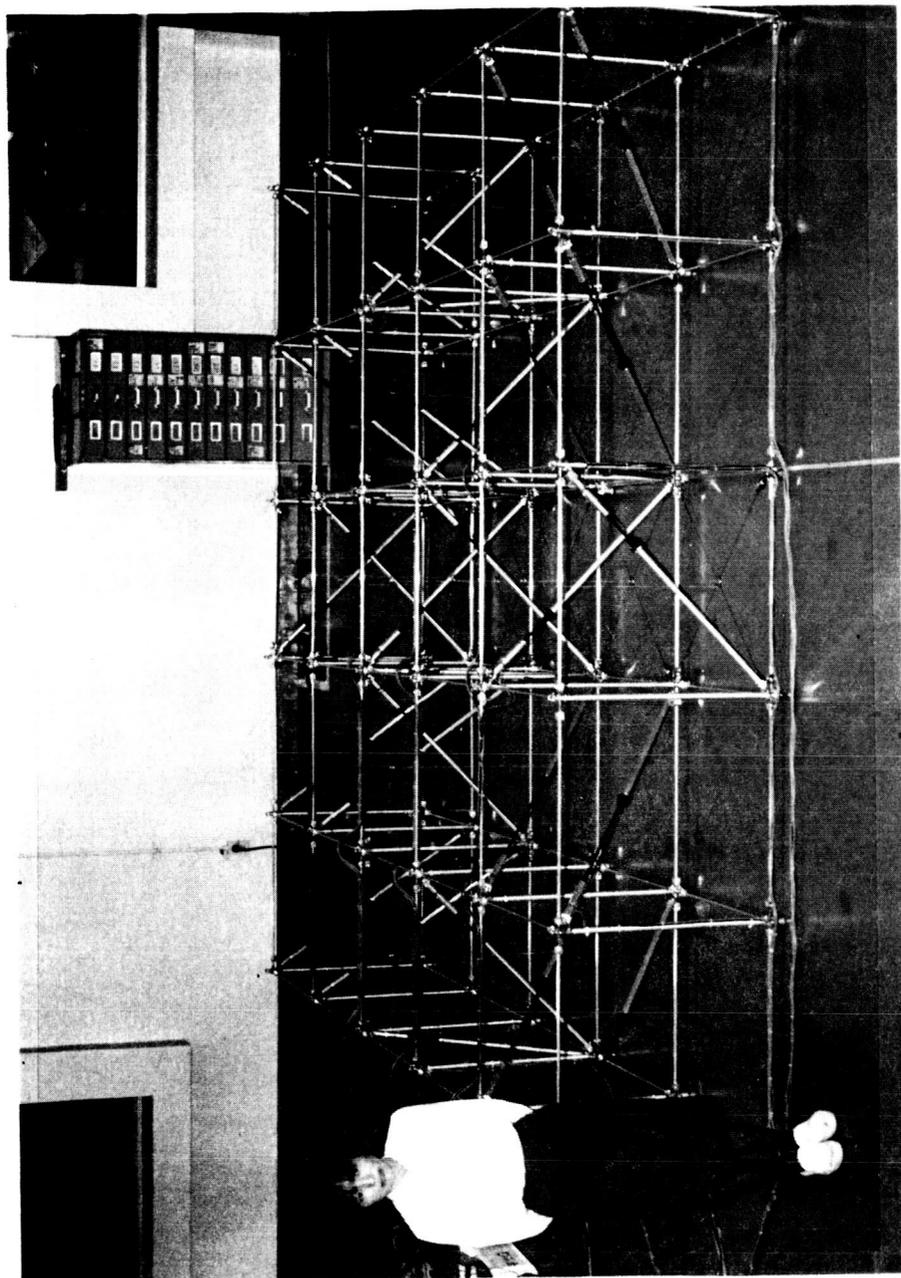
Figure 5. Functional Model of Two-Dimensional Adaptive Truss
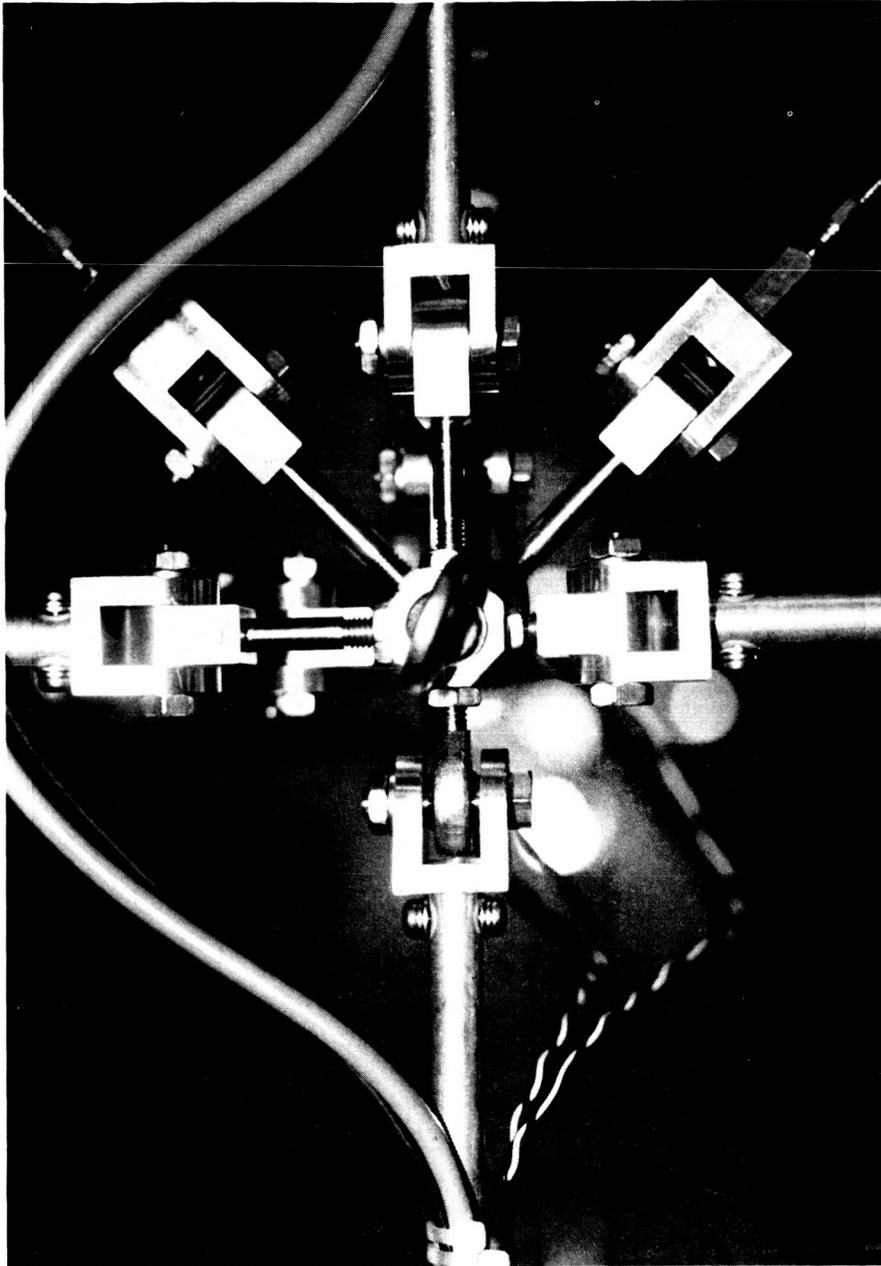
Figure 6. One of Major Joints (Functional Model)
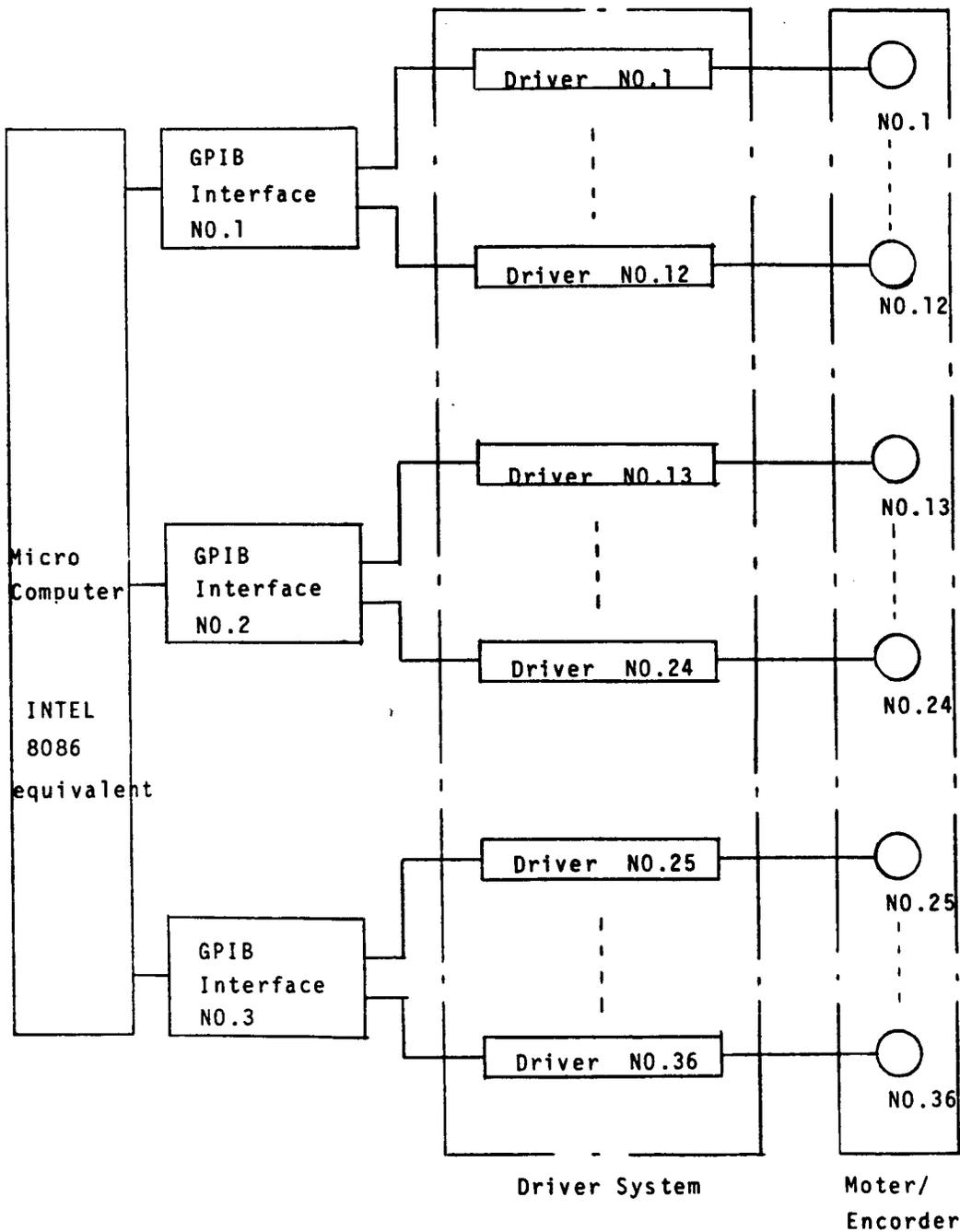
Figure 7. Functional Block Diagram of the Actuator/Control Modules

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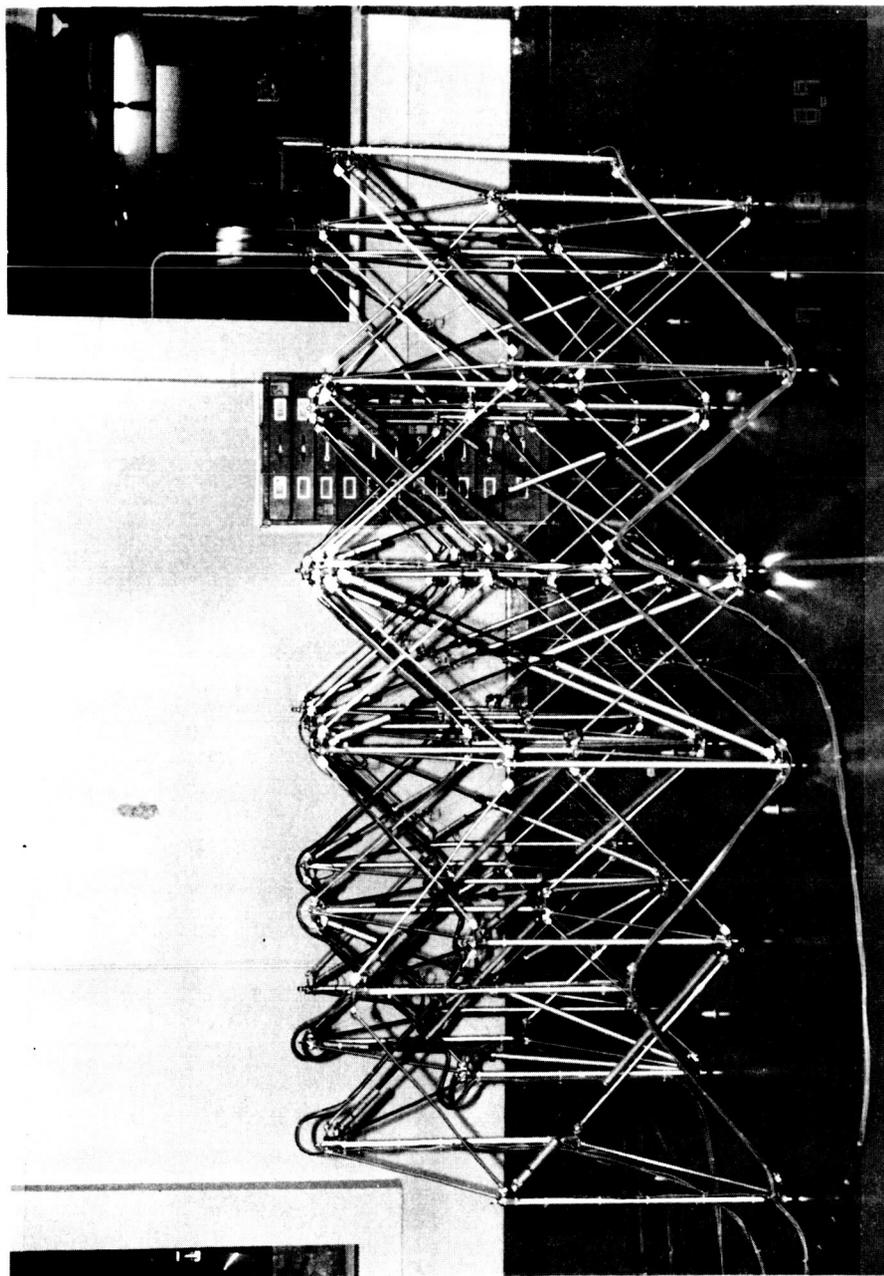
Figure 8. Stowed Configuration at θ=40 deg (Functional Model)
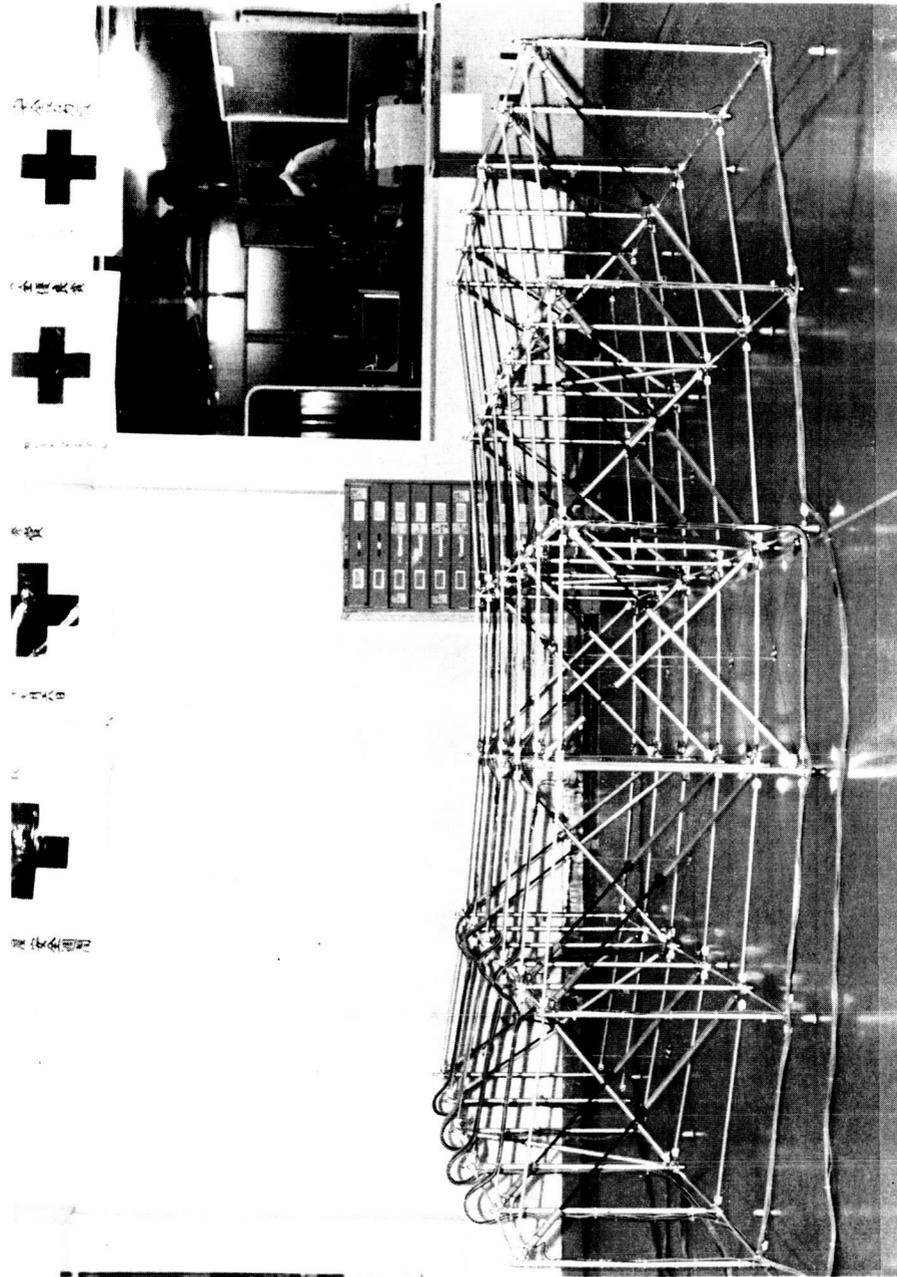
Figure 9. Cylindrical Surface Configuration (Functional Model)

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