Variable Geometry Truss Concept

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Summary: In the PART I of this paper, a new concept for the one-dimensional deployable truss structure is presented. The deployed configuration of the structure consists of the repetition of an octahedral truss module longitudinally, and thus it is exactly the so-called "geodesic beam" structure. The principal mechanical feature of the truss is that the lateral members comprising the lateral triangular truss are telescoping beams. Contracting of the lateral members results in the deployment of the truss structure. The geometric transformation of this truss of variable geometry is presented. It is shown that both simultaneous and sequential modes of transformation are possible. The validity of the transformation applied to the deployment is verified through design of a conceptual model. In the PART II of the paper, a preview is presented as for the applications of the concept to a curvilinear truss and a space manipulator arm.

Key Words: Truss, Deployable, Large Space Structure, Mainpulator, Robotics

PART I*

DESIGN AND OPERATION OF A DEPLOYABLE TRUSS STRUCTURE

I. INTRODUCTION

At present, the only established concept for the deployable one-dimensional structure for space applications is the coilable longeron beam. However, a study (reference 1) has shown that the coilable longeron beam (Astromast) is limited to beam dimensions of less than 1 meter due to difficulties in packaging the stowed energy in the beam. For applications which require large beams, deployable beams with hinged longerons or erectable beams must be developed.

Recently, the Rockwell International Corporation and the Vought Corporation studied a number of existing structural concepts for fully deployable beams and platforms (references 2, 3). In spite of these efforts, a satisfactory structural concept which has an advantage over others in every respect has not yet been found. This situation is not changed even if a different set of criteria for selection is used. Under these circumstances, the derivation of new concepts through various possible approaches seems to be

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beneficial.

The present author has succeeded in devising a new concept for a one-dimensional deployable structure through a unique geometric approach. The concept was verified through a conceptual model. This paper describes briefly the theoretical foundation of the concept, the inherent mechanisms, and the mode of the deployment.

II. DEPLOYABLE TRUSS CONCEPT

The concept of the deployable truss which the author proposes herein is essentially a truss of variable geometry. Figure 1 illustrates a typical example of the proposed concept for the deployable truss structure. The fundamental module of the truss is an
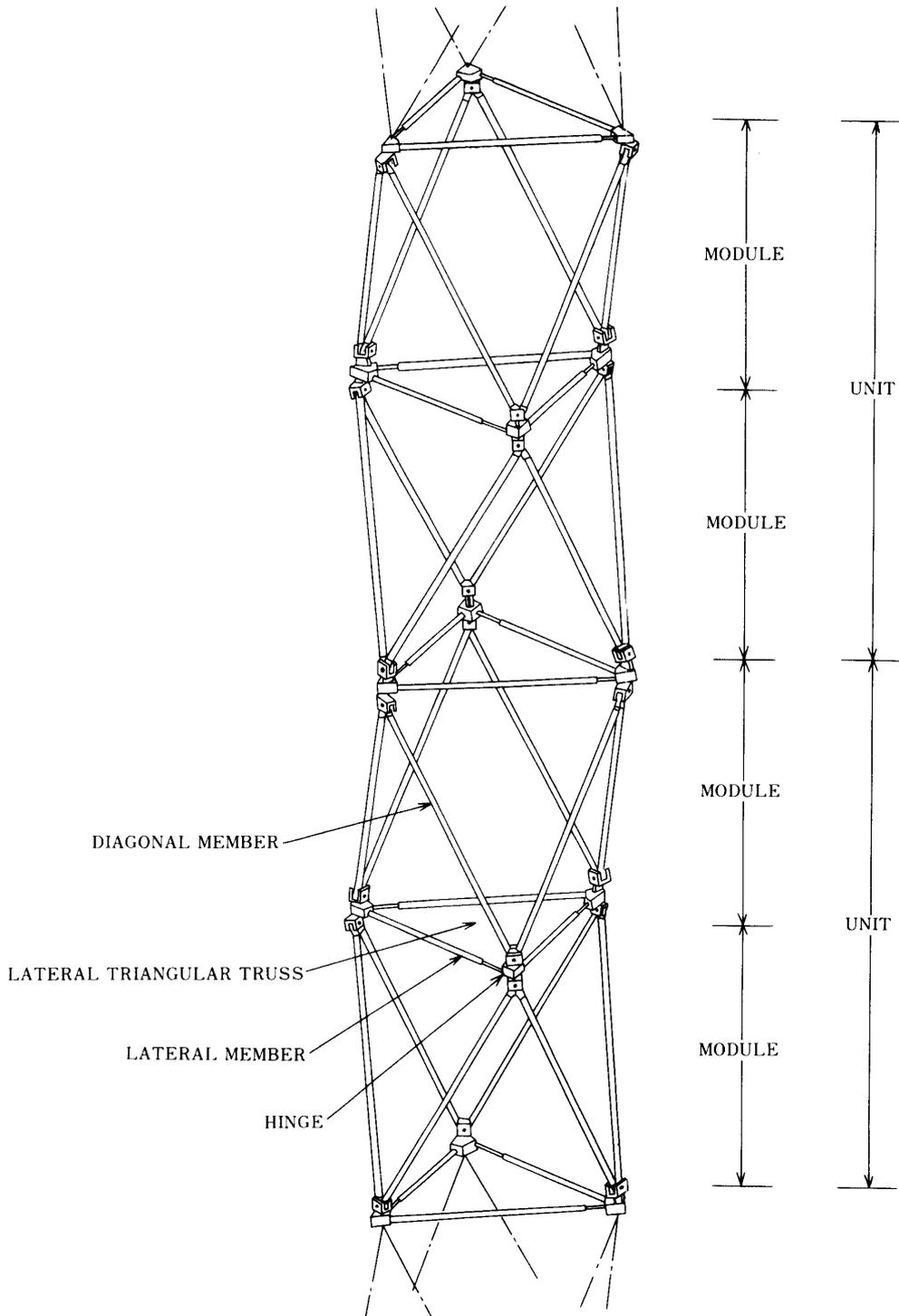

Fig. 1.   Proposed concept of deployable truss structure.

octahedral truss composed of a pair of lateral triangular trusses and six diagonal members. The two adjacent modules, which share the lateral truss, compose a repeating unit of the truss. Thus, the repetition of the unit in the longitudinal direction forms the whole structure of the deployable truss.

A part of Figure 1 is enlarged and shown in Figure 2. It illustrates the vicinity around a lateral triangular truss. The details of a lateral member are shown in Figure 3. It is a telescoping beam whose length can vary. The telescoping beam contains inside the tubular section an elastic tensile spring which is connected to both ends of the beam. A latch is also installed in the beam in order to fix its length at the shortest state. Figure 4 illustrates the change in the configuration of the truss from the folded state to the fully deployed state. Shown in Figure 5 is the almost folded state of the truss.
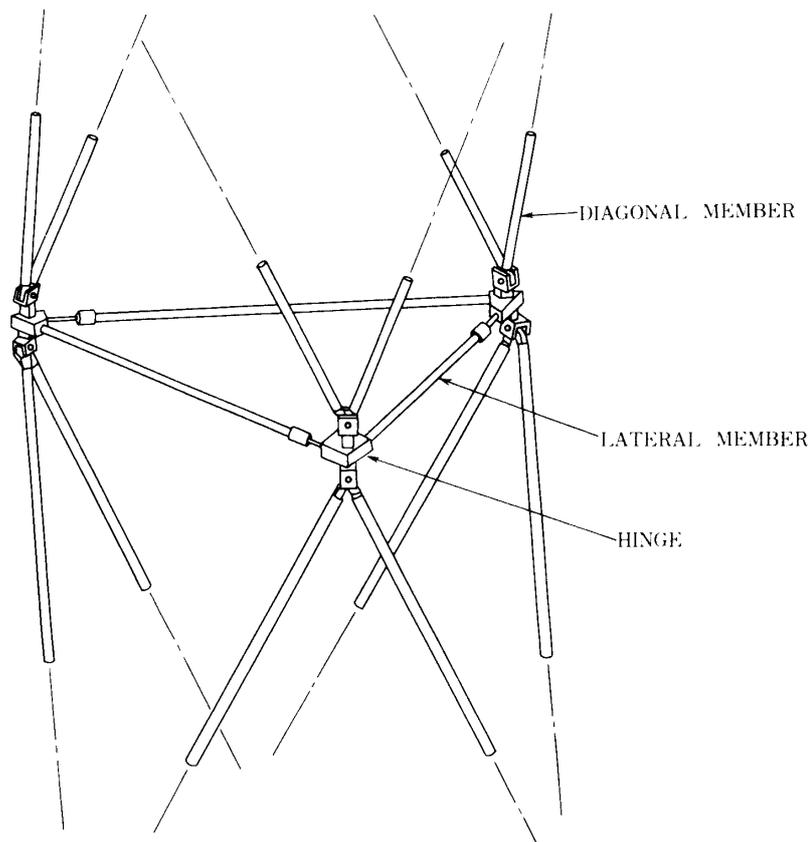
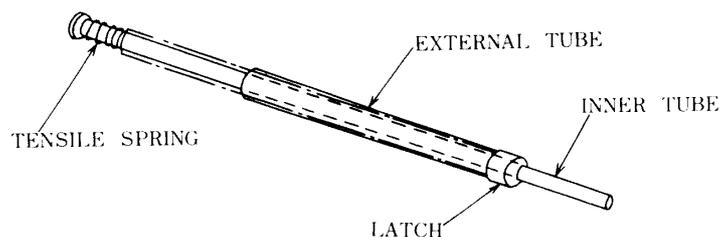Fig. 2.   Details of deployable truss structure.
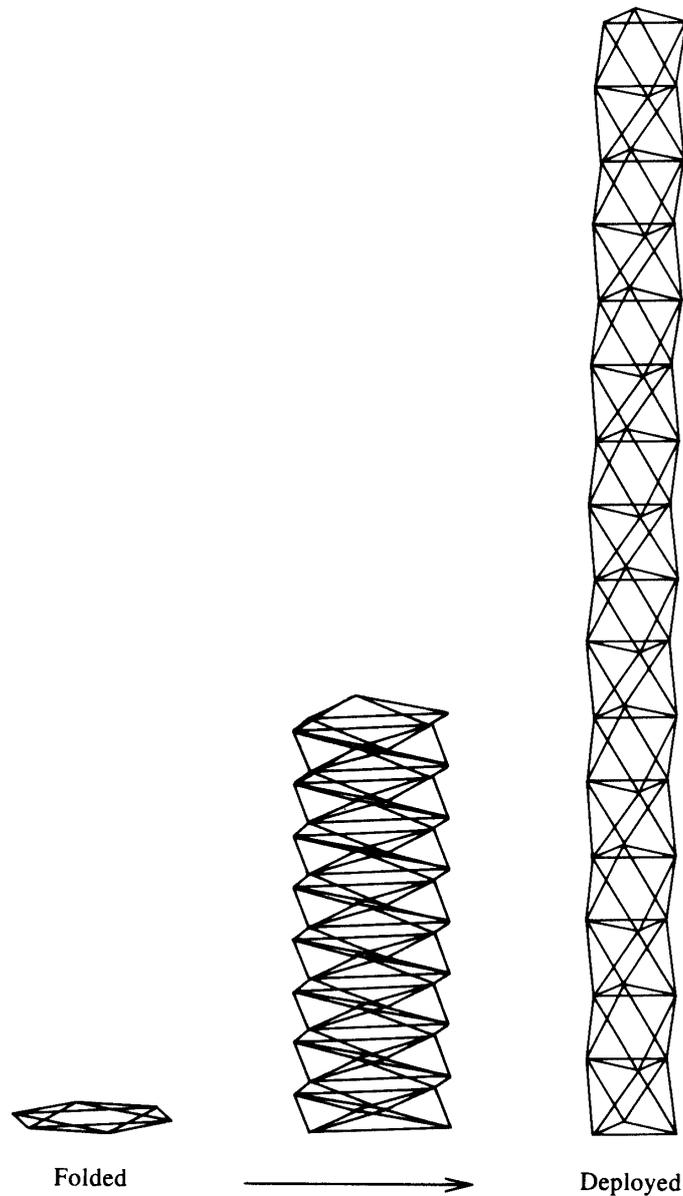
Fig. 3.   Details of lateral member.

Folded   ⟶   Deployed

Fig. 4. Geometric configurations of deployable truss.

III. GEOMETRIC TRANSFORMATION OF THE TRUSS (SIMULTANEOUS MODE)

The outward appearance of the deployable truss shown in the preceding section is known elsewhere if it is a rigid static structure instead of a structure of variable geometry. For instance, in reference 4, that type of truss (geodesic or inverted batten beam) is studied in order to verify the theory of continuum analogy for large space structures. Actually, such truss is one of the most efficient light weight structures using the minimum number of component members. In this section, the author shows the geometric transformation by which the truss can be transferred to a compact configuration. With the mechanisms installed in the truss as described in the previous section, the truss becomes deployable.

The geometric transformation explained in this section is the mode where the folding/
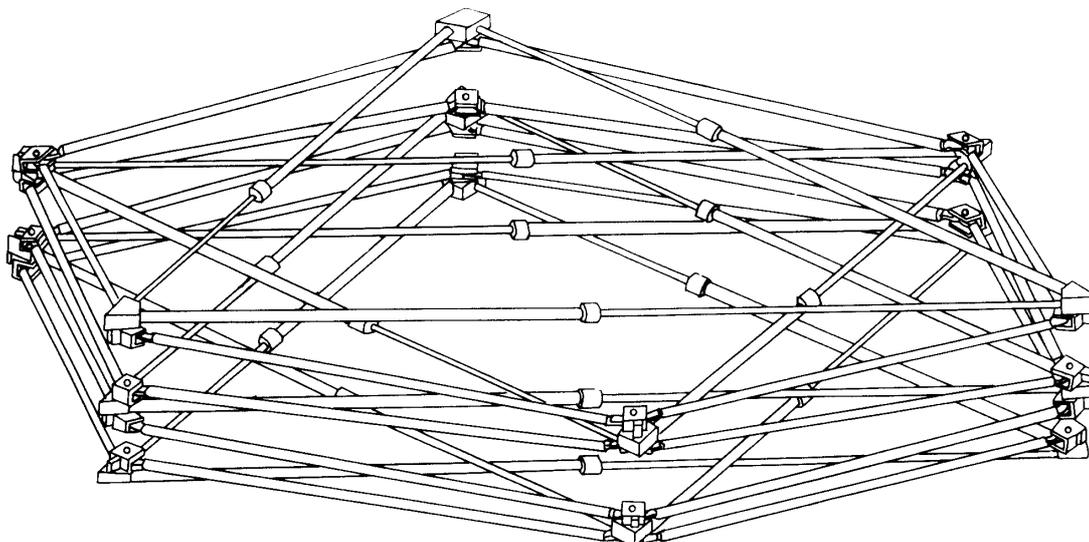
Fig. 5.   Deployable truss in almost folded state.

deploying is carried out simultaneously through the whole structure. Let it be called the simultaneous mode transformation.

Let us consider a single unit which is composed of a pair of octahedral trusses as shown in Figure 6. It is assumed that the lateral triangular truss is regular, the length of a diagonal member is a, and the length of the side of the lateral triangle is b. Then the geometry of the octahedral truss is completely defined by the magnitude of a and b. If a is equal to b, the truss becomes a regular octahedral truss. We shall start with this case and study how the truss is transformed, depending on the relative magnitude of b to a.

As shown in Figure 6a, the face angle between a pair of triangles which compose a concave diamond pattern is taken as 2θ. Then we have

$$\theta = \cos^{-1} (b/2\sqrt{3} \ \sqrt{a^2 - b^2/4}). \tag{1}$$

For the configuration of Figure 6a, a equals b, and therefore

$$\theta = \cos^{-1} (1/3) = 70.53 (\text{deg.}).$$

We are immediately aware that Eq. (1) has also a non-trivial solution for θ equal to zero. This is the fundamental fact on which the present concept of deployable truss depends. That is

$$\theta = 0, \quad \text{if} \quad b = \sqrt{3} \ a. \tag{2}$$

The vanishing of the face angle θ means that the height of each octahedral module vanishes, too. In other words, the complete truss is transformed to a flat configuration as shown in Figure 6b.

The proposed concept of deployable truss uses this fact. If we are able to design the lateral member with variable length (i.e. a telescoping beam), we are close to the
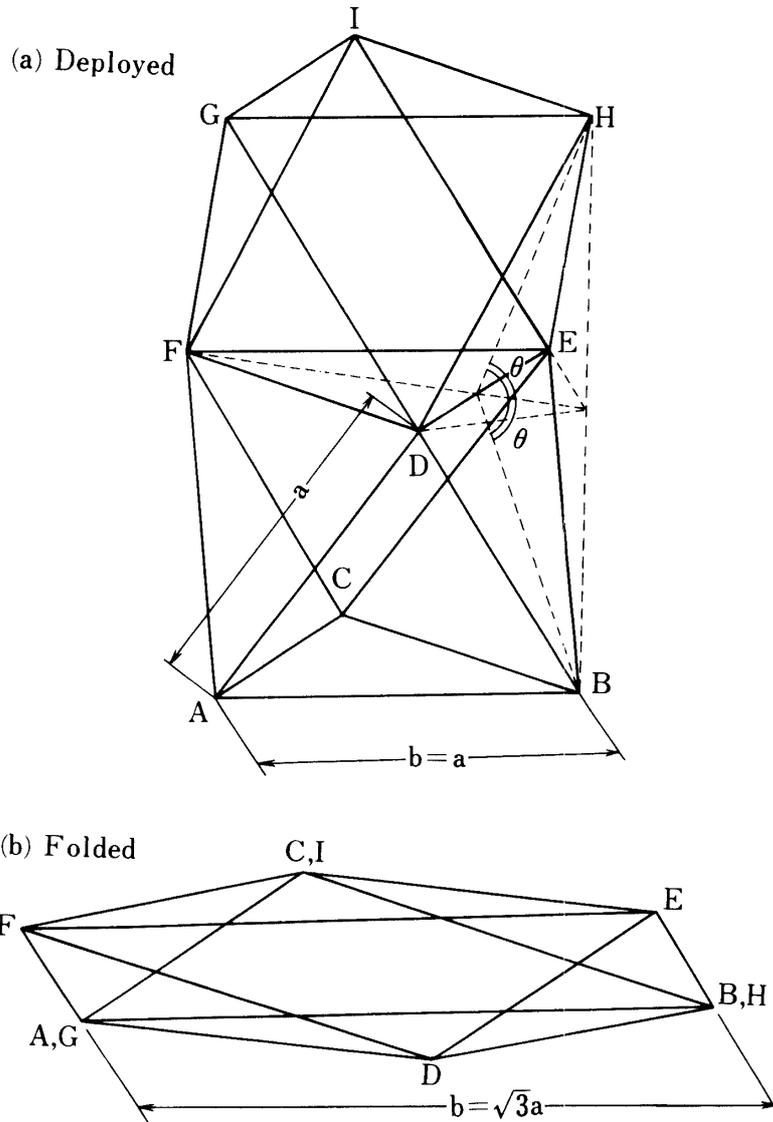
(a) Deployed

(b) Folded

Fig. 6. Repeating unit of truss.

solution. Let the length of the lateral member vary as follows:

$$a \leq b \leq \sqrt{3}\, a, \tag{3}$$

then, the height of a module h varies between the limits:

$$\sqrt{a^2 - b^2/3} \geq h \geq 0. \tag{4}$$

This means that, by extending the lateral members by a factor of $\sqrt{3}$, the height of the truss should vanish.

An example of the lateral telescoping member is shown in Figure 3. It is comprised of an external tube, an inner tube, a tensile elastic spring inside the tube, and a latch mechanism which is actuated when the member is shortened to a defined length. The

diagonal members are fixed length members. Though it is not shown in detail, the hinge mechanism is so designed as to follow the movement of the truss. Figure 5 shows the shape of the truss at almost fully folded state. This rather strange folding mechanism may be somewhat beyond one's insight. It is easier for one to understand the mechanism through a three dimensional kinetic model.

IV. Geometric Transformation of the Truss (Sequential Mode)

Theoretically speaking, a geometric transformation in a sequential mode is possible in which each module is deployed successively while other modules remain fixed. Since the sequential mode is important from the point of view of deployment control, we will study that mode in this section.

Figure 7 shows the zone of the truss where the sequential deployment is under way. For clarity of explanation, it is better to divide the whole truss into three zones, that is, the deployed zone, the transient zone, and the folded zone. It is assumed that the truss comprises n lateral triangular trusses and n−1 modules. The above three zones are explained as follows:
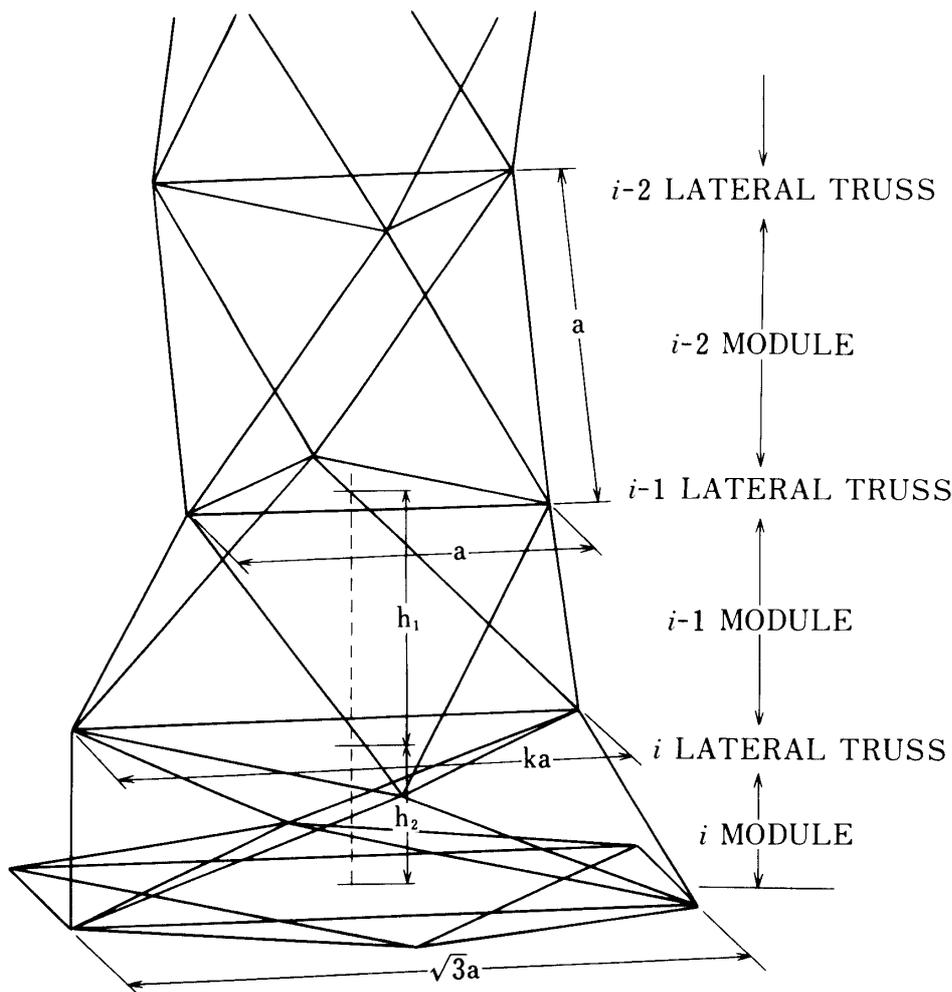

Fig. 7. Sequential mode deployment.

	(DEPLOYED ZONE)	(TRANSIENT ZONE)	(FOLDED ZONE)
LATERAL TRUSS	1,2,3, . . . i−1	i	i+1, . . .
MODULE	1,2,3, . . . i−2	i−1, i	i+1, . . .

The important fact is that there exists a geometric transformation which allows the contraction of the i-th lateral triangular truss and the following deployment of the (i−1)-th and i-th modules without interfering with other zones of the truss.

The sequence of motions of the truss which constitutes the contraction of the i-th lateral truss is explained as follows: When the i-th triangular truss starts contracting, it is raised from the base, and the i-th module starts to deploy. Before that, the (i−1)-th module is partially deployed, and is continuing to deploy. When the i-th lateral truss finishes its contraction, and is latched, the (i−1)-th module completes the deployment. The sequence of this process is illustrated in the series of figures in Figure 8.
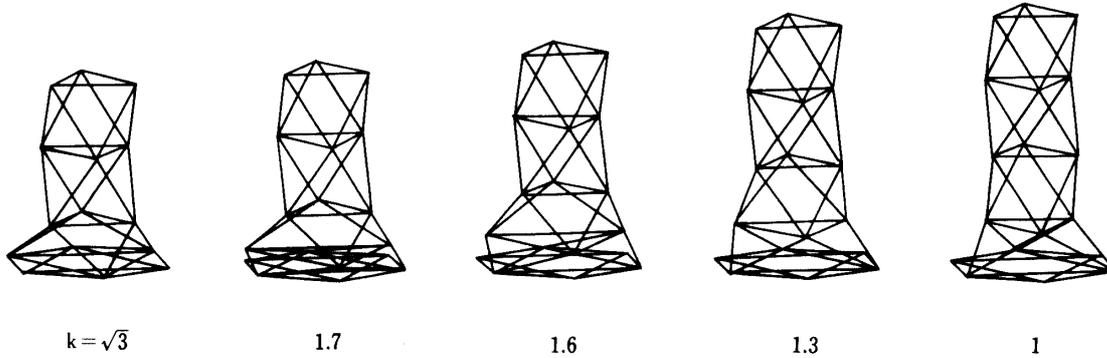

| $k=\sqrt{3}$ | 1.7 | 1.6 | 1.3 | 1 |

Fig. 8.   Contracting of lateral member and birth of module.

The relation between the length of the diagonal member a, the length of the lateral member b, and the height of the module h is obtained easily by using Figure 7. If a and b are connected with the variable parameter k,

$$b=k \cdot a, \qquad \text{where} \quad \sqrt{3} \geq k \geq 1, \tag{5}$$

then, the heights of the modules are

$$h_1=\sqrt{(2+k-k^2)/3} \cdot a, \qquad [(i-1)\text{-th module}] \tag{6}$$

$$h_2=\sqrt{k/\sqrt{3}-k^2/3} \cdot a. \qquad [i\text{-th module}] \tag{7}$$

From a practical standpoint, the sequential mode transformation possesses a great advantage over the simultaneous one. This is because in the former case the deploying/ folding takes place near the base and thus design of the mechanism is simpler. The outer truss is then always extending from the base as a rigid structure.

V.   Conceptual Model

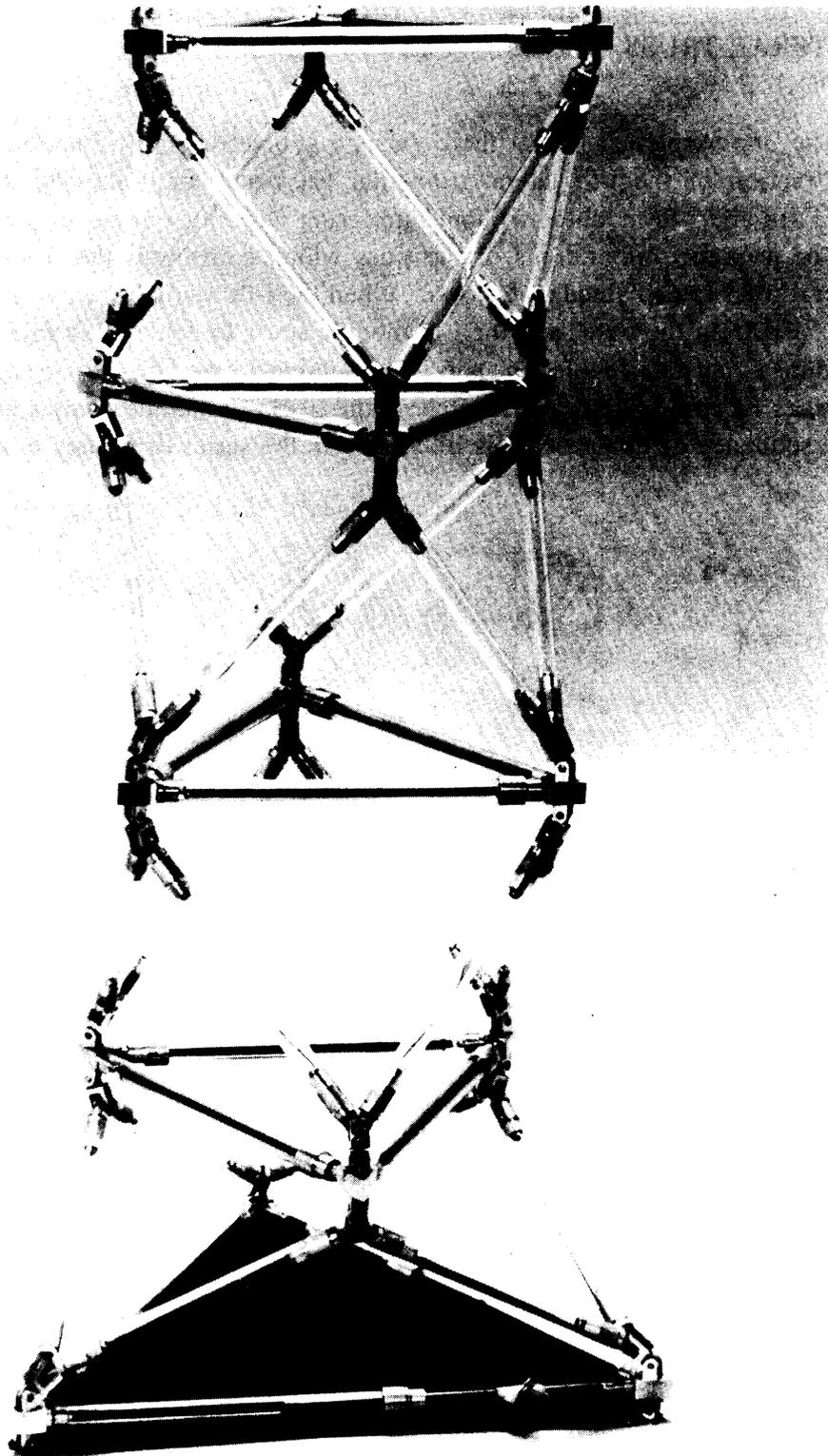Although there is no doubt of the validity of the geometric transformations, a model

Fig. 9.   Conceptual model.

has been constructed to demonstrate the concept.   This model is made of acrylic glass
tubes and aluminum hinges as shown in Figure 9.   The deployment of the model in a
sequential mode is shown in the series of photos in Figure 10.   The model works as is

expected and thus the validity of the geometric transformation is demonstrated.
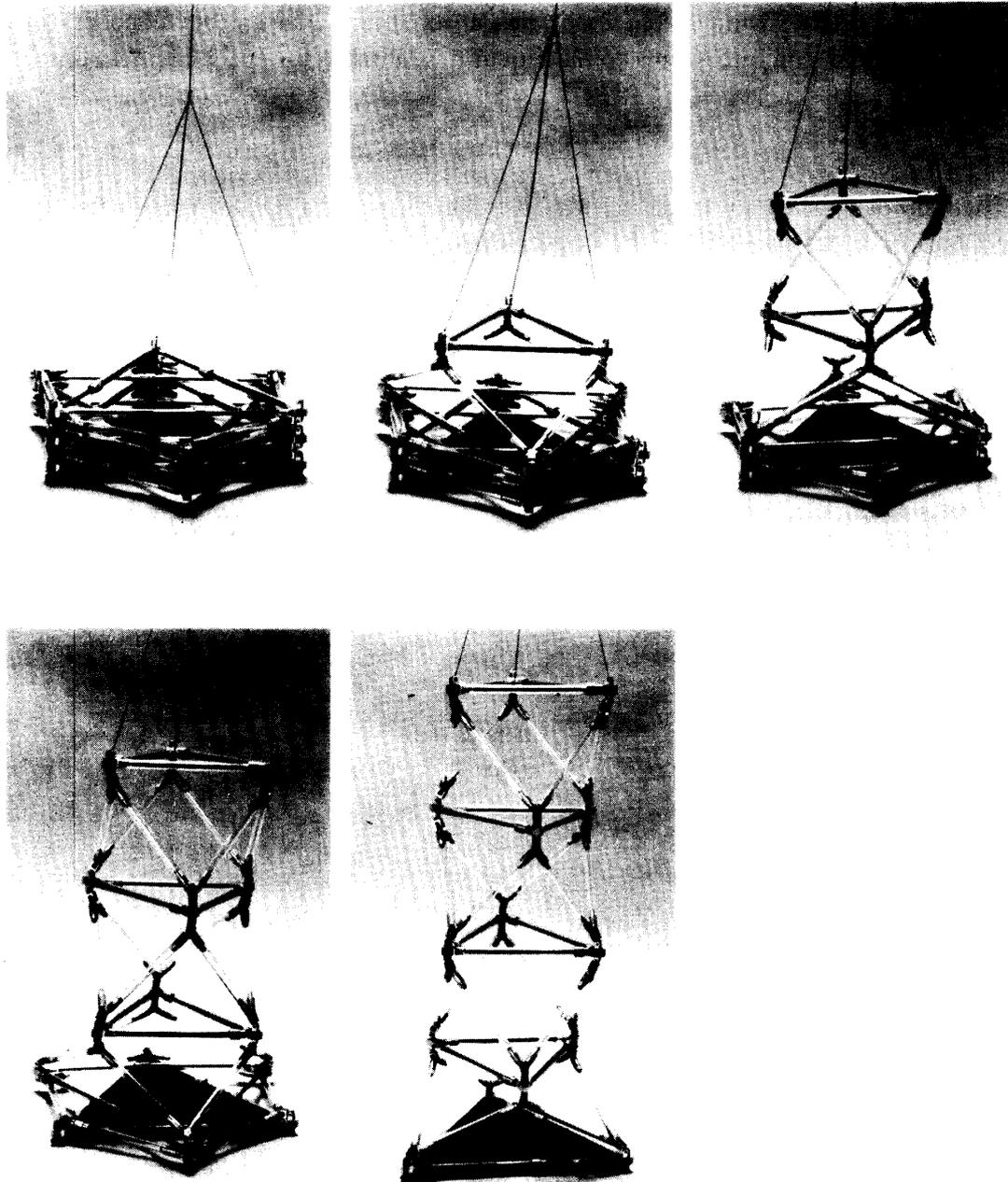

Fig. 10. Deployment of model in a sequential mode.

VI. Concluding Remarks

A new concept for the one-dimensional deployable truss structure is presented. The deployed configuration of the structure consists of the repetition of an octahedral truss module longitudinally, and thus is exactly the so-called "geodesic beam" structure. The principal mechanical feature of the truss is that the lateral members comprising the lateral triangular truss are telescoping beams. Contraction of the lateral members results in deployment of the truss. The geometric transformation of this truss of variable

geometry is presented. It is shown that both simultaneous and sequential modes of deployment are possible. The validity of the concept is verified by means of a conceptual model. Though the study is in its initial phase, this concept for the deployable truss structure seems to have qualities suitable for space applications.

ACKNOWLEDGEMENT

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PART II

PREVIEW ON SPECIAL APPLICATIONS OF VARIABLE GEOMETRY TRUSS

I. Introduction

The deployable truss structure proposed in the PART I of this paper is for the present named the "variable geometry truss" and the "VG-truss" for an abbreviation. Through the study on the behavior of VG-truss, the author founds that it has two distinct characteristics which are without parallel in conventional deployable structures. The first one is that the concept can be applicable to a truss having an arbitrary curvature in the three dimensional space. The second one is that it is applicable to a manipulator arm having multiple degrees of freedom. By the VGT manipulator arm, the highly flexible motion in the 3-space is possible without losing its high rigidity.

II. Curvilinear VG-Truss

The drawing in Figure II-1-a represents a part of a VG-truss. In this case the lengths of both diagonal and lateral members are identical $(b=a)$. In Figure II-1-b, the lengths of one member of every other lateral trusses, that is, PP' and RR', increase to $1.2a$. In like manner, the lengths PP' and RR' in Figure II-c increase further to $1.4a$. It is apparent that this operation deforms the straight truss to the one having a macroscopic curvature, the amount of which depends on the differences of the lengths of lateral members. In Figure II-2, an example is shown for the case when PP'$=$RR'$=1.2a$, OO'$=$QQ'$=$SS'$=0.8a$.

In practice, the above operation can be carried out by simply adjusting the latch positions to either $b=1.2a$ or $b=1.4a$. The retrieved configuration of this curvilinear VG-truss is exactly the same as the straight one. Then, it may be said that the truss having an arbitrary curvature can be deployed by VG-truss by adjustment of latch positions of lateral members. Since the directions of lateral members differ as much as 60 degrees in a module, the curvature in any direction is possible by differentiating the lenghts of lateral members. Figure II-3 shows a simple example for such cases. It simulates a space curve having torsion as well as curvature. Theoretically speaking, it is possible to deploy a VG-truss to a configuration simulating an arbitrary curve in the 3-space. Figure II-4 is such an example. The most important case is, however, the one having a constant curvature, that is, a "deployable ring truss".

III. Manipulator Arm

The discussion at the previous section may probably lead the reader almost simultaneously to the concept of the "VG-truss manipulator arm". The basic concept of the VGT manipulator arm is schematically presented in Figure II-5. As shown in the figure, each lateral member is equipped with an actuator-encorder and is able to change its
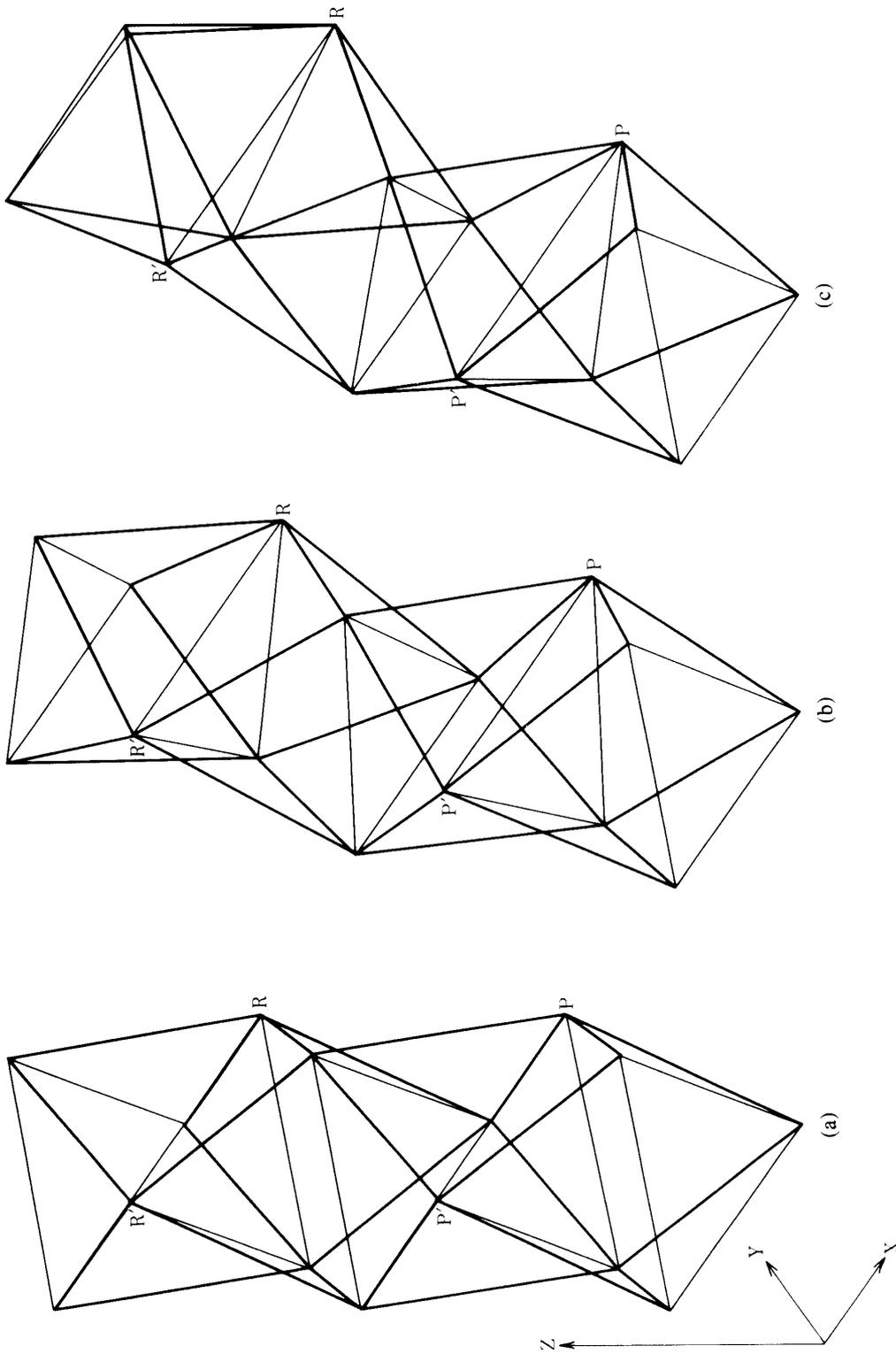
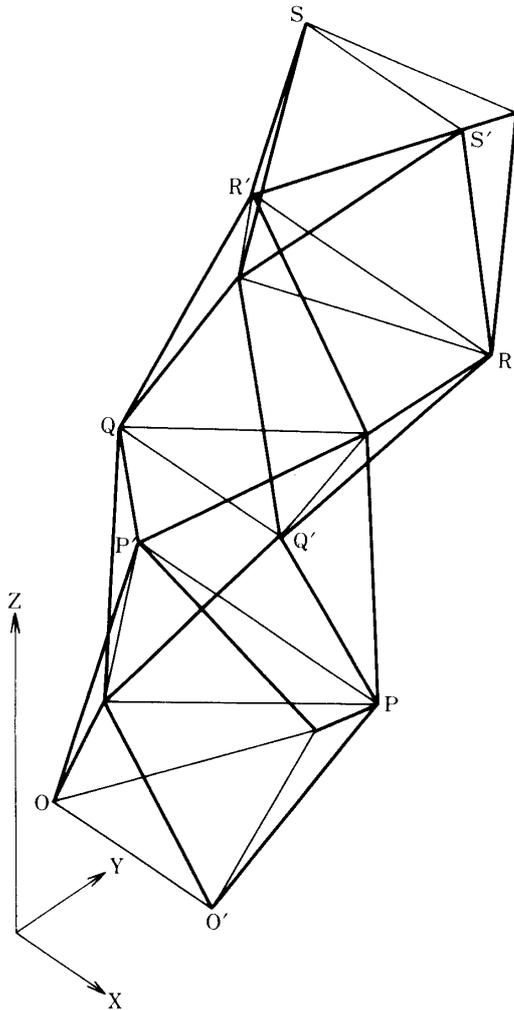Fig. II-1. Curvilinear VG-Truss.
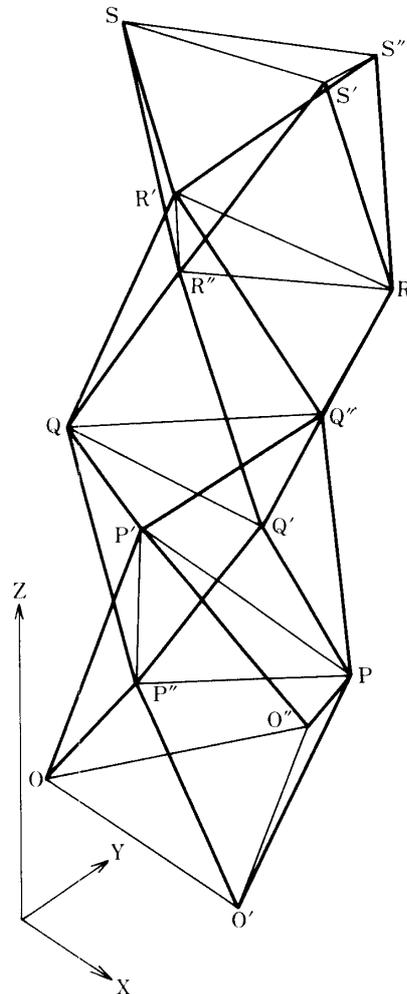
Fig. II-2.   Curvilinear VG-Truss.

Fig. II-3.   Curvilinear VG-Truss simu-
lating curvature and torsion.

length. Thus, by changing the lengths of lateral members as programmed, the VGT manipulator arm can vary its configuration to an arbitrary curve in the 3-space.

In general, the manipulator arm must have three basic functions of motion; revolution, rotation, and sliding. The VGT manipulator arm can accomplish all of these functions in a manner which is entirely different from current articulated manipulator arms. As for the functions of motion of revolution and sliding, the description in the previous chapter is almost sufficient for the explanation. But as for the function of rotation, some explanation might be needed. The truss shown in Figure II-5 has a curvature in y-z plane. By changing the lengths of lateral members, it is always possible to give the same amount of curvature in x-z plane. This transformation produces the 90 degrees of rotation as a consequent result. In conclusively, the VGT manipulator arm has high degrees of freedom of motion which is without a parallel in conventional manipulator arms.

Since, the VG-truss is considered as a stiff and light-weight structure, the VGT manipulator arm succeeds the same quality. It should be beneficial for the accuracy as
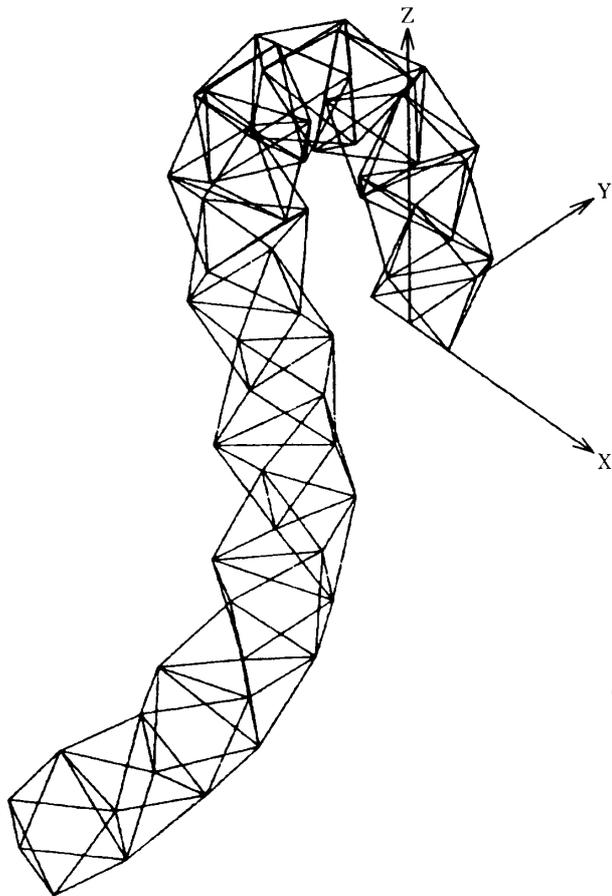
Fig. II-4. Curvilinear VG-Truss simulating an arbitary curve in 3-space.
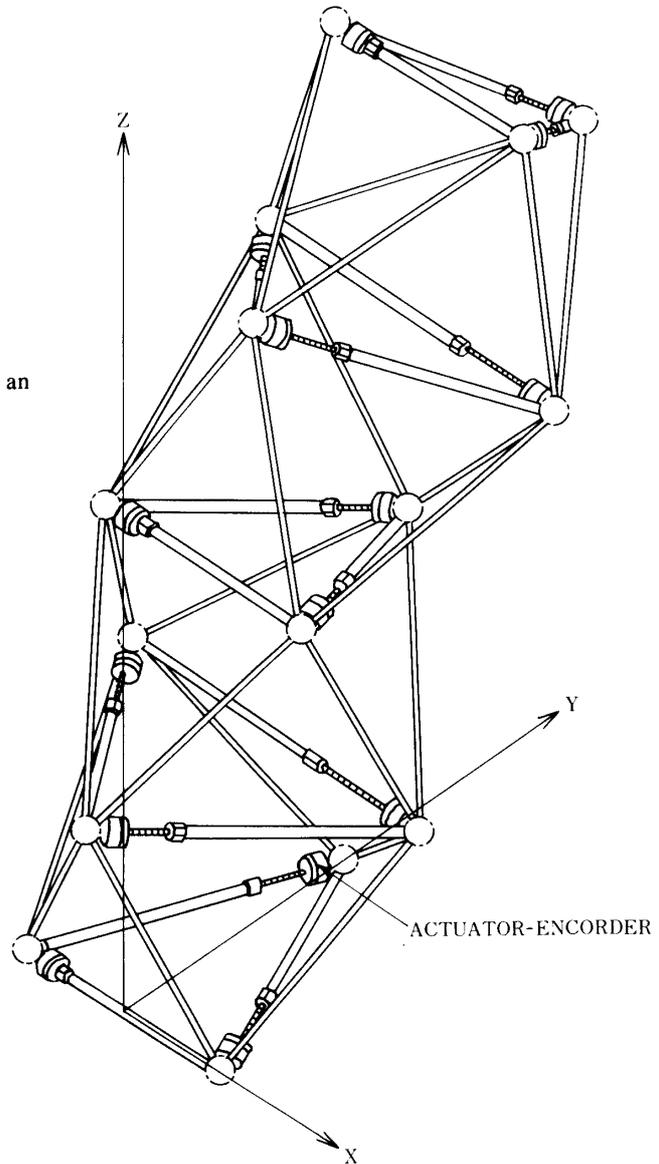

Fig. II-5. Concept for VGT manipulator arm.

well as stiffness of the arm. The designing the complex joint, however, is the most difficult problem which must be overcome before the realization of the concept.

In conclusion, the present author presents the new concept for the manipulator arm of multiple degrees of freedom.

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