Adaptive Structure Concept for Future Space Applications

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A concept of an adaptive structure for future space applications is investigated. The definition of the adaptive structure is that the structure can purposefully vary its geometric configuration as well as its physical properties. It is shown that the variable geometry (VG) truss is the basic form of the adaptive structure. It consists of a repetition of an octahedral truss module in which some of the truss members can vary their lengths continuously using actuators. By this mechanism, the VG truss can change its configuration arbitrarily in three-dimensional space while inherent high stiffness is maintained during the transformation. The basic formulations for its geometry, structural errors, and vibrational properties are established. Some applications, including a second-generation manipulator arm, support architecture for a space station, and others, are discussed. The functional model controlled by a computer demonstrates satisfactorily the basic motions of the VG truss.

Nomenclature

$[A]$ = diagonal matrix; $[A] = \mathrm{diag}[a_i]$, $a_1 \geq a_2 \geq \cdots \geq a_p > a_{p+1} = \cdots = a_M = 0$
d = diagonal member length
$\mathrm{d}l$ = error vector of member length; $\mathrm{d}l = (\mathrm{d}l_1,\cdots,\mathrm{d}l_M)^t$
$\mathrm{d}l^*$ = nondimensional error vector of member length; $\mathrm{d}l^* = (\mathrm{d}l_i/\sigma_i)$
$\mathrm{d}s$ = residual error vector; $\mathrm{d}s = (\mathrm{d}x_1,\mathrm{d}y_1,\mathrm{d}z_1,\cdots,\mathrm{d}x_n\mathrm{d}y_n\mathrm{d}z_n)^t$
$E[\,]$ = expected value function
EA = extensional stiffness
EI = bending stiffness
GJ = torsional stiffness
J = number of joints
k = nondimensional lateral member length
M = number of members
$[M]$ = error matrix; $[M] = [m_{ij}]_{i=1,\cdots,3n;\, j=1,\cdots M}$
n = number of reference points
p = rank $[M]$
$[P]$ = orthonormal matrix; $[P] = [P_1,\cdots,P_N]$, $[P][P]^t = [P]^t[P] = [I]$
r = see Eq. (15)
$[S]$ = $[S] = \mathrm{diag}[\sigma_i]$
$V[\,]$ = variance function
z = variance vector
λ = deployment ratio
σ, σ_i = standard variation of truss member, $\sigma_i^2 = V[\mathrm{d}l_i]$
$\omega_0, \omega_a, \omega_b, \omega_t$ = natural frequency of VG truss
$[\,]$ = matrix

Introduction

IN the present report, the concept of an adaptive structure for future space applications is described. The definition of the adaptive structure in this paper is that the structure can purposefully vary its geometric configuration as well as physical properties. In the biological world, adaptive behavior is extensive; we can find many examples for adaptive structures in animals and plants. The principle of adaptivity may be that biological life can change its physical/chemical properties so that it can inhabit the environment for optimal survival. In the history of structures, however, we can find no era when adaptive behavior in structures was strongly required. Now, such a trend is changing as we enter the era of space stations. One typical example is the support architecture (structure) of a space station involving a system of structures that interconnects modules and payloads and keeps them at their appropriate positions and directions. It must meet various and ever-changing payload requirements. One possible approach to solve such a difficult problem is to design a structure that can vary its own configuration. This is exactly the concept of an adaptive structure. Another example of structural adaptation is the case for large precision antennas. If the configuration of the antenna is controllable, difficulties in maintaining mechanical or thermal distortions within a small limit are greatly relieved. Without a doubt, future space activities will need such accommodating structures.

The variable geometry (VG) truss concept was presented at the 18th Aerospace Mechanisms Symposium and 35th Congress of the International Astronautical Federation (IAF) by the present author and others.[1,2] These papers were written from the viewpoint of the deployable truss structure. However, the versatility of the configuration taken by the VG truss indicates the apparent sign of the adaptive structure. The following study will show that the VG truss is not only a natural adaptive structure but also is the basic form of a one-dimensional adaptive structure.

This paper contains four main themes: presentation of the concept of an adaptive structure, formulations of structural errors, changes of vibrational properties due to varied configurations, and a discussion on its applications. Part of this paper was presented at the 36th Congress of the IAF in 1985.[3]

Concept of the Adaptive Structure

To be adaptive, the structure must be equipped with a mechanism for changing its own configuration. The simplest example of this is a manipulator arm, in which the mechanism of change is composed of several beam members and adjoining hinges. However, such a structure is weak in its stiffness, which is one of the principal drawbacks in present-day manipulator arms. In order for an adaptive structure to be efficient and lightweight, the structural topology in a one-dimensional case should be similar to that of the spatial truss. Then the question arises of how the spatial truss can change its configuration.

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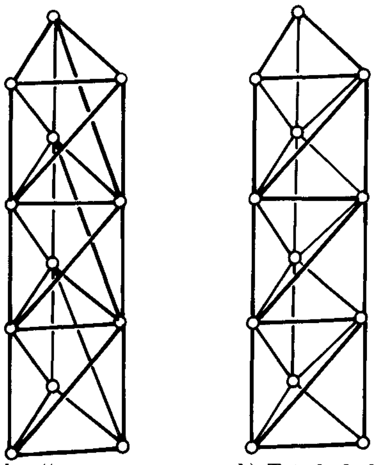
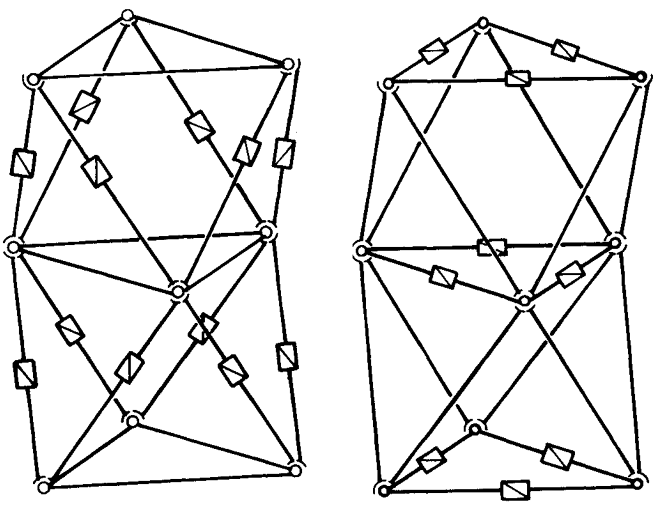


a) Octahedral pattern b) Tetrahedral pattern

Fig. 1 One-dimensional statically determinate spatial-truss structures.



a) Stewart's platform b) VG truss unit

Fig. 2 Layout of variable-length members.

Let us consider the condition under which the truss structure might be adaptive. The condition is tentatively given as follows: an arbitrary member of the truss can vary its length independent of the other members without increasing internal stress. This condition is satisfied if the truss is statically determinate. The necessary condition for the statically determinate truss is

$$M - 3J + 6 = 0 \tag{1}$$

where M is the number of truss members and J the number of joints. Because space structures are usually made by repeating large numbers of modules, the third term of the equation is negligible. This simple equation provides a tool for deducting the topological construction of a one-dimensional adaptive truss. In general, two-dimensional truss structures such as antennas and platforms can easily satisfy Eq. (1), but they would have less stiffness than statically indeterminate structures such as a tetrahedral truss antenna and a box truss antenna.

Figure 1 shows two configurations for the one-dimensional statically determinate spatial-truss structures. When we assume symmetry and topological equivalence, an octahedral truss is obtained from Fig. 1a and a tetrahedral truss is obtained from Fig. 1b. Since the octahedral truss is in essence a symmetry-rich structure in comparison with the tetrahedral truss, the octahedral truss is considered to be adequate for the adaptive structure.

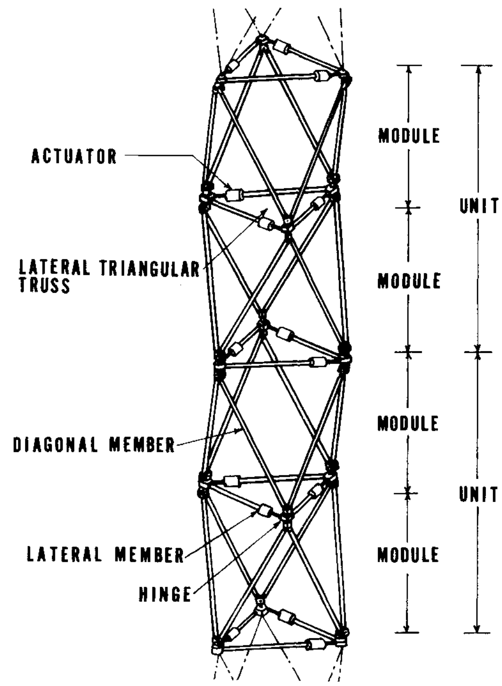


Fig. 3 Configuration of variable geometry truss.

The next problem is to determine the layout of the members, which are of variable length. Attaining maximum flexibility on the motion of the truss with a minimum number of variable-length members is a natural requirement of the engineering. Possibly, there are two systems of layout, with either the diagonal members or the lateral members being of variable length, as shown in Fig. 2. Figure 2a represents the system used for the mechanism of the pilot training simulator called Stewart's platform. It requires six variable members, i.e., six actuators per module. On the other hand, the truss in Fig. 2b requires only three variable members per module. This accurately represents the VG truss. Since its highly flexible motion has been already proved in the previous studies,[1,2] the VG truss is the basic form of adaptive structures.

An adaptive structure can vary not only its own configuration but also its elastic and vibrational properties by taking account of the change in its configuration. Therefore, adaptive structures have a geometrical adaptivity as well as an elastic adaptivity.

Variable Geometry Truss

In the following sections, some of the basic properties of the variable geometry truss (VG truss) are described. Figure 3 illustrates a typical example of the proposed concept for the VG truss structure. The fundamental module of this truss is an octahedral truss composed of a pair of lateral triangular trusses and six diagonal members. 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. The principal mechanical feature of the VG truss is that the lateral members comprising a lateral triangular truss are variable-length beams, each of these equipped with an actuator, while the diagonal members are fixed-length beams. By controlling the lengths of the lateral members, we can change the configuration of the VG truss into an arbitrary curve in three-dimensional space. The motion of the VG truss is highly flexible, but its rigidity is inherently high. The elastic and vibrational properties of the VG truss vary depending on its configuration. The details of the geometric properties, which were given in Ref. 2, are reproduced here.

Simultaneous Mode Deployment

The mode in which the folding/deploying is carried out simultaneously through the whole structure is called simulta-

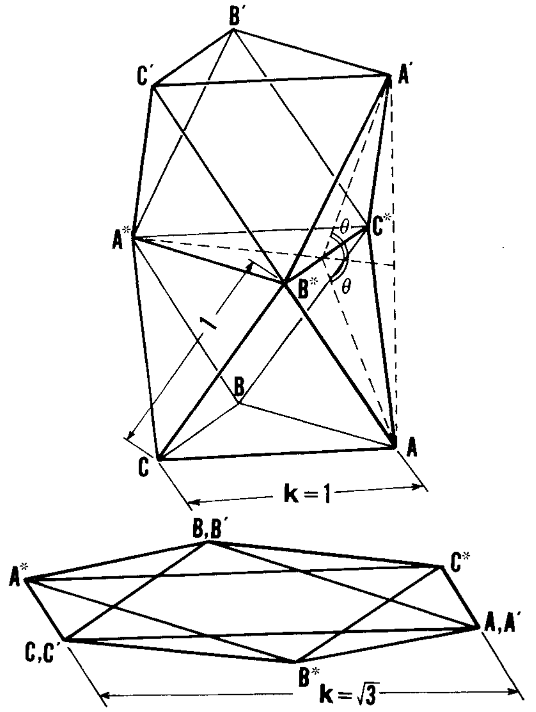


Fig. 4 Change in configuration of VG truss.

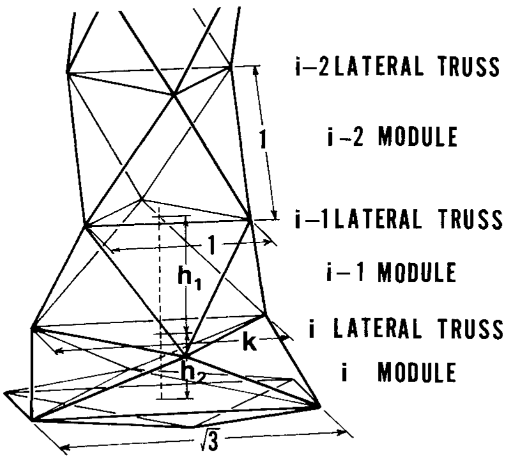


Fig. 5 Sequential mode deployment.

neous mode deployment. Let us consider a single unit composed of a pair of octahedral trusses, as shown in Fig. 4. The geometry of the octahedral truss is completely defined by the magnitude of k. As shown in Fig. 4, the face angle between a pair of triangles that compose a concave diamond pattern is taken as 2θ. Then we have

$$\theta = \cos^{-1}\{k/[12(1-k^2/4)]^{1/2}\} \tag{2}$$

We are immediately aware that Eq. (2) has a nontrivial solution for θ equal to zero. That is,

$$\theta = 0 \quad \text{if } k = \sqrt{3} \tag{3}$$

The vanishing of the face angle θ means that the height of each octahedral module also vanishes. Therefore, the complete truss is transformed into a flat configuration, as shown in Fig. 4. The height of a module h varies between the limits:

$$(1-k^2/3)^{1/2} \geq h \geq 0 \tag{4}$$

Sequential Mode Deployment

Figure 5 shows the sequential deployment mode. In the case of this deployment mode, a geometric transformation exists that allows the contraction of the ith lateral triangular truss and the following deployment of the i-1th and ith modules without interfering with other zones of the truss.

The sequence of motions that constitutes the contraction of the ith lateral truss is explained as follows. When the ith triangular truss starts to contract, it is raised from the base, and the ith module starts to deploy. At this time, the i-1th module is already partially deployed and continues its deployment. When the i lateral truss finishes its contraction and is latched, the i-1th module completes its deployment.

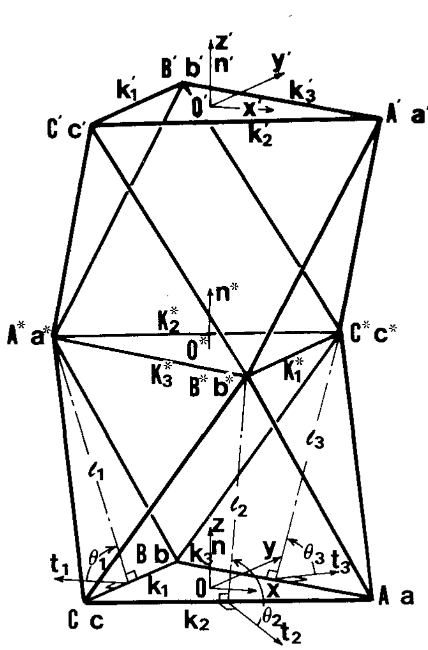


Fig. 6 Geometry of VG truss unit.

Basic Formulation of the VG Truss Structure

The unit of repetition that composes the VG truss is shown in Fig. 6. The lengths of the truss members are normalized by the diagonal members, the lengths of the latter being equal to 1, and the length of the lateral member of each triangle being k_1, k_2, k_3 for the base, k_1^*, k_2^*, k_3^* for the elbow, and k'_1, k'_2, k'_3 for the top.

In order to reduce the complexity of the formulation of the VG truss structure without impairing the essence of the present conditions, the following assumption is made. Both the base and the top lateral trusses are always in the shape of an identical equilateral triangle, and the length of the lateral members of the elbow plane $A^*B^*C^*$ varies arbitrarily. By this simplification, the number of parameters per unit can be reduced to four. Let it be called here a four-parameter VG truss unit. In the case of a four-parameter VG truss unit, the set of parameters (k_1^*, k_2^*, k_3^*, k) expresses its geometry completely.

In general, the position vectors of the elbow triangle are expressed as

$$\boldsymbol{a}^* = (\boldsymbol{b}+\boldsymbol{c})/2 + l_1\cos\theta_1\boldsymbol{t}_1 + l_1\sin\theta_1\boldsymbol{n} \tag{5a}$$

$$\boldsymbol{b}^* = (\boldsymbol{c}+\boldsymbol{a})/2 + l_2\cos\theta_2\boldsymbol{t}_2 + l_2\sin\theta_2\boldsymbol{n} \tag{5b}$$

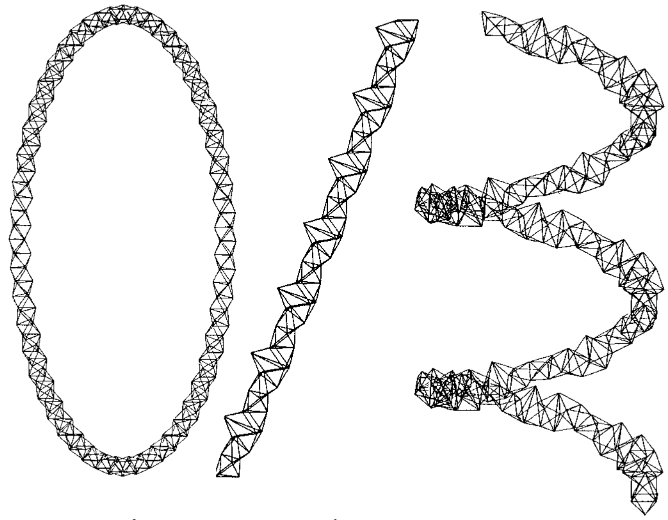
$$\boldsymbol{c}^* = (\boldsymbol{a}+\boldsymbol{b})/2 + l_3\cos\theta_3\boldsymbol{t}_3 + l_3\sin\theta_3\boldsymbol{n} \tag{5c}$$

In the case of the four-parameter VG truss unit, since the base triangle is equilateral, Eqs. (5a-5c) become

$$k_1^{*2} = 2l^2[1-\cos(\theta_3-\theta_2)] + 3(r+l\cos\theta_2)(r+l\cos\theta_3) \tag{6a}$$

$$k_2^{*2} = 2l^2[1-\cos(\theta_1-\theta_3)] + 3(r+l\cos\theta_3)(r+l\cos\theta_1) \tag{6b}$$

$$k_3^{*2} = 2l^2[1-\cos(\theta_2-\theta_1)] + 3(r+l\cos\theta_1)(r+l\cos\theta_2) \tag{6c}$$



a) b) c)

Fig. 7 VG truss configurations: a) circle (1-unit repetition); b) inclined line (2-unit repetition); c) helix (3-unit repetition).

where

$$l = (1 - k^2/4)^{1/2}, \qquad r = k/(2\sqrt{3}) \tag{7}$$

Using Eqs. (6), when a set of parameters (k_1^*, k_2^*, k_3^*, k) is given, a set of angles $(\theta_1, \theta_2, \theta_3)$ can be computed. From the results, the position of the points A^*, B^*, C^* can be calculated, so that the position vector of the center of the elbow triangle is yielded as $\boldsymbol{g}^*$, and the normal unit vector of the elbow triangle plane $\boldsymbol{n}^*$, is calculated from the positional vectors $\boldsymbol{a}^*$, $\boldsymbol{b}^*$, and $\boldsymbol{c}^*$.

The base and top equilateral triangles are congruent with each other, and the length of the diagonal members is equal to 1; therefore, the base plane ABC and the top plane $A'B'C'$ are symmetrical to the elbow plane $A^*B^*C^*$. Then, the center vector of the top triangular $A'B'C'$ and its normal vector are calculated as

$$\boldsymbol{g}' = 2(\boldsymbol{n}^*\boldsymbol{n}^{*t})\boldsymbol{g}^* \tag{8}$$

$$\boldsymbol{n}' = [2(\boldsymbol{n}^*\boldsymbol{n}^{*t}) - I]\boldsymbol{n} \tag{9}$$

The coordinates transformation matrix $\boldsymbol{C}$ is given by Eqs. (8) and (9) as

$$[x',y',z',1]^t = \boldsymbol{C}[x,y,z,1]^t \tag{10}$$

with

$$\boldsymbol{C} = \begin{bmatrix} n_y'^2/(1+n_z') + n_z', & -n_x'n_y'/(1+n_z'), & n_x', & g_x' \\ -n_x'n_y'/(1+n_z'), & n_x'^2/(1+n_z') + n_z', & n_y', & g_y' \\ -n_x', & -n_y', & n_z', & g_z' \\ 0, & 0, & 0, & 1 \end{bmatrix} \tag{11}$$

where $\boldsymbol{C}$ is the homogeneous transformation matrix from the base plane coordinates to the top plane coordinates. From these relations, the four-parameter VG truss configuration can be calculated.

Typical Configurations by VG Truss Unit

Some typical configurations that can be given by the use of the four-parameter VG truss unit are presented in the following sections. To simplify the presentation, constancy of the parameters is assumed in most cases. Of course, there is no difficulty in calculating the cases with variable curvature.

The first type of configuration consists of a 1-unit repetition, i.e., a line or circle (Fig. 7a). The second type consists of a 2-unit repetition, which is an inclined line (Fig. 7b). Using a 3-unit combination, it is easy to construct a space curve having constant curvature (Fig. 7c).

Structural Errors of Adaptive Structures

Estimating structural errors during construction is important. Hedgepeth[4] and Greene[5] have estimated the structural errors for a tetrahedral truss antenna and other statically indeterminate structures. In the case of an adaptive structure, since it is a statically determinate truss structure, estimating structural errors can be carried out with relative ease.

We can consider that structural errors of the statically determinate truss structure depend not on the elastic properties of the members but on the length errors of each member.

The length of the member n between nodes i and j is described as

$$l_n = (x_i - x_j)^2 + (y_i - y_j)^2 + (z_i - z_j)^2 \tag{12}$$

In the case of a small change in the member length and displacement, Eq. (12) yields

$$\mathrm{d}l_n = (1/l_n)[(x_i - x_j)(\mathrm{d}x_i - \mathrm{d}x_j) + (y_i - y_j)(\mathrm{d}y_i - \mathrm{d}y_j) + (z_i - z_j)(\mathrm{d}z_i - \mathrm{d}z_j)] \tag{13}$$

Since we are considering the statically determinate truss structure, the ith nodal displacements induced by a change in the member length can be rewritten as

$$\mathrm{d}x_i = \sum_{j=1}^{M} c_{ij}\mathrm{d}l_j \tag{14}$$

where c_{ij} is an influence coefficient. From this equation, the residual errors of each reference point or direction are described as follows:

$$\mathrm{d}\boldsymbol{s} = [M]\mathrm{d}\boldsymbol{l} \tag{15}$$

where $\mathrm{d}\boldsymbol{s}$ is the residual error vector of the reference points, $[M]$ is the error matrix calculated by Eq. (14) and a linear transformation from the nodal displacements to the reference vector, and $\mathrm{d}\boldsymbol{l}$ is the error vector of the member length. From the preceding equation, matrix $[M]$ means the weight of the member length errors to the error vector of the reference points. When the square of the residual errors is considered, using Eq. (15), it becomes

$$\|\mathrm{d}\boldsymbol{s}\|^2 = \mathrm{d}\boldsymbol{l}^t[M]^t[M]\mathrm{d}\boldsymbol{l} \tag{16}$$

If the standard variations of each member (σ_i) are given, the next vector $\mathrm{d}\boldsymbol{l}^*$ is considered as

$$\mathrm{d}\boldsymbol{l} = [\sigma_i][\mathrm{d}l_i/\sigma_i] = [S]\mathrm{d}\boldsymbol{l}^* \tag{17}$$

From Eqs. (15–17), the residual errors and the square are rewritten as follows:

$$\mathrm{d}\boldsymbol{s} = [M][S]\mathrm{d}\boldsymbol{l}^* \tag{18}$$

$$\|\mathrm{d}\boldsymbol{s}\|^2 = \mathrm{d}\boldsymbol{l}^{*t}[S][M]^t[M][S]\,\mathrm{d}\boldsymbol{l}^* \tag{19}$$

The matrix $[S][M]^t[M][S]$ becomes non-negative definite and is symmetrical. Then, the diagonal matrix $[A](=\mathrm{diag}[a_i])$ and the orthonormal matrix $[P]$ are as follows:

$$[S][M]^t[M][S] = [P][A][P]^t \tag{20}$$

Each of the row vectors of the matrix $[P]$ and eigenvalue a_i indicates the direction and the length of the principal axis. From this result, we define the vector z as

$$z = SQRT[A][P]^t\mathrm{d}\boldsymbol{l}^* \tag{21}$$

Then $\|ds\|$ is equal to $\|z\|$. Therefore, when the errors of each member are assumed to be a normal distribution, the covariance matrix of vector z is calculated as

$$E[z^t z] = \mathrm{diag}[a_i] \quad (i = 1,2,\ldots,p) \tag{22}$$

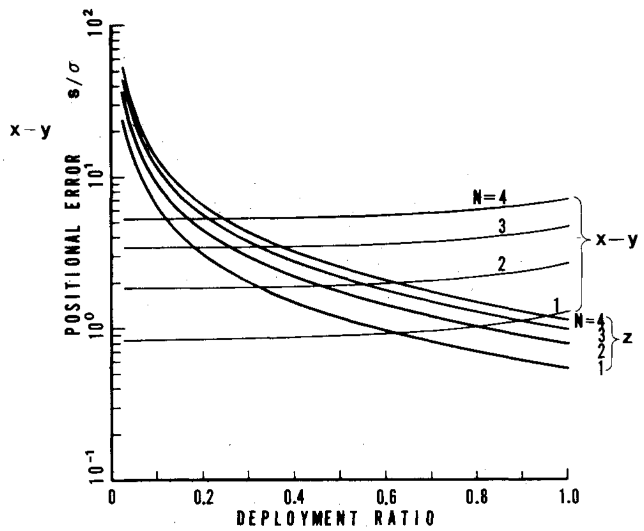


Fig. 8 Positional errors of VG truss.

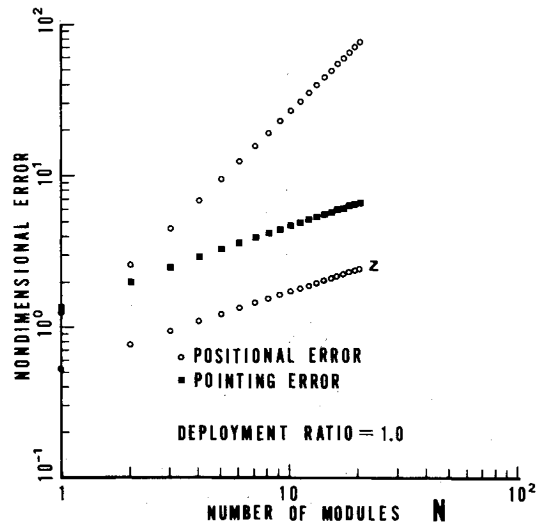


Fig. 9 Positional and pointing errors of VG truss.

The expectation of the variance of the vector z is calculated as

$$E[z'z] = \mathrm{tr}[a_i] \tag{23}$$

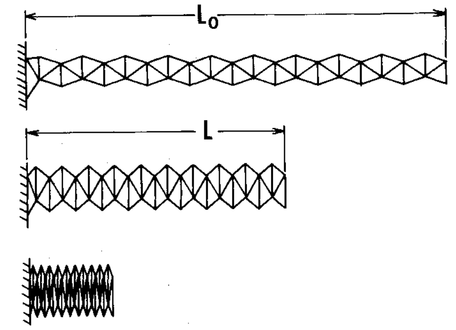
Thus, the structural errors of the arbitrary reference points are characterized by the eigenvalues a_i.

This result indicates that the structural errors of the adaptive structure can be estimated by the eigenvalue of the matrix $[S][M]'[M][S]$. This formulation is adaptable for all statically determinate structures: truss beam, truss antenna, wire-stiffened structures, and so on.

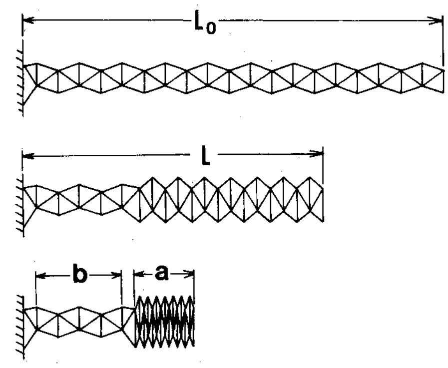
In the following sections, some numerical examples of the VG truss are given. In the calculations, we assume that the variance of each of the members is equal to the others.

Figure 8 shows the positional errors of the endpoint of the VG truss and its deployment ratio. The errors of the lateral directions increase as deployment takes place. On the other hand, the errors of the axial direction decrease as the VG truss is deployed. These results show that as the VG truss is deployed, the lateral positional errors become more sensitive to each member length; on the contrary, the axial errors become more sensitive as it is folded.

The positional and pointing errors together with the number of octahedral truss modules are shown in Fig. 9. This figure shows the case in which the VG truss is completely deployed. As shown in the figure, the lateral errors are approximately proportional to the 1.5 power of the number of modules, and the axial errors as well as the pointing errors are proportional to the 0.5 power.



a) Uniform axial operation mode



b) Selective axial operation mode

Fig. 10 Operation modes.

Vibrational Characteristics of the VG Truss

The elastic and vibrational properties of the adaptive structure (VG truss) vary depending on its configuration. Such a structure can be configured to the shape that is optimal with regard to the stiffness and fundamental frequencies. If it is used as a space crane arm, one can design an optimal control path with respect to the stiffness and fundamental frequencies. Such a development may be called elastic adaptivity.

In the following sections, the VG truss is analyzed using a finite-element computer program, and the fundamental vibration frequencies and mode shapes are determined at several deployment/retraction operation modes, which are similar to those used for the case of a plane truss by Dorsey.[6]

Uniform Axial Operation Mode

As shown in Fig. 10a, this operation mode is called the uniform axial operation mode. In this operation, all lateral members are actuated simultaneously. The deployment ratio of the truss is defined as L/L_0, where L is the current length of the truss and L_0 is the length of the fully deployed truss. By this operation mode, the VG truss becomes what we call the inverted batten truss beam.

Selective Axial Operation Mode

The operation mode for the axial deployment and retraction, as shown in Fig. 10b, is called the selective axial operation mode. With this mode, the truss is divided into two sections. Each section can be retracted uniformly as well as independently.

Continuum Model

In the case of a uniform axial operation mode, the elastic properties of the VG truss can be approximated by the continuum model. For example, Noor et al.[7] used an energy method in which the nodal displacements of the truss are related to a

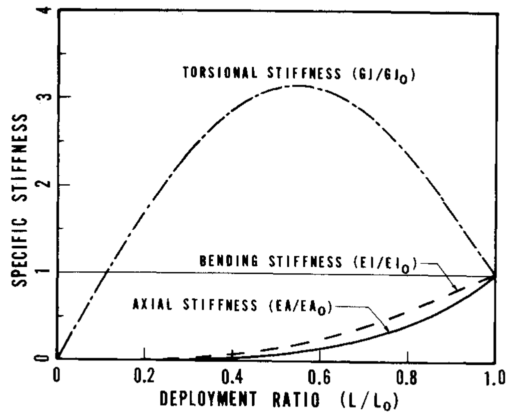


Fig. 11 Specific stiffness of VG truss by continuum model.

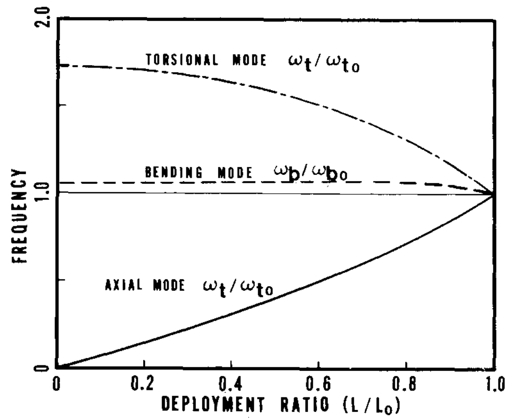


Fig. 12 Fundamental frequencies of VG truss by continuum model.

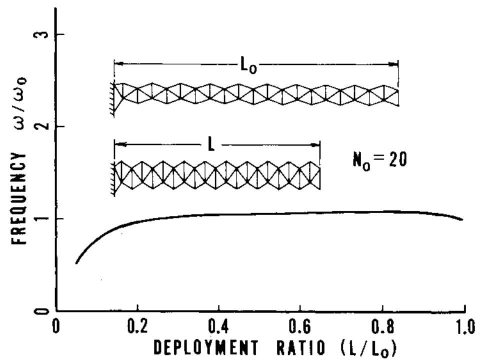


Fig. 13 Fundamental frequency of VG truss by finite-element method (uniform axial operation mode).

linearly varying displacement field for an equivalent bar. This method is applied to trusses with triangular cross sections where the nine parameters fully describe the displacements. The transition from the discrete lattice structure to the continuum model is carried out by 1) introducing assumptions regarding the variation of the displacement components and temperature in the plane of the cross section for beamlike lattices, 2) expressing the strains on the individual members in terms of the strain components in the coordinate directions that result from the assumed displacements, and 3) expanding each of the strain components in the coordinate directions in a Taylor series. The replacement of the member strains by the Taylor series expansions of the strain components in the coordinate directions provides a transition from a discrete structure to a continuum. By this procedure, the stiffness coefficients of the continuum model are calculated.

The stiffness coefficients of the VG truss under uniform axial operation mode are calculated as

$$EI = 3b^2/[4(1+r/2)](h/d)^3E_dA_d \tag{24a}$$

$$EA = 6/(1+5r/18)(h/d)^3E_dA_d \tag{24b}$$

$$GJ = (1/2)(b/d)^4(h/d)^3d^2E_dA_d \tag{24c}$$

$$r = (b/d)^3(E_dA_d)/(E_bA_b) \tag{24d}$$

In the case of the VG truss, the length of the battens (lateral members) b and the height of the module h are described as follows:

$$b = kd \tag{25}$$

$$h = d(1-k^2/3)^{1/2} \tag{26}$$

where k is the nondimensional length of the lateral member. The stiffnesses of the VG truss are calculated as

$$EI = 3k^2d^2/[4(1+r/2)](1-k^2/3)^{1.5}E_dA_d \tag{27a}$$

$$EA = 6/(1+5r/18)(1-k^2/3)^{1.5}E_dA_d \tag{27b}$$

$$GJ = (k^4/2)(1-k^2/3)^{0.5}d^2E_dA_d \tag{27c}$$

$$r = k^3(E_dA_d)/(E_bA_b) \tag{27d}$$

Using Eqs. (27a-27c), the fundamental frequencies of the N_0 module VG truss are described as follows:

$$\omega_b = 3.52/(N_0^2d)[k^2/(12+6r)]^{0.5}E_d/\rho_d \tag{28a}$$

$$\omega_a = \pi/(2N_0d)[12/(18+5r)]^{0.5}(1-k^2/3)^{0.5}E_d/\rho_d \tag{28b}$$

$$\omega_t = \pi/(2N_0d)(3/13)^{0.5}kE_d/\rho_d \tag{28c}$$

where the following assumptions are made:

$$E_b = E_d,\ A_b = A_d,\ b\rho_b = d\rho_d \tag{29}$$

The fundamental angular frequency of a bending mode is ω_b; ω_a is that of an axial mode, and ω_t is that of a torsional mode. In the following results, the deployment ratio is defined as

$$\lambda = [(3-k^2)/2]^{\frac{1}{2}} \tag{30}$$

Results and Discussion

Figure 11 shows the specific stiffness of the VG truss by the continuum model given by Eqs. (27a-27c), where EI_0, EA_0, and GJ_0 are the stiffnesses of the VG truss at a deployment ratio equal to 1. As shown in the figure, the bending stiffness and the axial stiffness are maximum when the truss is fully deployed, and the torsional stiffness is maximum when it is partially retracted. Figure 12 shows the fundamental frequencies given by Eqs. (28), where the subscript 0 refers to the fully deployed VG truss.

The VG truss is modeled with a finite-element program (SAP-IV) by using rod elements. The number of modules is 20, and the nondimensional fundamental frequency ω/ω_0 is now considered, where ω is an angular frequency of the VG truss and ω_0 is the natural angular frequency of the fully deployed VG truss. In the computation, the mass of joints and actuators are assumed to be uniformly distributed to those of the lateral and diagonal members. The cross-sectional stiffness of the lateral members is assumed not to change due to the telescopic action of the members.

In this calculation, the length between the fixed points of the cantilever VG truss is assumed to be $\sqrt{3}$; in this manner, the VG truss can be completely retracted. Figure 13 shows the variation of the fundamental frequency with the deployment ratio during the uniform axial operation mode of the VG truss.

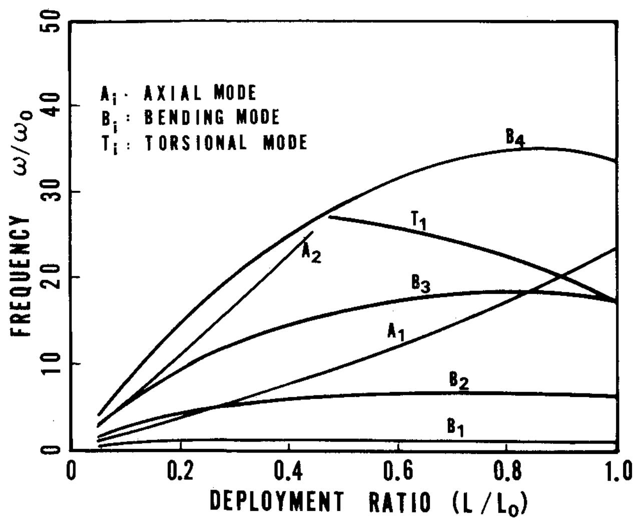


Fig. 14 Higher mode frequencies of VG truss by finite-element method (uniform axial operation mode).

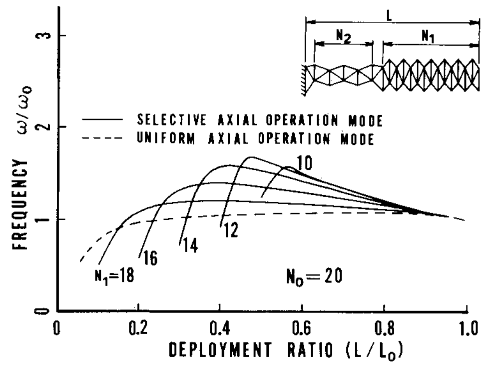


Fig. 15 Fundamental frequencies of VG truss by finite-element method (selective axial operation mode).

The fundamental mode shape is that of the first cantilever bending mode in all deployment/retraction operations. The calculation is not valid at the region where the VG truss is nearly completely retracted.

Figure 14 shows the variation of the higher mode frequencies during the uniform axial operation mode. The axial mode and the bending mode frequencies decrease as the VG truss retracts, while the frequency of the torsional mode increases. With respect to the fundamental bending mode, the behavior is more varied than that of the continuum model as the VG truss is retracted farther. Such behavior is due to the fact that the mode shape of the retracted VG truss is far from that of the beam theory.

Figure 15 shows the variation of the fundamental frequency with the deployment ratio during the selective axial operation mode, where the modules of section **b** are fully deployed. The peaks shown in this figure are higher than those of the uniform axial operation mode. As shown in the figure, the fundamental frequencies of the selective axial operation mode can be increased by as much as 50% of that of the uniform axial operation mode at a deployment ratio of 0.5. These results show us that the VG truss can change its elastic properties by changing its configuration.

Applications of the Adaptive Structure

It has been shown in the preceding sections that the adaptive structure represented by the VG truss has very special properties that are unparalleled to those of conventional structures. Therefore, it would open up a complex field of application in space activities. The following sections include a few examples of such applications, although these by no means represent the only uses.

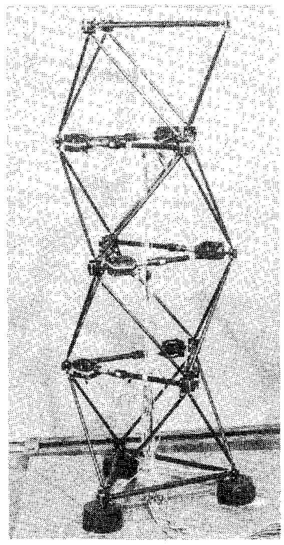
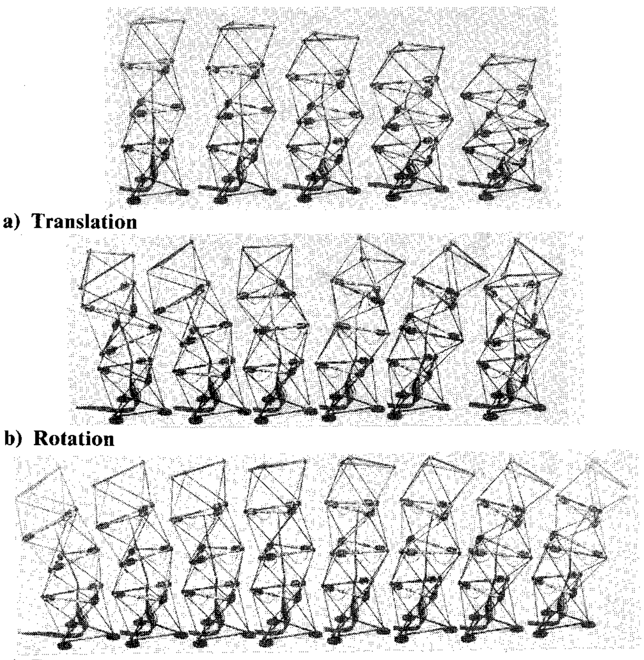


Fig. 16 Photograph of the functional model.



a) Translation

b) Rotation

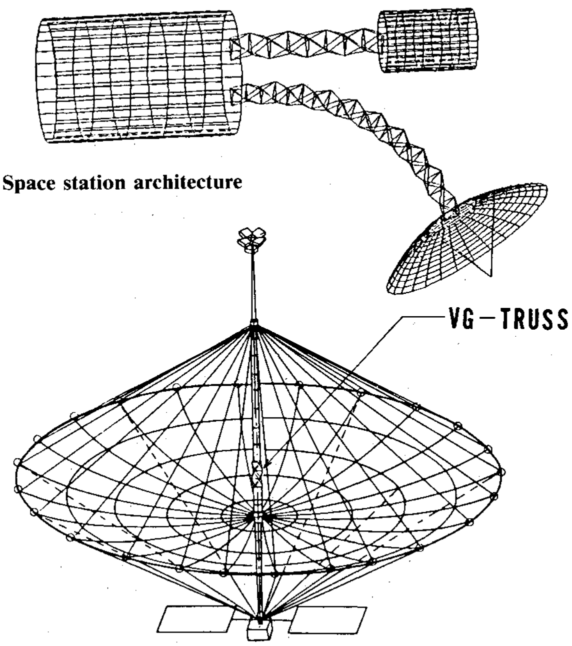
c) Revolution

Fig. 17 Concept of VGT manipulator arm.

VGT Manipulator Arm

As the lengths of lateral members are continuously variable and controllable, the VG truss can vary its configuration to an arbitrary curve in three-dimensional space. The concept of the VG truss manipulator arm (VGT manipulator, for short) is based on this fact. A functional model of the VG truss was designed in order to verify this concept. A photograph of the functional VG truss model is shown in Fig. 16. The model consists of four VG truss modules. The upper and lower lateral members are fixed-length members, and all the remaining nine lateral ones are of variable length. The length of the diagonal members and the fixed-length lateral members is 400 mm, and the length of the variable-lateral members ranges from 400 to 600 mm. The total height of the model is about 1300 mm when it is completely deployed. The basic motions of the VG truss, i.e., extension/retraction, rotation, and revolution have been demonstrated by the model as shown in Fig. 17.

This model is installed with nine actuators and is program-controlled by a microcomputer. Each actuator consists of a dc motor with an encoder, and the variable-length member used



a) Space station architecture

b) Adaptive structure

Fig. 18 Possible applications of the VG truss.

here is a telescopic beam actuated by a motor through a ball screw. The nominal speed of the dc motor is 42 rpm, and the nominal torque is 2000 gf/cm. An encoder is installed in each motor to measure the rotation angle of the ball screw. The resultant pulse density is 16 pulses per revolution, and the pitch of the screw is 3 mm. The control system of this model is due to proportional control, and the length of the lateral members extends 1–1.5 times that of the initial length. In general, the manipulator arm must have three basic functions of motion; translation (Fig. 17a), rotation (Fig. 17b), and revolution (Fig. 17c). The VGT manipulator arm can accomplish all of these functions in a manner entirely different from that of current articulated arms.[8,9]

Another feature of the VGT manipulator arm is its high stiffness because of its three-dimensional truss form. Therefore, by using the VGT manipulator arm, highly flexible motion is possible without any loss of stiffness. Naturally, the system of the VGT manipulator arm is more complex, and the control is also more complicated. Therefore, an advance in robotics in this field is to be expected.

Space Station Support Structure

Figure 18a shows an artist's view for a space station's experimental module. The module consists of three portions: a pressurized part, an antenna part, and an exposed part. The antenna part and the exposed part have a bridge that connects each with the pressurized part by a linear adaptive structure (VG truss). Since this linear adaptive structure can change its configuration into an arbitrary curve in three-dimensional space, the bridges are easily transferred to required positions as well as directions and can keep their positions during operation. These functions can be used conveniently for external vehicle activities (EVA) and assembling projects; e.g., a bridge is transferred to a place near the pressurized part for assembly or replacement and then is again transferred to a certain position for a following operation. The adaptive structure, therefore, requires dual characteristics as a deployable structure and as a manipulator arm.

Large Space System

The adaptive structure has an attractive feature of a controllable structural system that makes it possible to use the adaptive structure as an active control system; i.e., it shares the control with the current control systems. In future large space systems, it should be necessary for this structure to play an important role.

Figure 18b shows the Hoop-Column antenna using an adaptive structure (VG truss) as a central deployable column. The Hoop-Column is required to keep its tensile cables so as to maintain the surface accuracy. The adaptive structure operates so as not to change the equality of the tension cables through the thermal distortion.

Conclusions

An adaptive structure concept has been described, and its applications for future space missions have been presented. It is shown that the variable geometry truss is the basic form of the adaptive structure. The basic formulations for its geometry as well as the vibrational properties are established. The structural errors of the adaptive structure have been formulated. Some applications, such as a second-generation manipulator arm, a support architecture for a space station, and others, are discussed.

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