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Two-Dimensional Deployable Hexapod Truss

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A two-dimensionally deployable truss structure is newly proposed for space application. The most significant feature is the small number of mechanisms to be locked when the structure is deployed. Its packaging efficiency is shown to be better than that of many known deployable trusses. Several versions of the truss are also proposed. To confirm that the new deployable truss has enough design flexibility, a paraboloidal truss platform is designed for trial. Furthermore, a numerical investigation shows that the platform is actually deployable and foldable from a practical point of view.

Nomenclature

a = a constant
d = diameter of rigid members, m
E_{ki} = value of the left-hand side of the ith equation represented by Eq. (k)
L_{ij} = effective node-to-node length of the member connecting node i to node j in the fully folded condition as shown in Fig. 10b, m
l = length of members, m
l_{fi}, l_{ci} = node-to-node length of the ith face member and cross member, respectively, m
l_{ri} = length of the ith rigid member calculated from the node locations (node-to-node length of cross and central members, and hinge-to-hinge length of the other rigid members), m
l_{ri}^* = designed length of the ith rigid member (node-to-node length of cross and central members, and hinge-to-hinge length of the other rigid members), m
l_{ti} = length of the ith tension member calculated from the node locations, m
l_{ti}^* = designed length of the ith tension member
n_a, n_r, n_t = numbers of angles and of rigid and tension members, respectively
n_k = number of equations represented by Eq. (k)
q_1, q_2, q_3 = weighting factors
s_d = driven stroke of the sliding hinge block from the position at the fully deployed condition, m
s_t = total stroke of a sliding hinge block, m
w_k = kth weighting factor
x_j, y_j, z_j = location of the jth front face node, m
β_j = jth projected angle between the two adjacent rigid face members on a plane that is normal to the central member to which the rigid members are connected in the fully deployed condition (see Fig. 12), rad
$\Delta\varphi_i$ = relative rotation angle between two hinge blocks connected to the ith rigid member, rad

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Introduction

VARIOUS space missions are expected to require larger structures than can be transported. One attractive method for constructing such large structures is to use deployable structures, which are folded in a compact volume in the transportation phase and are deployed into the final configurations in orbit. For such deployable structures, several kinds of deployable truss structures have been proposed and investigated in the last decade.[1–6]

This paper proposes a two-dimensionally deployable truss concept called a hexapod truss. The most significant advantage of this new truss is the small number of mechanisms to be actuated and locked when it is deployed. A small number of such mechanisms is essential to increase the reliability of deployment and to reduce the mass. In a previous investigation,[1] deployable trusses with a small number of mechanisms are shown to have more constraints on the length of the truss members, and to lose design flexibility in forming various curved surfaces. To demonstrate that this new deployable truss still has enough design flexibility from a practical point of view, a paraboloidal deployable truss is designed and shown by a numerical investigation to be actually deployable and foldable.

Concept of Deployable Hexapod Truss

Figure 1 shows a fully deployed module of the deployable hexapod truss. It is composed of six front-surface rigid members, six

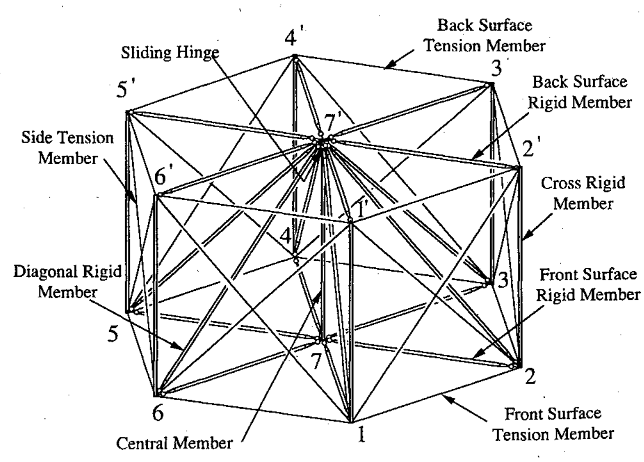

Fig. 1 Fully deployed hexapod-truss module.

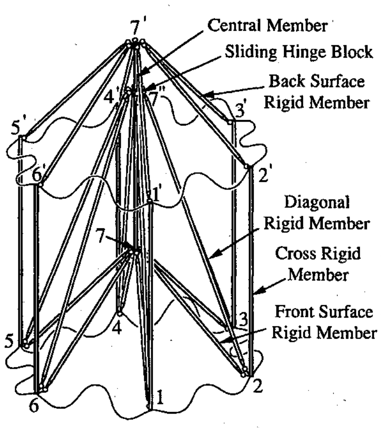

Fig. 2 Half-folded hexapod-truss module. (The side tension members are omitted to avoid excessive complexity.)

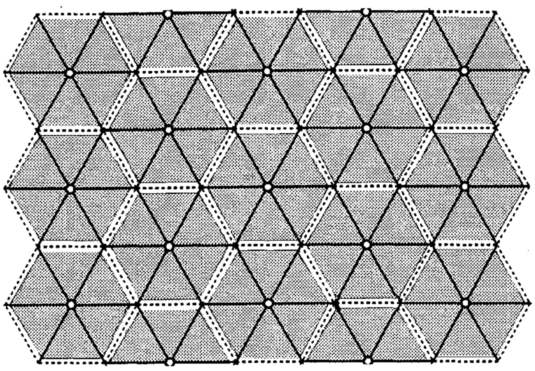

Fig. 3a Hexapod-A assembly configuration (plan view).

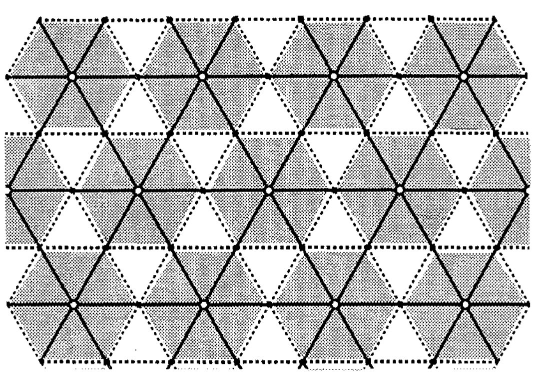

Fig. 3b Hexapod-B assembly configuration (plan view).

back-surface rigid members, six cross rigid members, six diagonal rigid members, a central rigid member, one sliding hinge block, six front surface tension members, six back surface tension members, six pairs of side tension members, and many hinge blocks. The sliding hinge can slide along the central member, and it is held against node 7′ in the fully deployed condition. The small hollow circles in the figure are hinges. When the sliding hinge block is slid away from node 7′, the module can be folded as shown in Fig. 2. When the module is folded further, all the rigid members become parallel to each other, and the module is folded into a compact slender space. The folded module can be deployed by driving the sliding hinge block in the reverse direction. Large two-dimensionally deployable structures can be formed by connecting more than one module together.

Various versions of two-dimensionally deployable structures can be derived from the hexapod-truss concept. Figures 3a and 3b show two possible arrangements of the modules. In the figures, each of the shadowed hexagons is a hexapod-truss module. The solid lines are rigid members, the broken lines are tension members, and the small hollow circles are central members with sliding hinge blocks. In Fig. 3a, the modules share the sides of hexagons, whereas they share vertices with each other in Fig. 3b. In this paper, the configuration

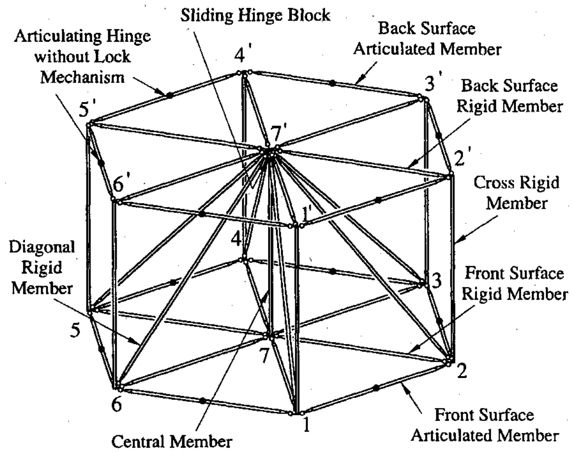

Fig. 4 Fully deployed hexapod-truss module with articulated members.

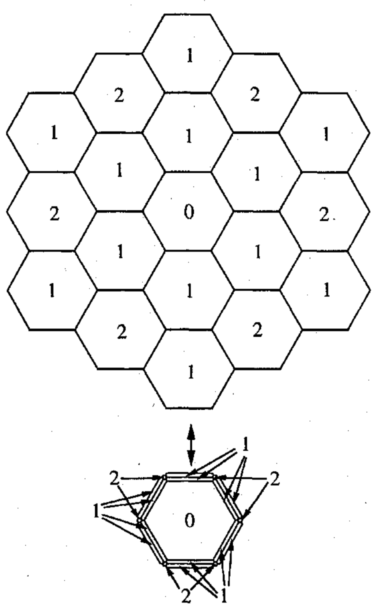

Fig. 5 Hexapod-truss with an unfolded module (plan view).

shown in Fig. 3a is called hexapod A, and the other is called hexapod B.

Provided that stiffness requirements are satisfied, five pairs of the side tension members in Fig. 1 can be eliminated for a module to be statically determinate. When more than two modules are combined, the resulting structure can hold its shape even if all the side tension members are eliminated. By omitting these members, the deployable structures can be simplified.

In some actual applications, tension members may not be preferable from the viewpoint of stiffness and durability. In such cases, they can be replaced by articulated rigid members. Figure 4 shows a hexapod-truss module whose face tension members have been replaced by articulated members. The small solid circles are the articulating hinges for these members. No lock mechanisms are required for the hinges. Side tension members have been eliminated.

Furthermore, if it is preferable, a module can be kept unfolded even when all the other modules are folded. Figure 5 schematically illustrates plan views of a deployed and folded hexapod-A truss in such a configuration. In this configuration, the module marked with 0 is kept unfolded, and those marked with 2 are folded and deployed two-dimensionally. The modules marked with 1 are folded and deployed almost one-dimensionally. Figure 6 shows such a module in an almost folded condition. The module is a hexapod-truss module. However, the two side faces 1-1′-6′-6 and 3-3′-4′-4 are kept unfolded. Therefore, all the tension members composing these side faces are replaced with rigid members. The result is still compatible with the adjacent folded modules because the other four side faces

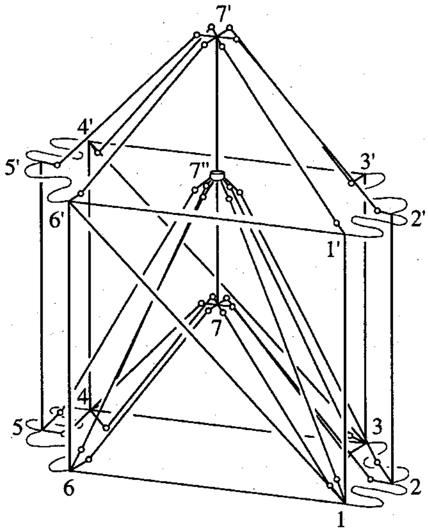

Fig. 6 One-dimensionally folded hexapod-truss module.

are folded. In a practical application, the unfolded module might contain, e.g., a spacecraft bus system, and the others an antenna reflector. The unfolded module could be an interface with other structures that are not deployable or foldable, especially when it is placed at the edge of such a structure. So, as described previously, various versions of the hexapod truss can be derived.

As will be described later, paraboloidal macroscopic surfaces can be formed by assembling the hexapod-truss modules. Therefore, one of the most attractive applications of the deployable truss is for large antenna structures. It could be used for the back structures of the mesh antennas proposed by, e.g., Meguro[2] and Mitsugitet et al.[7] In such a situation, the front surface, but not the back surfaces, should compose the paraboloidal macroscopic surface. If the node 7 shown in Fig. 1 is located lower than nodes 1–6 in the deployed condition, the front-surface tension members have to be overstressed once during the fold–deploy process. Similarly, the back-surface tension members will be overstressed once if node 7′ is located lower than nodes 1′–6′ when the structure is deployed. Therefore, the front surfaces of the modules should be used for a concave macroscopic surface, and the back surfaces should be used for a convex macroscopic surface.

Number of Mechanisms

Major requirements for deployable space structures are high packaging efficiency, light weight, high reliability, high design flexibility, etc. To maintain high reliability in deployment, it is essential to minimize the number of mechanisms, especially those that have to be locked at the completion of deployment. A reduction in the number also contributes to a reduction of the total structure mass, because the mass of the mechanisms would be substantial in the case of lightweight structures.

The plan view of a hexapod-truss module is basically hexagonal. Such a hexagonal configuration is convenient for some applications, such as the back structure of the segmented antenna proposed by Meguro[2] and Mitsugi et al.[7] Among the known two-dimensionally deployable trusses, Packtruss[3] and Synchro-Truss[2] modules are also hexagonal. Such a hexagonal deployable truss module can also be composed of three modules, or two complete and two half modules, of many other known two-dimensionally deployable truss-modules types, as shown in Figs. 7a and 7b, by modifying their originally square surface to a rhombus. Actually, a synchrotruss module[2] is basically a combination of two complete and two half sliding-hinge double-fold (SHDF) truss[1] modules shown in Fig. 8, although it differs in that some sliding hinge blocks are not actively driven. Similarly, hexagonal deployable truss modules may be composed of various modules such as the box truss,[4] Vought double-fold (VDF) truss,[5] Vought biaxial double-fold (BADF) truss,[5] variable-length diagonal (VLD) member truss,[1] SHDF truss,[1] etc. In other words, a hexapod truss, packtruss, or synchrotruss module corresponds to three modules of the other above-mentioned deployable trusses. Therefore, to compare these truss concepts fairly, a section amounting to one-third of a hexapod truss, packtruss, or synchrotruss module is referred to as a unit in this paper, and one of these units is regarded as equivalent to a module of the other deployable trusses, which is also called a unit. Furthermore, hexagonal or rhombus configurations are assumed for all types of deployable trusses in the following comparison.

Table 1 Comparison of two-dimensionally deployable trusses[a]

Truss	Per-unit number of mechanisms to be locked	Per-unit number of tension members and articulated members without lock	Packaging efficiency
Hexapod A	1/3	2	0.039
Hexapod B	1/4	3	0.041
Box truss[4]	4	8	0.11
Packtruss[3]	4	0	0.031
SHDF[1]-TM	1/2	4	0.031
SHDF[1]-AM	5/2	0	0.031
VLD[1]	4	0	0.031
VDF[5]	4	0	0.021
BADF[5]	1	4	0.044

[a]Hexapod A and hexapod B denote the arrangements shown in Figs. 3a and 3b, respectively. Structures are assumed to be composed of a large number of modules. Modules are assumed to be hexagonal. Packaging efficiency = (deployed volume)/(packed volume) × $(d/l)^2$. Values are calculated assuming that hinges are strictly on the line connecting nodes.

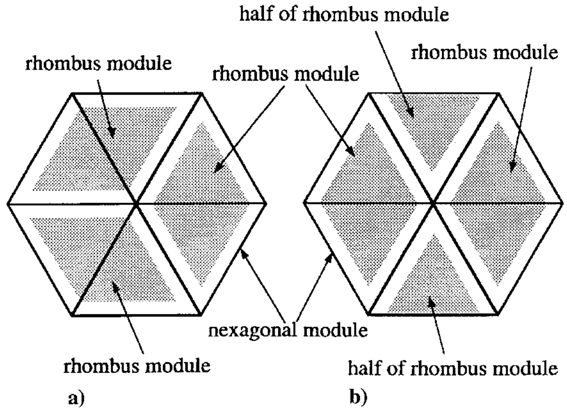

Fig. 7 Hexagonal module and rhombus modules (plan view).

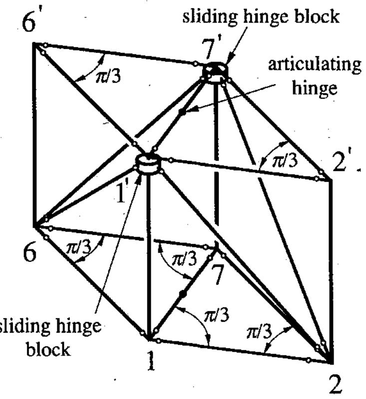

Fig. 8 Rhombus SHDF module with articulated members.

Table 1 lists the average per-unit number of mechanisms of the hexapod truss to be locked when deployed, in comparison with those of some other known deployable trusses. The hexapod-A truss module has only one mechanism to be locked, i.e., a sliding hinge block. Therefore, the number is $\frac{1}{3}$ per unit. In the hexapod-B configuration, the average number of modules per unit area is three-fourths that of the hexapod-A configuration. Therefore, the average number of mechanisms of hexapod B is $\frac{1}{4}$. The packtruss module has 16 articulating hinges to be locked. However, eight of them are shared by two modules when many modules are assembled into large structures. Therefore, the number of mechanisms is 12 per module, i.e., four per unit. Two sliding hinge blocks must be locked when a SHDF truss module with tension members (SHDF-TM) is deployed. However, each of them is shared by four modules when it is assembled. Therefore, the number of mechanisms is $\frac{1}{2}$ per unit. If the two pairs of tension members are replaced by two articulated members (abbreviated as SHDF-AM), their articulating hinges have to be locked. Therefore, the number is $\frac{5}{2}$ per unit. A box-truss module has eight articulating hinges to be locked. Because they are all shared by two modules, it has four mechanisms per unit. Both the VDF module and VLD module have six variable-length members to be locked, four of which are shared by two modules. A BADF module has four sliding hinge blocks, which are shared by four modules when they are assembled.

The table shows that of the deployable trusses shown the hexapod truss has the fewest mechanisms to be locked.

Packaging Efficiency

Packaging efficiency is an essential performance index of deployable structures. In the following investigation, the packaging efficiency is defined as the ratio of the volume of the deployed structure to that of the folded one. Furthermore, all the rigid members are assumed to be tubes whose diameter is d for the sake of simplicity. The faces of the modules are assumed to be either a hexagon or a rhombus whose edge length is l. The height of the module is also assumed to be l when it is completely deployed. It is also assumed that the central axes of all the members connected to a node exactly coincide with the nodal point in the deployed state.

Based on the above assumption, the most compactly folded side faces of various deployable trusses are as shown in Fig. 9. The plan view area of hexapod A is reduced approximately $\{d[3 + (1/\sqrt{3})]/l\}^2$ times by folding, whereas that of hexapod B is reduced approximately $(3.5d/l)^2$ times. Because their thicknesses are approximately doubled from l to $2l$, their packaging efficiencies are $l^3/\{[3 + (1/\sqrt{3})]^2 d^2 \times 2l\} \approx 0.039(l/d)^2$ and $l^3/[(3.5d)^2 \times 2l] \approx 0.041(l/d)^2$, respectively. We also obtained the packaging efficiencies of other deployable trusses through similar investigations. The table shows that the hexapod truss has better packaging efficiency than the others except for the BADF[5] and the box truss.[4]

The above investigation shows that, for example, a 5-m-thick, approximately 7900-m^2-large hexagonal hexapod-B platform whose edge length is 55 m can be transported to the orbit folded into a 4-m-diam × 10-m-long volume in the STS cargo bay if we select $l = 5$ m and $d = 5$ cm. If it is determined that more slender members can be used, the deployed area will further increase.

Design Flexibility

As shown in Ref. 1, the deployable trusses with fewer mechanisms generally tend to have more restrictive conditions on the lengths of members and, as a result, less design flexibility. Usually, these conditions are not a problem when a plane platform is constructed. If the number of constraints is small, various curved platforms can be constructed by properly designing the length of truss members. However, if a deployable truss has a large number of constraints, they could make it impossible to construct various curved platforms, such as a paraboloid, by using the truss. Therefore, we need to investigate whether the hexapod truss, which has only a small number of mechanisms (as has been described), retains enough design flexibility in forming various curved macroscopic surfaces. To demonstrate its design flexibility, a paraboloidal hexapod-A deployable truss composed of 19 modules is designed, and it is shown by a numerical kinematics investigation that the structure can be deployed and folded.

Necessary Conditions for Folding

For the structure shown in Fig. 10a to be completely folded, as shown in Fig. 10b, it is necessary that, for example,

$$L_{12} + L_{23} - L_{34} - L_{14} = 0 \tag{1}$$

where L_{ij} is shown in Fig. 10b. (Note that, e.g., L_{14} is different from the node-to-node length in the deployed condition.) These kinds of conditions are referred to as the necessary conditions for folding in this paper.

The necessary conditions for folding for the hexapod-truss module shown in Fig. 1 are

$$L_{77'} + L_{7i} - L_{7'i'} - L_{ii'} = 0 \qquad \text{for} \qquad i = 1, \ldots, 6 \tag{2}$$

$$L_{17'} + L_{7i} - L_{17} - L_{7'i} = 0 \qquad \text{for} \qquad i = 2, \ldots, 6 \tag{3}$$

When the module is connected to another module in the manner shown in Fig. 3a, we can see from Fig. 11 that the following conditions also need to be satisfied:

$$L_{2'7'} + L_{3'8'} - L_{2'8'} - L_{3'7'} = 0 \tag{4}$$

$$L_{27} + L_{38} - L_{28} - L_{37} = 0 \tag{5}$$

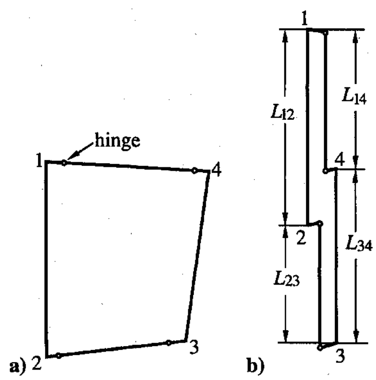

Fig. 10 Simple example of folding.

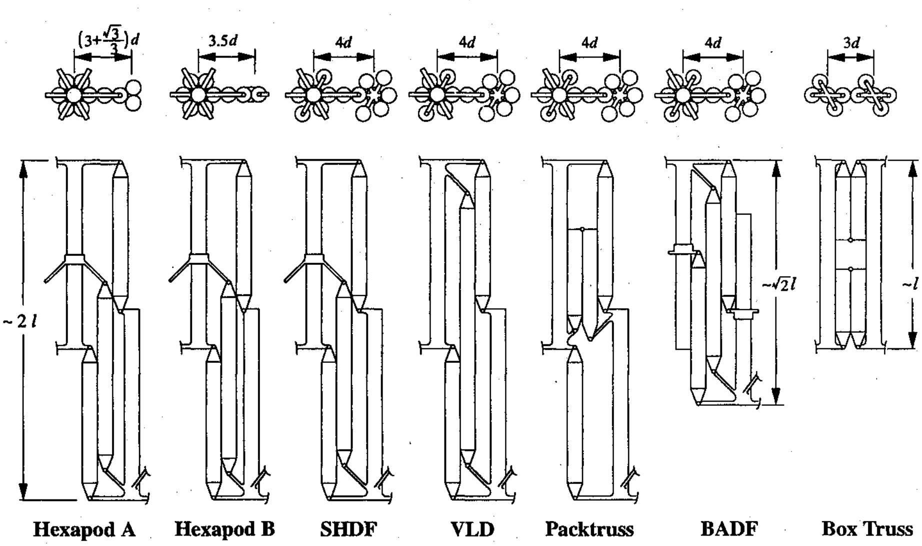

Fig. 9 Most compactly folded side surfaces of various deployable trusses.

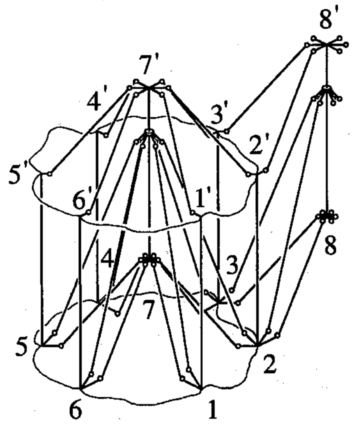

Fig. 11 Module and some members of an adjacent modules of hexapod-A truss during deploy–fold process.

Because a module is connected to six modules in the hexapod-A configuration, 10 more similar conditions need to be satisfied in addition to Eqs. (4) and (5). As a result, the length of the rigid members of a hexapod-A module needs to satisfy 23 conditions, i.e., Eqs. (2–5) and 10 equations similar to each of Eqs. (4) and (5), some of which are dependent. The necessary conditions for folding for hexapod B can be derived similarly. To derive the necessary conditions for the configuration shown in Fig. 5 (in which a module is not deployed or folded), we have to be careful because some truss members are not parallel to each other even in the fully folded condition.

Design of a Paraboloidal Hexapod Truss Platform

A paraboloidal hexapod-A deployable truss platform is designed by numerically obtaining the locations of the nodes of the fully deployed truss such that we have 1) the necessary conditions for folding, 2) conditions for the front-surface nodes to be in a given paraboloid, and 3) some other desirable constraints satisfied in the sense of least weighted mean square. Figure 12 shows a schematic plan view of the truss platform, which is composed of 19 modules.

The condition in item 2 is

$$z_j - \frac{x_j^2 + y_j^2}{al} = 0 \qquad \text{for all front face nodes } j \tag{6}$$

The constraints in item 3 are

$$\beta_j - \pi/3 = 0 \qquad \text{for all } j \tag{7}$$

$$l_{fi} - l = 0 \tag{8}$$

$$l_{ci} - l = 0 \tag{9}$$

The packaging efficiency of the hexapod truss has been derived by assuming that $\beta_j = \pi/3$, as shown in Fig. 9. Therefore, the restriction (7) is introduced to maintain the packaging efficiency listed in Table 1. Because a slight degradation in packaging efficiency is acceptable from a practical point of view, the restriction (7) does not need to be satisfied strictly. Equations (8) and (9) are introduced to make the resulting truss structure regular by making the lengths of the truss members as nearly equal as possible. These two conditions are preferable, but do not need to be strictly satisfied.

By using the conjugate-gradient scheme, the locations of the nodes in fully deployed condition, i.e., x_j, y_j, and z_j, are numerically determined so that

$$f \equiv \sum_{k=2}^{9}\left(w_k \sum_{i=1}^{n_k} E_{ki}^2\right) \tag{10}$$

is minimized, where E_{ki} denotes the value of the left-hand side of the ith equation represented by Eq. (k) and n_k denotes the number of equations represented by Eq. (k). It is clear that E_{ki} is a function of the locations of the nodes. Because of the symmetry of the structure, only a $\frac{1}{12}$ section of the entire structure needs to be investigated in the actual design.

In the design, all the rigid members are assumed to be tubes whose diameters are d. The centerlines of the rigid members connecting two nodes are assumed to coincide exactly with the line connecting the nodes in the fully deployed condition. The hinges are also assumed to be exactly on the line when the truss is deployed. The offsets of the hinges from the nodes are determined by assuming the most compact folding for the assumed member diameter d as shown in Fig. 9.

Figure 13 shows the designed hexapod truss in the fully deployed condition. To avoid excessive complexity, tension members are neglected in the figure. The root-mean-square (rms) values of E_{ki} were as shown in Table 2 when the iteration of numerical search was terminated, where $\text{rms}[E_{k1}, \ldots, E_{kn}]$ is defined as

$$\text{rms}[E_{k1}, \ldots, E_{kn}] \equiv \left(\frac{\sum_{j=1}^{n}\sum_{i=1}^{n_{kj}} E_{kji}^2}{\sum_{j=1}^{n} n_{kj}}\right)^{\frac{1}{2}} \tag{11}$$

The values of E_{ki}^2 were still decreasing when the iteration was terminated. In the calculation, the parameter values were set as

$$a = 20, \qquad l/d = 50, \qquad w_2 = w_3 = w_4 = w_5 = w_6 = 1$$

$$w_7 = w_9 = 10^{-4}, \qquad w_8 = 10^{-5}$$

Because the conditions (7–9) do not need to be satisfied in a strict sense, small values of the weighting factors are used for them.

The value of $\text{rms}[E_6]/l$ in Table 2 shows that the nodes on the front surface are in the given paraboloid with high precision. The necessary conditions for folding are not satisfied in a

Table 2 RMS values of E_{ki} of designed truss

$\text{rms}[E_2, E_3, E_4, E_5]/l$	5.2×10^{-6}
$\text{rms}[E_6]/l$	5.7×10^{-6}
$\text{rms}[E_7]$	2.1×10^{-2}
$\text{rms}[E_8]/l$	8.1×10^{-2}
$\text{rms}[E_9]/l$	5.4×10^{-2}

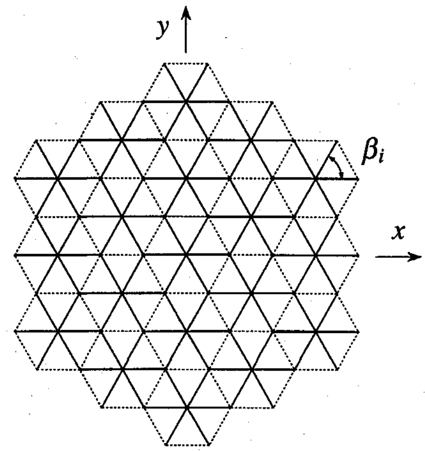

Fig. 12 Schematic plan view of a paraboloidal deployable hexapod-A truss composed of 19 modules.

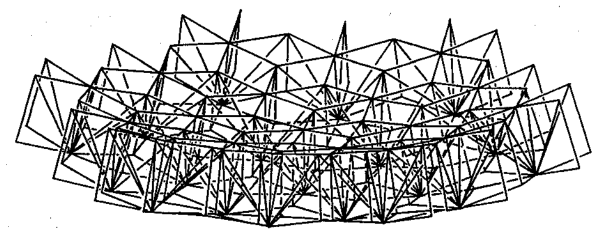

Fig. 13 Designed paraboloidal hexapod-A truss in fully deployed condition.

strict sense. However, the normalized rms errors for them, i.e., rms$[E_2, E_3, E_4, E_5]/l$, are so small that these errors in the lengths of the members can be easily compensated for by elastic deformations of the members. Strains in the truss members of the order of 10^{-5} are usually acceptable in actual situations. Therefore, we can regard the necessary conditions for folding as being practically satisfied. Equation (7) is not strictly satisfied either. However, we can see that the truss can be completely folded if the diameter of the members is made slightly less than the initially assumed value of d. Likewise, as has been mentioned, Eqs. (8) and (9) do not need to be satisfied in a strict sense. Therefore, we can conclude that the designed paraboloidal truss practically satisfies all the conditions that must be satisfied in the fully folded condition.

Investigation of Half-Deployed, Half-Folded Configuration

In the previous section, the design of a paraboloidal hexapod-A deployable truss was described, and the consistency of its truss members in the completely folded condition was confirmed from a practical point of view. However, we still need to investigate whether the truss can actually be deployed via a half-deployed, half-folded state. To investigate whether it is actually deployable, the locations of nodes and rotational angles of hinge blocks of the half-deployed, half-folded truss are obtained numerically for various degrees in the deployment process such that

$$G \equiv q_1 \sum_{i=1}^{n_r} \left(l_{ri} - l_{ri}^*\right)^2 + q_2 \sum_{i=1}^{n_a} (\Delta\varphi_i)^2 + q_3 \sum_{i=1}^{n_t} \left\langle l_{ti} - l_{ti}^*\right\rangle^2 \quad (12)$$

is minimized, where $\langle x \rangle$ is a function of x defined as

$$\langle x \rangle \equiv \begin{cases} x & \text{when} \quad x \geq 0 \\ 0 & \text{when} \quad x < 0 \end{cases} \quad (13)$$

To indicate the degree in the deploy–fold process, the folding ratio is defined as s_d/s_t. For example, $s_d/s_t = 0$ and $s_d/s_t = 1$ indicate fully deployed and fully folded conditions, respectively. In this numerical investigation, the values of folding ratios of all the sliding hinge blocks are assumed to be identical.

The deployable truss is assumed to keep its symmetry during the deploy–fold process, and only a $\frac{1}{12}$ section is investigated. The values of weighting factors used in the calculation are $q_1 = 1.0$, $q_2 = 1.0 \times 10^{-3}$, and $q_3 = 1.0 \times 10^{-2}$.

The rms values of $l_{ri} - l_{ri}^*$ and $\Delta\varphi_i$ were as shown in Table 3 when the numerical calculation iterations were terminated for each value of the folding ratio. The rms values of $\langle l_{ti} - l_{ti}^* \rangle$ are not shown in the table, because they were zero in all the cases listed in the table.

All the values listed in Table 3 are so small that such inconsistencies in the member lengths and the angles can be easily compensated for by elastic deformations. This fact indicates that the designed truss can be folded and deployed without any practical problems. Furthermore, we can conclude that the newly proposed two-dimensionally deployable truss has practically acceptable design flexibility.

Table 3 Final rms values of the components of the right-hand-side terms of Eq. (12)

Folding ratio s_d/s_t	rms$[l_{ri} - l_{ri}^*]/l$	rms$[\Delta\varphi_i]$
1.0	3.9×10^{-6}	3.4×10^{-8}
0.98	9.5×10^{-6}	4.2×10^{-6}
0.96	8.5×10^{-6}	2.7×10^{-6}
0.94	5.1×10^{-6}	1.2×10^{-5}
0.92	5.3×10^{-6}	9.4×10^{-6}
0.9	5.8×10^{-6}	2.7×10^{-6}
0.8	3.3×10^{-6}	8.3×10^{-6}
0.7	2.8×10^{-6}	2.3×10^{-6}
0.6	3.7×10^{-6}	1.0×10^{-5}
0.5	3.5×10^{-6}	6.1×10^{-6}
0.4	3.0×10^{-6}	9.1×10^{-6}
0.3	2.9×10^{-6}	4.7×10^{-6}
0.2	2.3×10^{-6}	1.0×10^{-6}
0.1	1.5×10^{-6}	2.6×10^{-7}

Conclusions

A two-dimensionally deployable truss concept has been proposed. Its most significant advantage is the small number of mechanisms to be locked when it is deployed. Some variations of configurations of deployable trusses composed of the new truss modules were also presented. Deployable trusses with fewer mechanisms generally tend to lose design flexibility in forming various curved surfaces. Therefore, to demonstrate that the new truss still retains design flexibility, a paraboloidal structure was designed and numerical investigations demonstrated that it can be actually deployed and folded.

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