NASA Technical Memorandum 86366

Deployable Controllable Geometry Truss Beam

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Summary

Deployable truss beam structures that can maneuver in a serpentine manner may be desirable for future space missions. Some typical applications include booms to position equipment, a berthing device between the Shuttle and an operational space station or other large satellite during servicing, a serpentine structure to position and support a transfer tunnel, and a joint in a crane or boom. One structural configuration that has potential for these and possibly other applications is the deployable geodesic truss beam. This truss beam is composed of a series of members connected together at joints that provide the required rotational degrees of freedom. During the current investigation, the beam configuration was studied to evaluate the requirements of the joints and to define preliminary joint designs that would provide both structural stiffness and maneuverability. This study indicated that two joint types would be required. Both joint types were fabricated and incorporated in a demonstration model. The model exhibited the required mobility and was structurally stable in every deployed position.

An analysis of the concept was performed to define the geometric relationships between members and the location and orientation of the beam tip during beam serpentine operation. Additional development is required to further refine both the joints and the analysis; however, the results of the current investigation fully demonstrate the concept and its potential for future space missions.

Introduction

Efficiently packaged deployable beams are necessary for many large space structures envisioned for future applications. Typical examples include space cranes and remote manipulator arms, masts to position and support feed horns for large antennas, and cantilever beams to deploy and tension blankets of a solar cell power system. Deployable beam concepts have been proposed in the past, and many of them were compared in evaluation studies reported in references 1 and 2. A major drawback to most of these concepts is that they require a relatively complicated deployment mechanism to unfold the beam structure. These mechanisms must deploy the beam in a straight line along its longitudinal axis and provide structural support to the partially deployed beam. Following deployment, the deployer mechanism serves no function.

A new concept in deployable beam technology called a controllable geometry truss beam is discussed herein. This truss beam does not require a special deployer mechanism and does not have to be deployed in a straight line along its longitudinal axis as noted for the previous concepts. The controllable geometry feature of this new beam concept means that by changing the length of a control member the longitudinal axis of the beam is deformed in a predictable manner. Controllable geometry allows the beam to correct for alignment errors or serve as a movable joint in structures such as space cranes and remote manipulators.

The purpose of the current paper is to present the features of the controllable geometry truss beam concept. The geometry of the configuration is described along with the rotational degrees of freedom required at the truss joints. An analysis is included which defines the position and angular orientation of the longitudinal axis of the truss beam as a function of control member length. A developmental model fabricated to verify the joint requirements is presented along with potential applications for this type of structure.

Symbols

a	length of actuator member
b	length of batten member
h	length of deployed bay when all actuators of bay undergo same displacement
i, j, k	unit vectors having direction of positive X-, Y-, and Z-axes
J	truss joint
$\mathbf{J}$	vector from origin of coordinate axes to truss joint J
ℓ	length of longitudinal crossed members (see fig. 6)
m, n, p	coordinates (x, y, and z, respectively) of point that is equidistant from apexes of actuator frame
N	normal to plane of actuator frame
r	radial distance from center of actuator frame or batten frame to any joint in that frame
u, v, w	coordinates (x, y, and z, respectively) of center of top batten frame of typical bay
x, y, z	Cartesian coordinates
α	angle between batten and intersecting longitudinal crossed member (see fig. 6)
β	deployment angle (see fig. 7)

ρ	angle between two actuators that are connected at common joint (see fig. 8)
ϕ, θ, ψ	angles between coordinate axes and normal (N) to plane of actuator frame

Subscripts:

d	deployed
i	typical bay
r	retracted
T	total effect; accounts for all bays in beam
X, Y, Z	Cartesian components
$1, 2, \ldots, 6$	joint nodes (see fig. 8)

Geometric Configuration and Joint Requirements

A simple conceptual model of the controllable geometry truss beam was assembled by using stick members connected by rubber joints. A photograph of two bays (a bay is a repeating section) of this model is shown in figure 1. The configuration is formed from a series of straight-sided triangular frames and is referred to hereinafter as a geodesic beam. There are 18 members in a typical bay. They are identified in figure 1 as battens, longitudinal crossed members, and actuators. The battens are of equal length and form an equilateral triangle hereinafter referred to as a batten frame. The batten frames form the ends of a typical bay. The 12 longitudinal crossed members in a bay are also of equal length and connect the batten frames to the actuators. The actuators are members whose length may vary independently and are also connected together to form a triangular frame. This scalene triangle is hereinafter referred to as an actuator frame. There are no special length requirements or length ratios between the fixed-length battens and longitudinal crossed members.

Most truss beam configurations considered in references 1 and 2 are structurally efficient configurations that have longeron members aligned with the longitudinal axis of the beam. These longeron members are structurally sized by anticipated axial and bending load/stiffness requirements. These truss beams also contain diagonal and batten members. The diagonals are sized by beam shear and torsion requirements, and battens, typically, are lightly loaded and serve to either preload the joints, stabilize the joint hinge body, or maintain the cross section under small inertial and extraneous loads. Therefore, the battens basically represent parasitic mass. The members in the controllable geometry truss (fig. 1) are all loaded and some serve several functions. For example, the longitudinal crossed members carry both the axial and shear loads that are applied to the structure. The battens and actuators are loaded under most applied load conditions during the various stages of deployment or controllable geometry applications. Since all members in the controllable geometry truss share in reacting to applied loads the configuration unlike some truss beams has no members that can be classed as parasitic mass.

To package the truss shown in figure 1, the actuator members would be lengthened; thus, this would cause the longitudinal crossed members to fold away from the beam center. The retracted truss is shown in figure 2; the length of the retracted truss is very small in relation to the deployed length. The retracted length is a function of member diameters and the size and shape of the connecting joints. More information on packaging and deployed length is given in a subsequent section.

The rotation required of the joints and their interaction with the actuators at various locations is defined in figure 3. In figure 3(a), a typical actuator frame joint along with the actuator (identified as actuator A) opposite this joint is shown. A change in length by the actuator requires the joint to permit a rotation of the longitudinal crossed members that intersect at this joint about an axis parallel to the actuator member A. The motion required at the same joint due to a length change in an adjacent actuator (identified as actuator B) is shown in figure 3(b). A length change in the adjacent actuator requires the joint to permit rotation about the three independent axes shown. The longitudinal crossed members must, as before, rotate about an axis parallel to actuator A (fig. 3(a)), and in addition, the plane formed by each pair of longitudinal crossed members must rotate about an axis that lies in the plane and bisects the angle between the longitudinal crossed members. Since the axes of rotation required for motion shown in figure 3(b) includes the axis of rotation required for the motion shown in figure 3(a), in addition to the other two rotational axes, the change in length of the adjacent actuator defines the total rotational requirements for the joint. A change in length of either actuator A or B causes batten frames to both translate and rotate. If only a translation of the batten frame is desired, then all three actuators in the adjacent actuator frame must be equally and simultaneously extended or retracted and the only rotational axes required are those associated with the motion described in figure 3(a). If the actuators are moved independently, the three rotational degrees of freedom identified in figure 3(b) are required at each of the three actuator frame joints.

The rotation required at the joints connecting the battens and the longitudinal crossed members is shown in figure 4. The longitudinal crossed members and battens form a triangle of fixed geometry. A change in actuator lengths requires these planes each to rotate about an axis that lies along the centerline of the batten in that plane. However, the longitudinal crossed members in one bay must move independently of those in an adjacent bay even though they have the same axis of rotation. All batten frame joints are identical.

The discussion of the joint rotational requirements makes it evident that two joint types are required for this truss beam concept, an actuator frame joint and a batten frame joint. During a preliminary development program, models of these two joint types were fabricated and are shown in figure 5. The location of the joints on the beam is indicated on the stick model shown in figure 5(a). Enlarged photographs of the joints are shown in figures 5(b) and 5(c) to depict details of the joint and their rotational axes.

An attempt was made to incorporate two important goals in the design of the joints. First, the structure should retract to the minimum length possible when folded for packaging. Second, all the members that come together at a joint should have lines of action which intersect at a common point. This condition ensures that the stiffness of the structure is governed by the axial stiffness of the members as opposed to the bending stiffness of a connecting section and that the joint does not introduce free play in the structure due to joint "rocking." These goals are difficult to satisfy simultaneously in a deployable truss beam that fully deploys before external loads are applied. They are even more challenging to satisfy simultaneously for loaded controllable geometry truss beam structures. An attempt was made to adhere to these goals in the design of the joints shown in figure 5. Packaging and mobility were used as the primary design goals, and the line of action of the members was the secondary design goal.

The actuator frame joint shown in figure 5(b) has a joint body section to which the various members are attached. Both actuators pivot about a single axis that is located in the center of the joint body and is parallel to the joint body axis. The actuators each have a circular disk end fitting that fits into a recess cut in the joint body. The disk stabilizes the joint body from moments caused by the offset of the intersecting longitudinal crossed members. Each set of longitudinal crossed members are connected away from the joint body to a ball end which fits into a socket in the joint body. Slots in the joint body enable each longitudinal crossed member to rotate without obstruction about the axes shown in figure 5(b).

A typical batten frame joint is shown in figure 5(c). The two batten members require no rotation and are affixed to each other. The longitudinal crossed members must each rotate independently about an axis that is aligned to the centerline of the attached batten members. Axial loads in the longitudinal crossed members are transferred to the batten frame joint by a connector section (fig. 5(c)); however, a large cross section enables the longitudinal crossed members to maintain a high effective axial stiffness.

The two joints defined previously represent preliminary designs that provide the required rotational degrees of freedom for the geodesic truss to deploy while providing structural capability in the partially deployed configuration. They provide the required maneuverability such that the central axis of the beam is not required to be straight. Modifications to improve the joint structurally may be possible.

Analysis of Deployment

The truss deployment analysis is governed by geometric considerations which are illustrated with the line sketch of a top view of a retracted beam shown in figure 6. As shown in the figure, the battens and actuators from equilateral triangles and the longitudinal crossed members form isosceles triangles with a batten as the base. Therefore, there are only two parameters that govern the length of a fully deployed bay: one is the length of the batten and the other is the base angle α. The length of a longitudinal crossed member is given by (fig. 6)

$$\ell = \frac{b}{2\cos\alpha} \tag{1}$$

For packaging considerations, the radius of the circle that encloses the retracted beam is an important parameter. For a beam where $\alpha \geq \pi/6$, the radius of the retracted beam is controlled by the size of the actuator frame and is

$$r_r = \frac{b}{2}\left(\frac{1}{\sqrt{3}} + \tan\alpha\right) \tag{2}$$

For a beam where $\alpha < \pi/6$, the radius of the retracted beam is controlled by the size of the batten frame and is

$$r_r = \frac{b}{\sqrt{3}} \tag{3}$$

If the beam is deployed so that the longitudinal axis is normal to the base plane, the change in length of the actuator and the length of the beam are related to the deployment angle β. This angle is shown in figure 7 as the angle between two planes, one formed by the actuator members and the other formed by the longitudinal crossed members. The actuator length and the length of the bay are, respectively,

$$a = \frac{b}{2}\left(1 + \sqrt{3}\tan\alpha\cos\beta\right) \tag{4}$$

$$h = b\tan\alpha\sin\beta \tag{5}$$

For a multibay beam, the total deployed length is given by

$$h_T = b\tan\alpha\sum_{i=1}^{n}\sin\beta_i \tag{6}$$

where n is the total number of bays. The change in the length of an actuator in a typical bay from fully retracted to fully deployed is

$$a_r - a_d = \frac{\sqrt{3}}{2}\,b\tan\alpha \tag{7}$$

If the beam is deployed in a serpentine manner so that each actuator undergoes an independent length change, the coordinates of the beam axis (the center of the batten frame) and the orientation of the batten frame can be determined by using a vector analysis approach. Shown in figure 8 is a line sketch of a typical half-bay of a truss beam for which each actuator is set at a different length such that the plane of the actuator frame is not parallel to the plane of the batten base frame. The origin of the Cartesian coordinate system is at the center of the batten base frame with the Z-axis normal to the batten base frame. From figure 8 the coordinates of the actuator frame joints denoted as J_4, J_5, and J_6 are

$$\left.\begin{aligned} x_4 &= 0 \\ y_4 &= \frac{b}{2\sqrt{3}} + \frac{b}{2}\tan\alpha\cos\beta_4 \\ z_4 &= \frac{b}{2}\tan\alpha\sin\beta_4 \end{aligned}\right\} \tag{8}$$

$$\left.\begin{aligned} x_5 &= \frac{-b}{4} - \sqrt{3}\,\frac{b}{4}\tan\alpha\cos\beta_5 \\ y_5 &= -\frac{b}{4\sqrt{3}} - \frac{b}{4}\tan\alpha\cos\beta_5 \\ z_5 &= \frac{b}{2}\tan\alpha\sin\beta_5 \end{aligned}\right\} \tag{9}$$

$$\left.\begin{aligned} x_6 &= \frac{b}{4} + \sqrt{3}\,\frac{b}{4}\tan\alpha\cos\beta_6 \\ y_6 &= -\frac{b}{4\sqrt{3}} - \frac{b}{4}\tan\alpha\cos\beta_6 \\ z_6 &= \frac{b}{2}\tan\alpha\sin\beta_6 \end{aligned}\right\} \tag{10}$$

The vectors from the origin to joints J_4, J_5, and J_6 (fig. 8) are therefore

$$\left.\begin{aligned} \mathbf{J}_4 &= x_4 i + y_4 j + z_4 k \\ \mathbf{J}_5 &= x_5 i + y_5 j + z_5 k \\ \mathbf{J}_6 &= x_6 i + y_6 j + z_6 k \end{aligned}\right\} \tag{11}$$

and the lengths of the actuators are

$$\left.\begin{aligned} a_{4,5} &= (x_4 - x_5)^2 + (y_4 - y_5)^2 + (z_4 - z_5)^2 \\ a_{5,6} &= (x_5 - x_6)^2 + (y_5 - y_6)^2 + (z_5 - z_6)^2 \\ a_{4,6} &= (x_4 - x_6)^2 + (y_4 - y_6)^2 + (z_4 - z_6)^2 \end{aligned}\right\} \tag{12}$$

The radius of the circle that circumscribes the actuator frame triangle with the joints of the frame lying on the circumference of the circle is given by

$$r = \frac{1}{2}\frac{a_{4,6}}{\sin\rho} = \frac{1}{2}\frac{a_{4,6}}{\sin\left(\cos^{-1}\frac{a_{4,6}^2 + a_{5,6}^2 - a_{4,6}^2}{2a_{4,5}a_{5,6}}\right)} \tag{13}$$

To determine the coordinates (m, n, and p) of the center of the circle whose radius is given by equation (13), it is necessary to write the location of each joint in the form of an equation of a sphere. Thus

$$\left.\begin{aligned} (x_4 - m)^2 + (y_4 - n)^2 + (z_4 - p)^2 &= r^2 \\ (x_5 - m)^2 + (y_5 - n)^2 + (z_5 - p)^2 &= r^2 \\ (x_6 - m)^2 + (y_6 - n)^2 + (z_6 - p)^2 &= r^2 \end{aligned}\right\} \tag{14}$$

Expanding these equations and solving them yield the following relations that can be solved simultaneously for the values m, n, and p:

$$\left.\begin{aligned} & m\,(x_5 - x_4) + n\,(y_5 - y_4) + p\,(z_5 - z_4) \\ & \qquad = \frac{1}{2}\left(x_5^2 - x_4^2 + y_5^2 - y_4^2 + z_5^2 - z_4^2\right) \\ & m\,(x_5 - x_6) + n\,(y_5 - y_6) + p\,(z_5 - z_6) \\ & \qquad = \frac{1}{2}\left(x_5^2 - x_6^2 + y_5^2 - y_6^2 + z_5^2 - z_6^2\right) \\ & m\,(x_6 - x_4) + n\,(y_6 - y_4) + p\,(z_6 - z_4) \\ & \qquad = \frac{1}{2}\left(x_6^2 - x_4^2 + y_6^2 - y_4^2 + z_6^2 - z_4^2\right) \end{aligned}\right\} \tag{15}$$

Therefore, m, n, and p define the coordinates of the center of the actuator frame. The normal to the actuator frame can be determined by taking the cross product of any two of the three vectors that lie along the actuators. For example,

$$\begin{aligned} \mathrm{N} &= \begin{vmatrix} i & j & k \\ x_5 - x_6 & y_5 - y_6 & z_5 - z_6 \\ x_5 - x_4 & y_5 - y_4 & z_5 - z_4 \end{vmatrix} \\ &= N_X i + N_Y j + N_Z k \end{aligned} \tag{16}$$

where

$$\begin{aligned} N_X &= (y_5 - y_6)(z_5 - z_4) - (y_5 - y_4)(z_5 - z_6) \\ N_Y &= (z_5 - z_6)(x_5 - x_4) - (x_5 - x_6)(z_5 - z_4) \\ N_Z &= (x_5 - x_6)(y_5 - y_4) - (x_5 - x_4)(y_5 - y_6) \end{aligned}$$

The direction cosines of the normal are given by

$$\left.\begin{aligned} \cos\phi &= \frac{N_X}{\sqrt{(N_X^2 + N_Y^2 + N_Z^2)}} \\ \cos\theta &= \frac{N_Y}{\sqrt{(N_X^2 + N_Y^2 + N_Z^2)}} \\ \cos\psi &= \frac{N_Z}{\sqrt{(N_X^2 + N_Y^2 + N_Z^2)}} \end{aligned}\right\} \tag{17}$$

The center of the top batten frame (defined as the beam axis) for this single bay can now be determined by extending the above relationships. The normal to the top batten frame makes an angle 2ψ with the Z-axis. The coordinates of the center of the tip batten frame noted as u, v, and w are

$$\left.\begin{aligned} u &= m + \sqrt{m^2+n^2+p^2}\left[\sin\left(2\sin^{-1}\frac{\sqrt{m^2+n^2}}{\sqrt{m^2+n^2+p^2}}\right)\right] \\ &\quad \times \frac{m}{\sqrt{m^2+n^2}} \\ v &= n + \sqrt{m^2+n^2+p^2}\left[\sin\left(2\sin^{-1}\frac{\sqrt{m^2+n^2}}{\sqrt{m^2+n^2+p^2}}\right)\right] \\ &\quad \times \frac{n}{\sqrt{m^2+n^2}} \\ w &= p + \sqrt{m^2+n^2+p^2}\cos\left(2\cos^{-1}\frac{p}{\sqrt{m^2+n^2+p^2}}\right) \end{aligned}\right\} \tag{18}$$

For a multibay truss beam, the position of the tip can be obtained by calculating the location and normal to the top batten frame of each bay in a local coordinate system and then transferring that location and direction to a global system for each bay. The top batten frame of one bay becomes the base batten frame of the next bay as one proceeds from the base to the tip of the beam. The analysis, however, has not included effects of member size (diameter) and joint rotations, both of which must be considered to accurately determine the tip position of an actual model.

Development Model

A development model was fabricated from conventional materials to evaluate the concept and verify joint maneuverability. Photographs of this model are shown in figure 9. The joints used in the model are identical to those shown in figures 5(b) and 5(c). The model has two bays and the batten length is approximately 48 inches and the angle α is 45°. All members were fabricated from 3/4-inch-diameter aluminum tubing with the exception of the interior telescoping section of each actuator member. These telescoping sections are 5/8-inch-diameter steel tubing.

The length of the actuator frame joint body (fig. 5(b)) and the diameter of the tubing control the retracted length of the beam. The joint body for this model was approximately 2 1/4 inches high. The ratio of deployed length to packaged length of this model is approximately 20:1, which is in the range that is generally considered for many deployable truss beam applications (ref. 1). The photographs in figure 9 depict the model in an axially straight deployed position, in a typically serpentine position, and in the retracted or packaged position. The model exhibited the desired mobility and is structurally stable in every deployed position. The actuators in the model are manually moved to discrete positions along the telescoping tube and locked by plunger pins that fit into machined slots. The model effectively demonstrates the geodesic beam concept and provides a focus for further study and evaluation.

Applications

Trusses such as the geodesic beam which are deployable and can sustain structural loads during deployment have many potential uses. A few of these uses which pertain to space applications are discussed.

One potential use for a serpentine truss beam is to position a camera or special end effectors at a location that is not otherwise readily accessible. Regions in future space platforms or space stations may require remote monitoring or services that would be conveniently and economically administered with serpentine truss beam structures. Use of such structures could reduce the extravehicular activity required of astronauts and they could be programmed to perform routine robotic operations.

Current studies for the space station recommend berthing the Shuttle to the station to maintain their relative positions and then transferring materials between the two vehicles. The geodesic beam has many attributes which make it suitable for this application. Berthing could be accomplished by moving the Shuttle in proximity to the station and then having the final capture by a geodesic truss beam. Likewise when deberthing the truss beam could provide the separating force required to move the vehicles apart; thereby, the need to fire Shuttle thrusters in the vicinity of the station would be reduced. The beam has an open center section which could be used to accommodate a transfer tunnel for astronauts and station stores. Pressurizing the tunnel could provide the necessary forces for deployment with retraction accomplished by cables. This system may maintain control by slide locks on the actuators as opposed to the use of motor driven mechanisms.

An additional application could be the use of one or more bays of a geodesic beam truss as a movable joint in a fixed geometry truss. This structural configuration could serve as a space crane. The geodesic beam would provide the required maneuverability found in more massive pin joints normally used in cranes. Also by using only few bays of the geodesic beam the number of actuators would be limited, which would reduce the complexity without necessarily sacrificing performance. A similar application may incorporate a bay or two in a structure that must be accurately positioned to function effectively. Such a system is required for the feed systems planned for use in large communication antennas. The position of the feed system could be changed to account for errors in initial placement, changes in location caused by thermal distortion, dimensional instabilities associated with aging or for vibration and damping control in long feed mast supports. Many future missions may require the use of truss beam structures that incorporate position control to ensure operational efficiency.

Concluding Remarks

A concept for a truss beam that deploys without the use of a special deployer mechanism and can be maneuvered in a predictable manner by changing the length of control members has been investigated. The rotational requirements of the joints in the beam were determined, and two joint types were shown to be required. Preliminary designs for these two joint types were formulated and the designs were incorporated in a two-bay demonstration model. The model, which was structurally stable in every deployed position, effectively demonstrated the mobility and packagability of the beam concept. An analysis was performed to find the position and direction of the beam axis. Although the analysis did not include the effect of member diameter and physical joint rotations it could be used to estimate the location and direction of the beam axis under general operating conditions.

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2. Cox, R. L.; and Nelson, R. A.: *Development of Deployable Structures for Large Space Platform Systems.* Rep. No. 2-32300/2R-53215 (Contract NAS8-34678), Vought Corp., Oct. 1982. (Available as NASA CR-170690.)

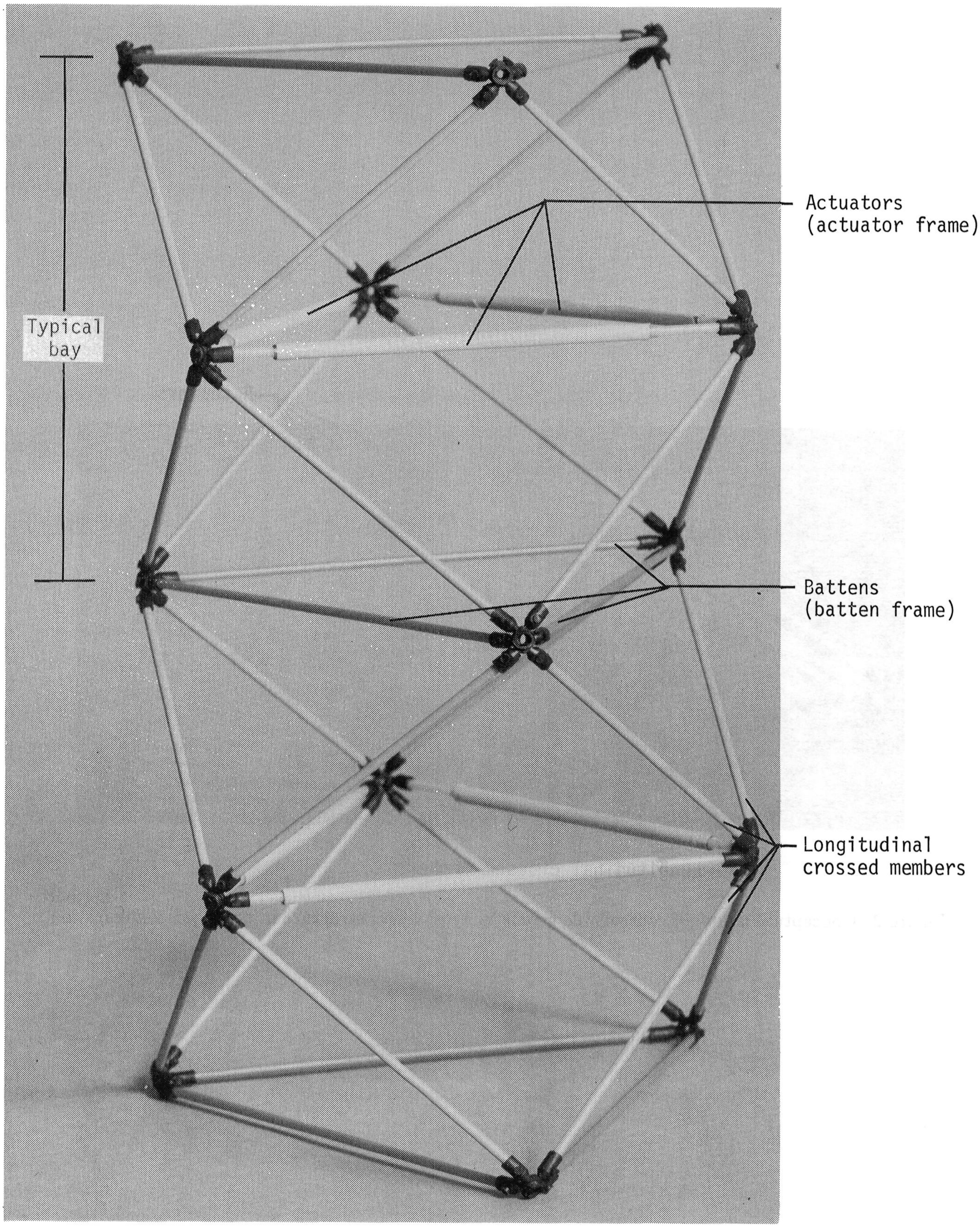

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Figure 1. Conceptual model of partially deployed controllable geometry truss beam structure.

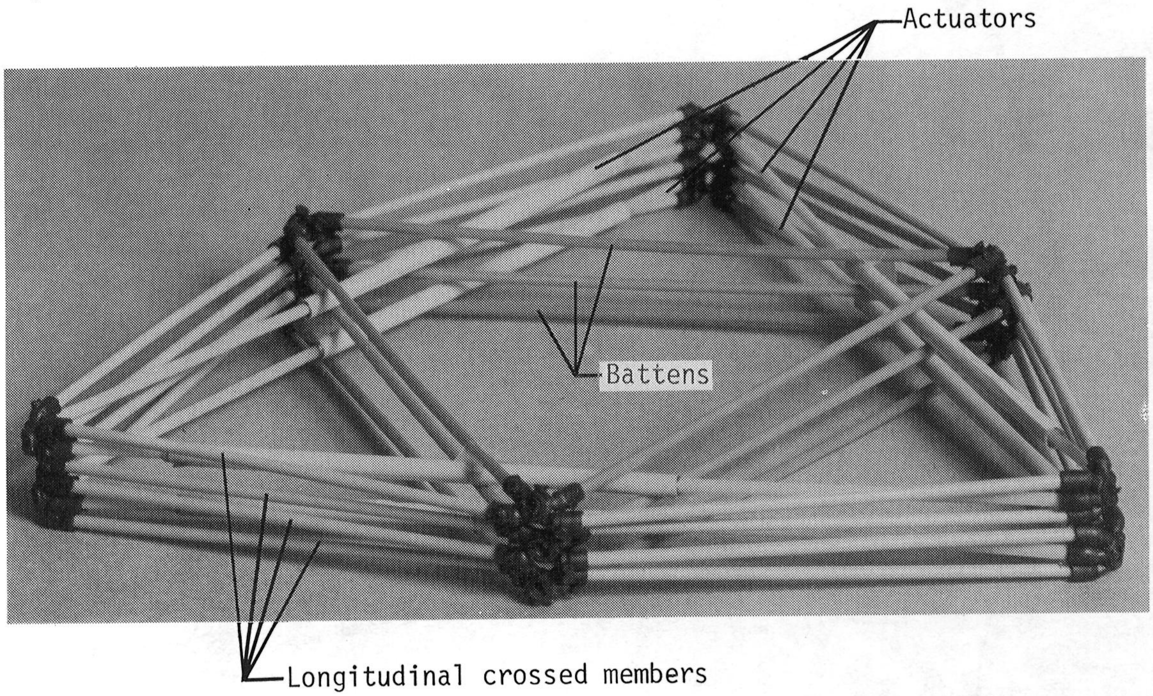

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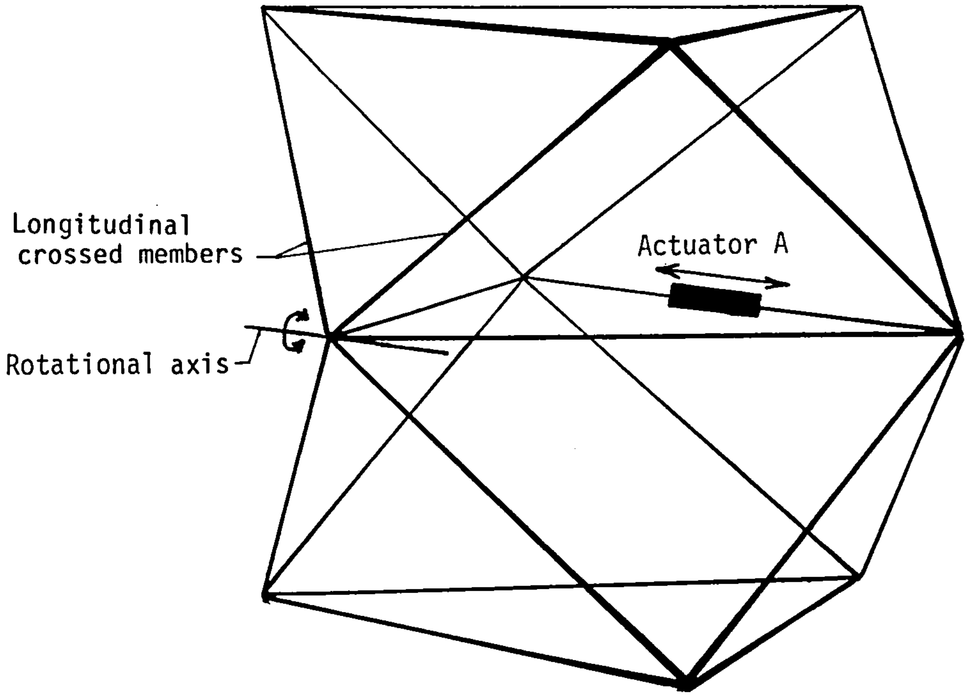
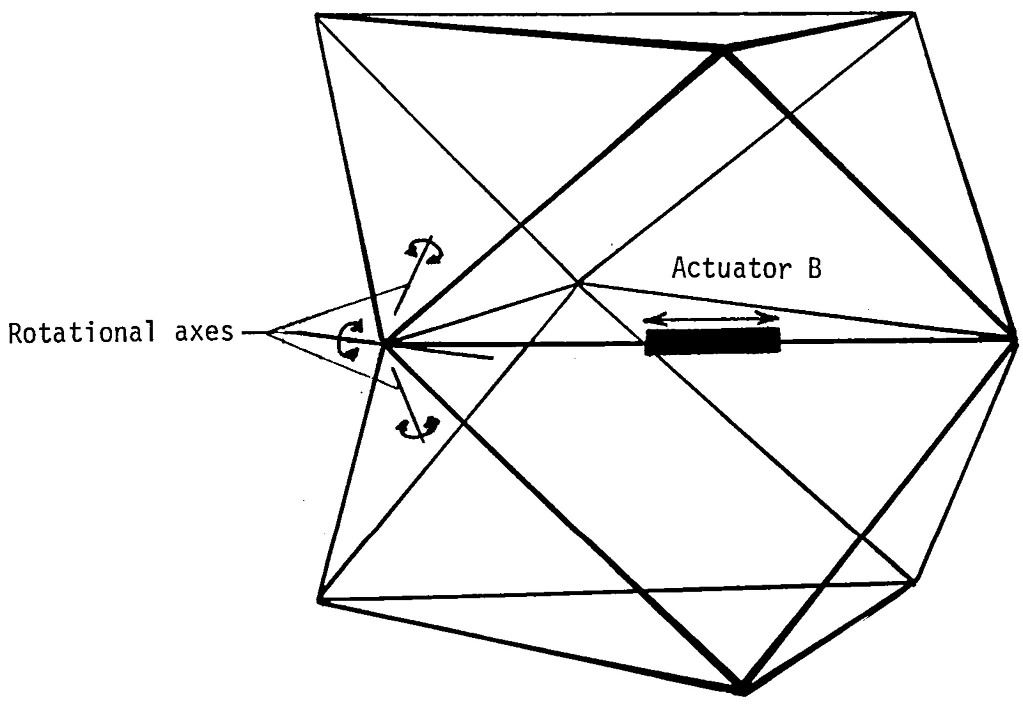
Figure 2. Conceptual model of controllable geometry truss beam structure in packaged configuration.



(a) Joint rotation requirements caused by changes in actuator length by actuator opposite joint.



(b) Joint rotational requirements due to changes in actuator length by actuator adjacent to joint.

Figure 3. Definition of actuator frame joint rotational requirements.

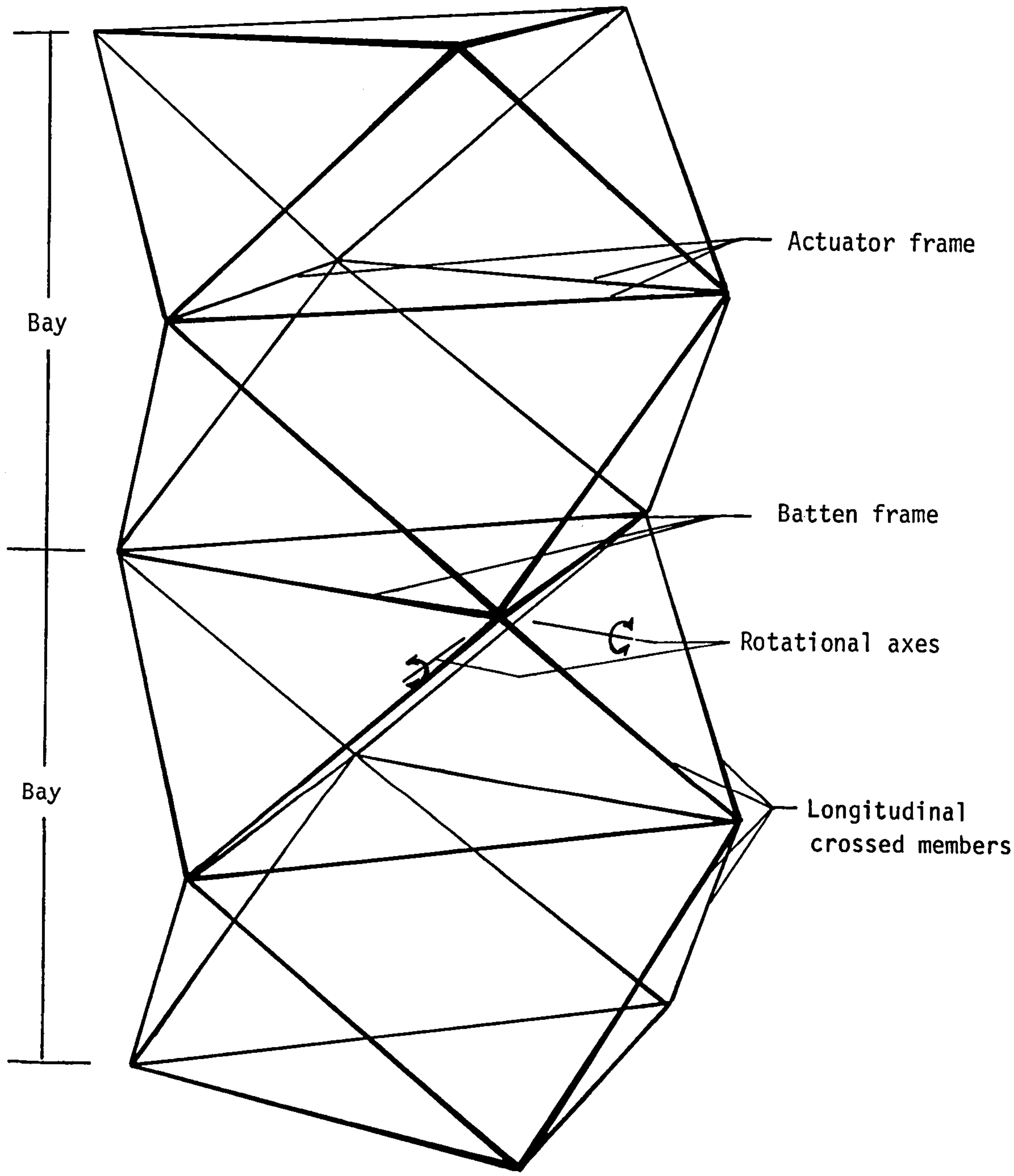
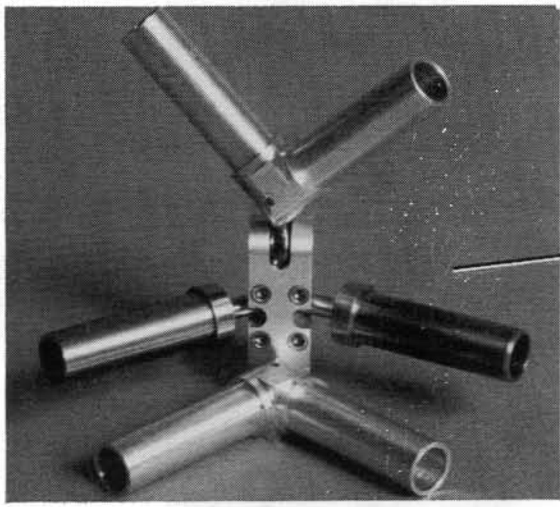
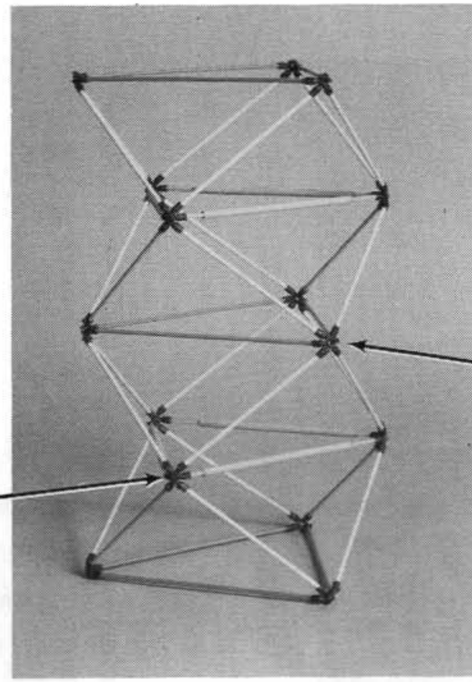


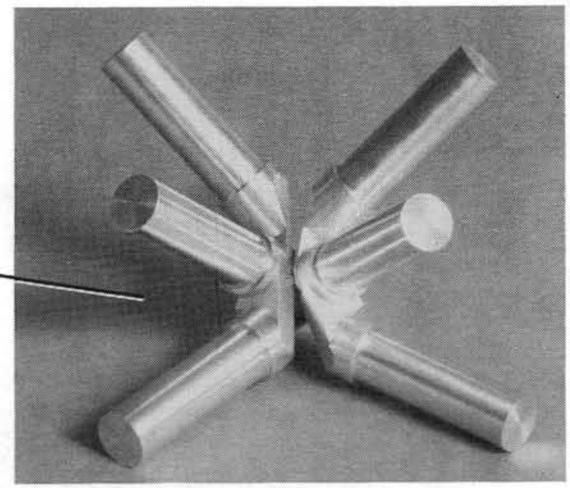
Figure 4. Definition of batten frame joint rotational requirements.



Actuator frame joint



Two-bay truss conceptual model



Batten frame joint

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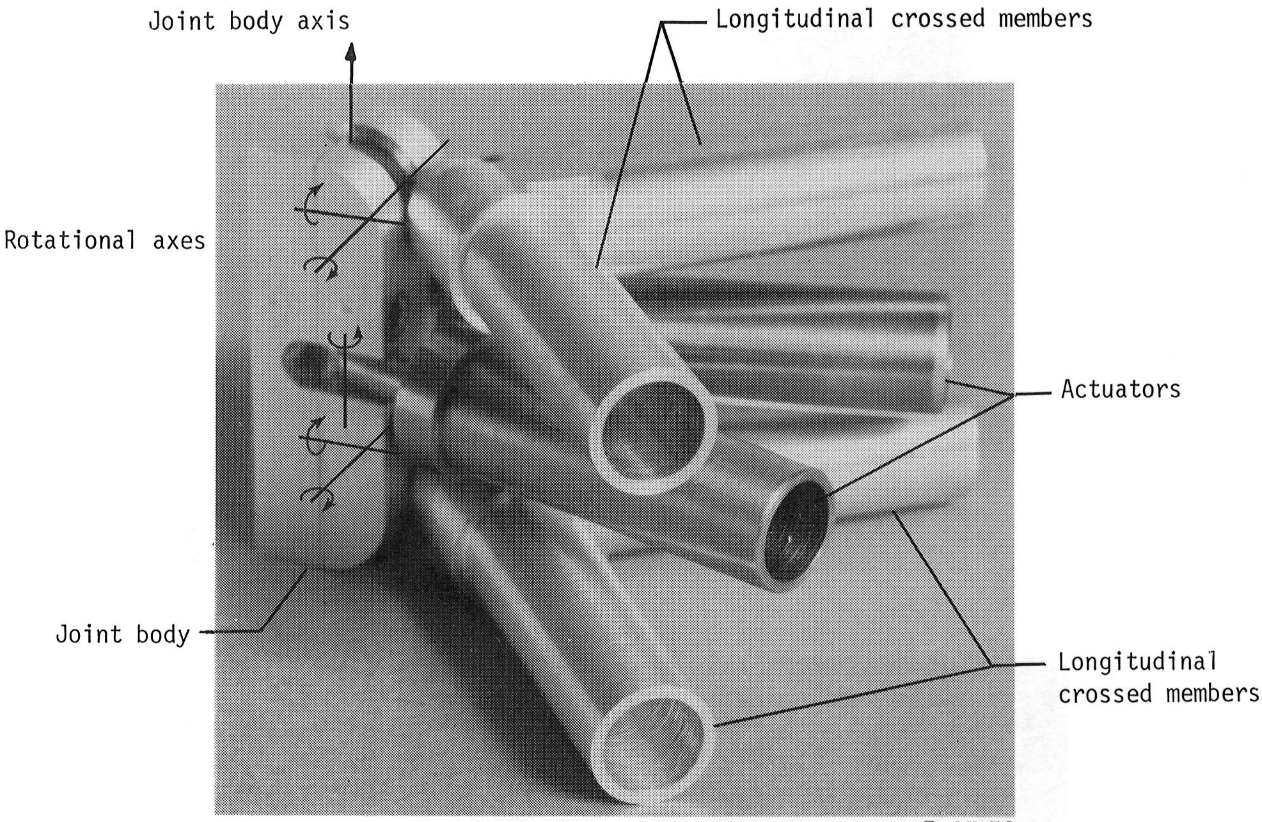
(a) Conceptual model and joints.

Figure 5. Development models of joints for geodesic truss beam.



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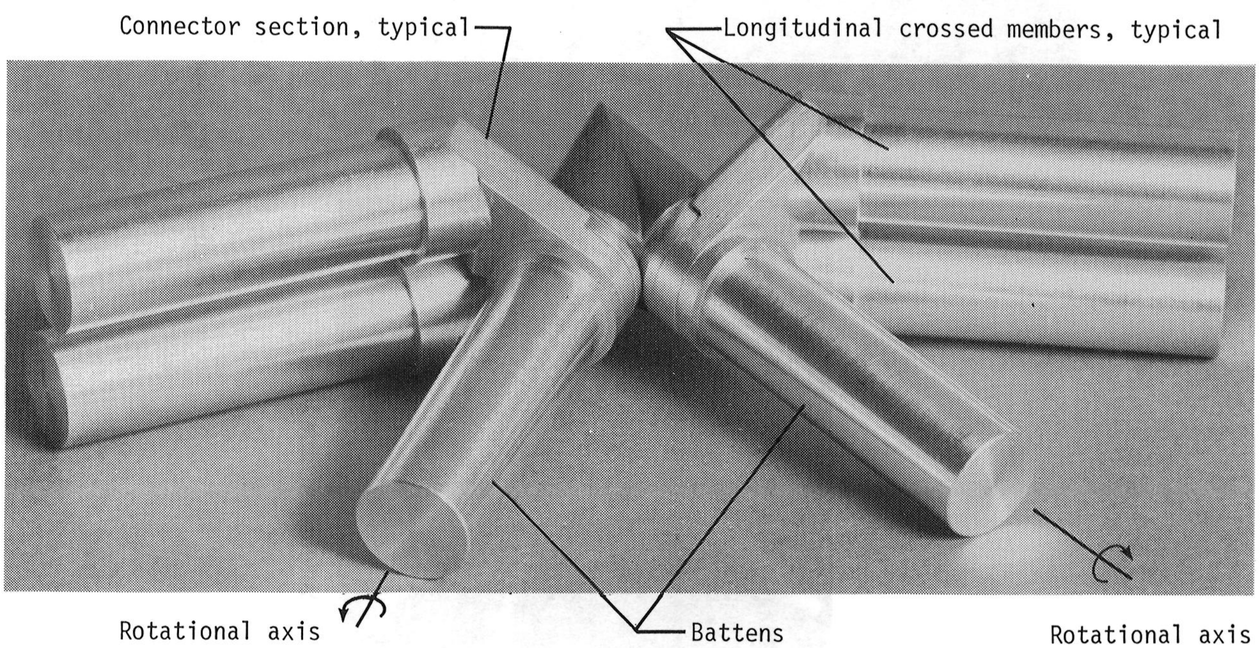
(b) Typical actuator frame joint.



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(c) Typical batten frame joint.

Figure 5. Concluded.

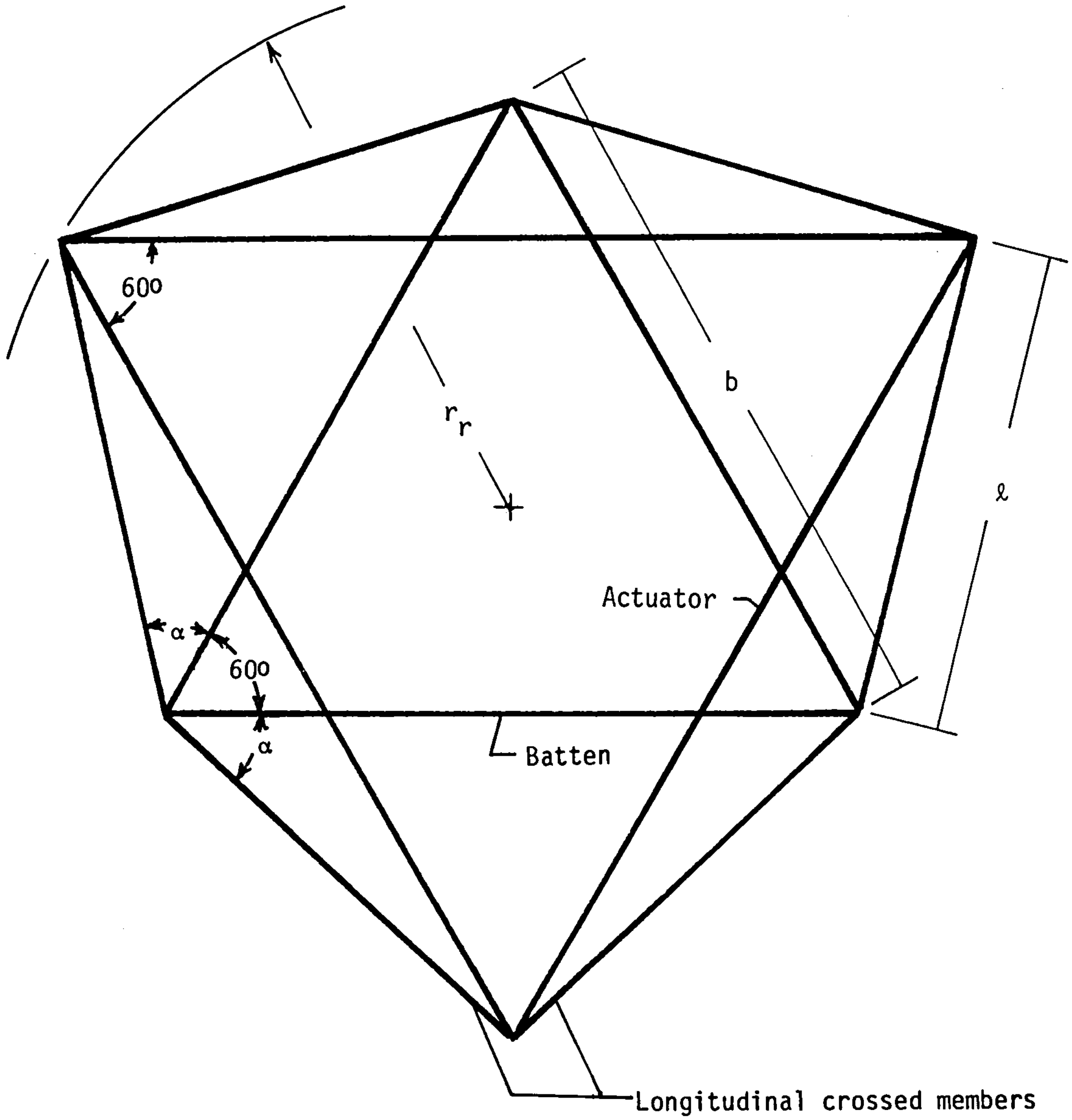


Figure 6. Top view of retracted geodesic beam truss.

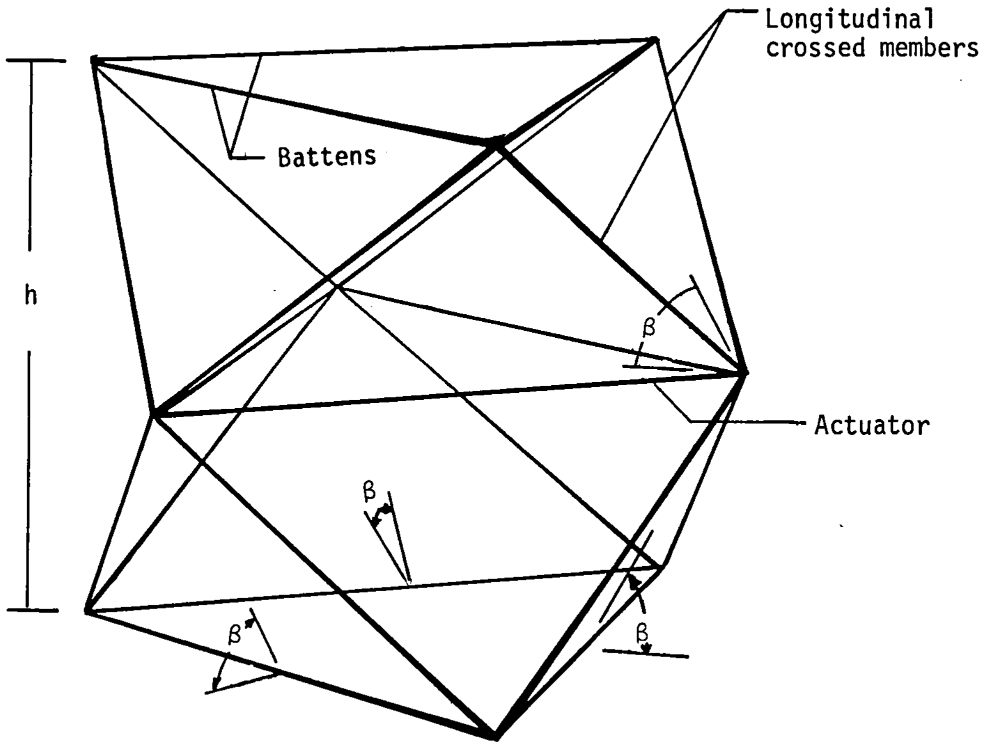


Figure 7. Sketch of geodesic beam showing uniform axial deployment.

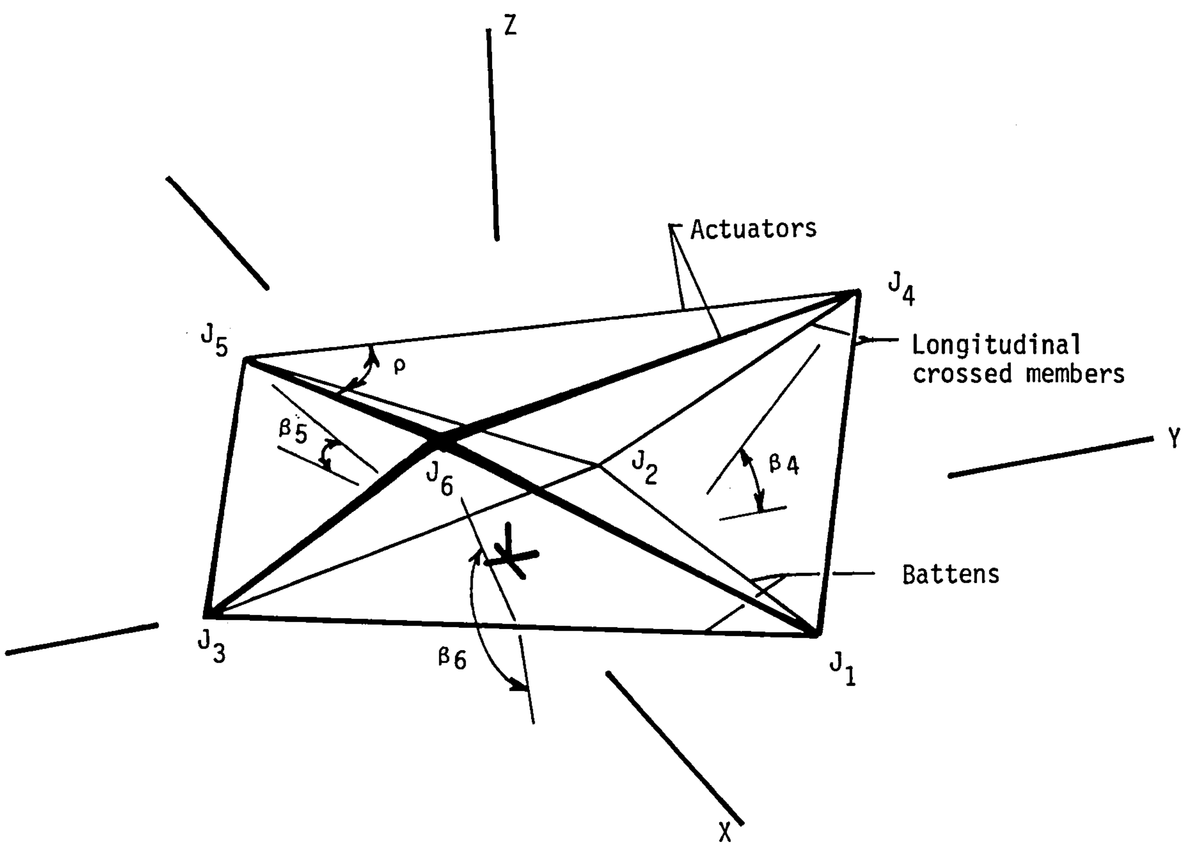
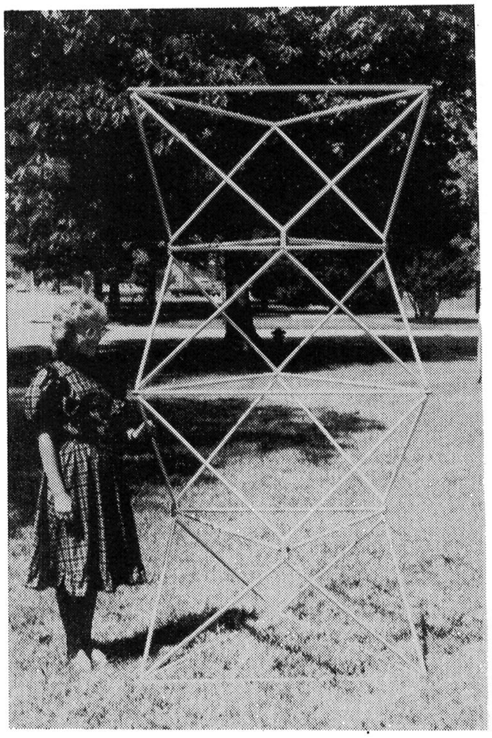
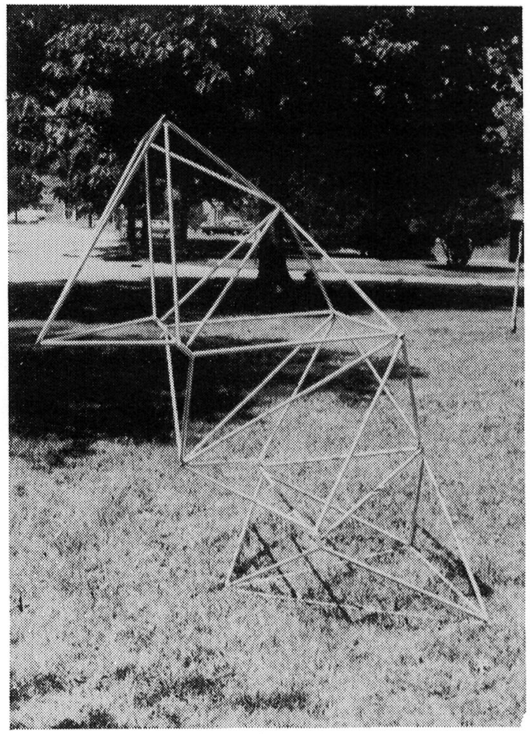


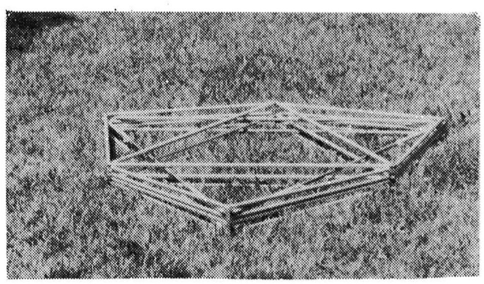
Figure 8. Typical half-bay of truss beam during serpentine deployment.



(a) Model deployed axially.



(b) Model showing typical serpentine operation.



(c) Model retracted.

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Figure 9. Photographs of development model of geodesic truss beam.

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15. Supplementary Notes

16. Abstract

A study has been conducted on a truss beam structural concept that can deploy and maneuver in a serpentine manner to align or position the truss beam tip. The truss beam is composed of a series of rod members connected together at joints that provide the required rotational degrees of freedom. The current study was conducted to evaluate the requirements of the joints and define a mechanical assembly that could provide both high structural stiffness and the required maneuverability. The truss beam requires two joint types; both types were fabricated and incorporated in a demonstration model. An analysis of the concept was also performed to define the location and orientation of the beam tip during deployment and serpentine maneuvers.

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