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Robotic Assembly of Truss Beams for Large Space Structures

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The paper describes an automated approach to constructing the major building blocks of large truss structures in space. Such an approach is necessary because manual construction in space is presently too time consuming, labor intensive, and hazardous to be practical. The paper initially identifies truss beams as fundamental building blocks of much larger structures within the general Coppatruss system. Automated construction of such building blocks reduces the problem of erecting large structures in space to that of connecting truss beams together, a task readily suited to telerobotic operations. The paper then describes a robotic apparatus and process for assembling truss beams of square and equilateral triangular cross section. The assembly system consists of 1) a frame feeder (FF), which continuously feeds protoframes, (PF, the basic building block of the beams); 2) an internal diagonal strut feeder (IDSF), which feeds internal diagonal struts (IDS), required for square section beams only; 3) a robot assembler, which picks up PFs and IDSs from the FF and IDSF, respectively, and transfers and assembles them to the beam; and 4) a frame-holding fixture, which fastens protoframes to the truss beam, holds the beam securely during construction, and advances it upon completion of the current beam bay. The construction of a square section beam is described.

Nomenclature

A, B, C	= protoframe struts (Fig. 1)
A', B', C'	= protoframe vertex fittings opposite struts A, B, and C respectively (Fig. 1)
AE, BE, CE	= end struts corresponding to A, B, and C struts, respectively; used to close beam ends
c, s	= length of side of protoframe triangle made up of strut centerlines and corresponding to struts C and both A and B, respectively
$F\,m\text{–}n$	= protoframe designator, where m is the assembly sequence number of the frame in a given bay of the beam and n the sequence number of the bay within the beam
H	= edge length of square beam cross section through strut centerlines
N	= number of beam bays
x, y, z	= assembly system orthogonal axes (Fig. 6)

Introduction

IN previous papers and patents[1–11] the author has described a general, three-dimensional truss system (Coppatruss) that offers great potential for constructing very large structures in space. The unique geometrical basis of the system—the 60, 90-deg close-packing tetrahedron—imparts to it an outstanding combination of such characteristics as optimum structural efficiency, design and construction modularity, great architectural variety, reusability, and ease of construction.[1] Such properties ensure high performance for derived large truss configurations such as those previously described.[2] Efficient, practical construction of even highly desirable configurations in space, however, is dependent on providing rapid, essentially labor-free methods of assembling them. Several such approaches leading to the present paper have been studied.[5,6,9] They were greatly aided by two key developments: 1) Identification of truss beams as fundamental building blocks of larger trusses and 2) invention of triangular frames as basic assembly elements of the truss beams.[3]

Development (1) proceeds from the geometrical basis of the system, the 60, 90-deg tetrahedral cell. Such cells can completely fill space in perfect register and with their vertices in contact with their neighbors everywhere. When such a filled region of space is viewed along a first characteristic direction, it is seen to consist entirely of triangular prisms of equilateral cross section. When viewed along a second characteristic direction only square section prisms are revealed. There are four such first directions and three second directions. If instead of solid cells, their corresponding wire frames are considered, the respective prisms are reduced to triangular and square section truss beams. It is evident, therefore, that within such a space, various segments of triangular and/or square section truss beams can be selected in connected arrangements so as to comprise a great variety of larger structures.[2] Thus, the individual truss beams can be viewed as being building blocks of more complex structures.[10]

Development (2) results from the effort to depart from the conventional method of assembling trusses from individual struts and node connectors. Employing prefabricated triangular frames for assembly elements results in reducing the number of assembly parts by a factor of three and connection operations by a factor of four. It also simplifies the handling and orientation of parts during assembly and reduces the complexity of robotic apparatus and operations. The frames, called protoframes (PF) are derived from the faces of the generic tetrahedral cell. They are composed of integrated struts and vertex fittings and contain all hardware for connecting adjacent frames together.

PFs are of two types, one used for constructing square-section beams and the other for triangular-section beams. They differ only in the configuration of their vertex fittings, but otherwise they share a common strut centerline geometry. A typical PF, shown in Fig. 1, consists of two struts, A and B, of equal length, s, and a third strut, C, of length $2s/(3)^{1/2}$, all rigidly joined together by their vertex fittings.

Protoframe Assembly Features

The PF vertex fittings possess design features that facilitate automated assembly. The fittings, situated at the PF vertices, are of three different types, A', B', and C', which are positioned opposite struts A, B, and C, respectively (Fig. 1). PFs are so arranged in a truss beam that the vertex fittings of three adjacent frames are connected together to form a typical node of the beam. Thus, the node is composed of a given fitting, A', of one PF, connected to both the C' fitting of another PF and a B' fitting of a third PF. A representative node of a square-section truss beam is shown in Fig. 2, with the C' fitting situated between A' and B' fittings, with the latter at its left and right respectively. An exploded view of the node is shown in Fig. 3. To attach the frames together the pin (or an equivalent fastener) of the B' fitting is passed through the hole in the connector

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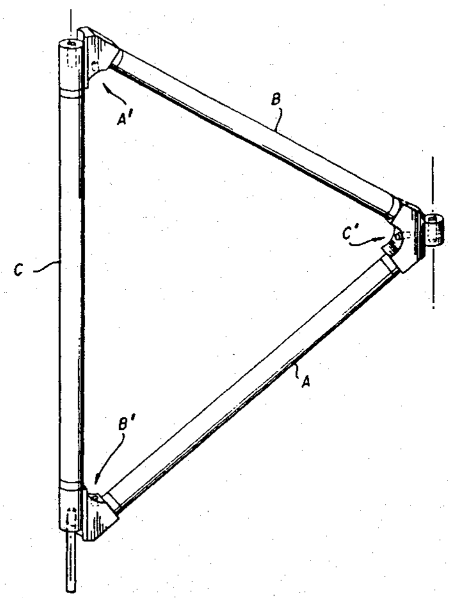

Fig. 1 Protoframe: basic building block of the truss beam.

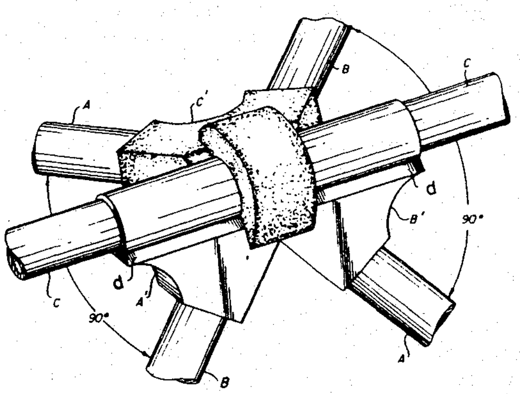

Fig. 2 Typical beam node (junction of three protoframes).

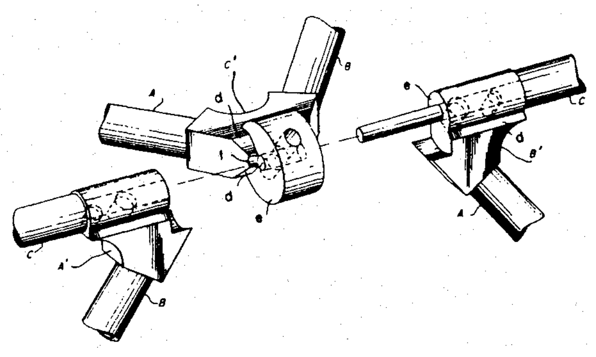

Fig. 3 Typical beam node (exploded view).

portion of the C' fitting and into the socket of the A' fitting until solid contact is made among their respective mating surfaces. The node is secured by tightening the lock screw in the A' fitting firmly against the pin. The mating surfaces referred to here include the bevel surfaces, d, of fitting C' with those positioned on the opposite sides of fittings A' and B', as well as the axial bearing surfaces, e. The beveled surfaces help guide the pin during the insertion process and contribute to node rigidity.

Although the A', B', and C' fittings differ from one another, they are easy and economical to fabricate. This is because they are made at once from a one-piece "master fitting" rather than individually.[4] As a result, mating surfaces and through-holes that in the final assembly of the resulting three fittings must be well matched and aligned are easily produced on the one-piece master. Once fabrication of the master fitting is complete, it is cut into three parts to yield the A', B', and C' fittings.

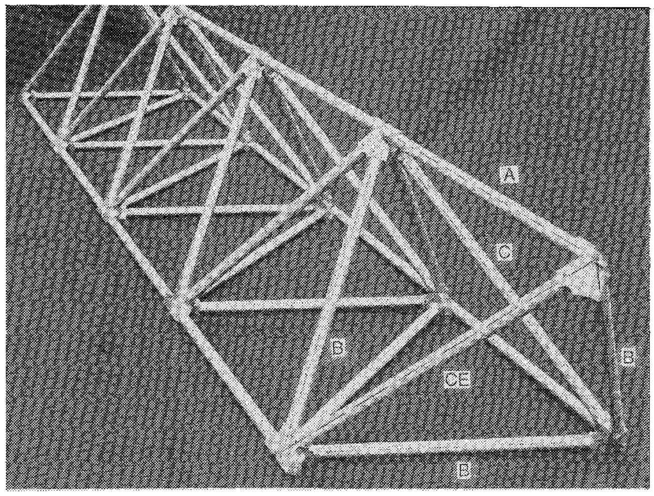

Fig. 4 Triangular section (type T) truss beam.

Figure 3 also helps to illustrate the relatively simple procedure involved in assembling frames together. In the beam-building process, the PFs associated with fittings A' and C' are already in the positions shown in Fig. 2, although not yet attached together. In the process of bringing the B' fitting into final position and securing it to the A' fitting, the PF associated with the B' fitting is thereby added to the truss beam. This is discussed later.

Description of Truss Beams

Triangular Section Beam

The triangular section or Type T beam, shown in Fig. 4, is composed of $3N$ protoframes and three end struts, where N is the number of bays. A bay is defined as the shortest length of the beam having a protoframe in each lateral face. The dashed lines in the forward bay of the beam show the basic tetrahedral cell situated on the centerlines of the struts and the centerlines as intersecting at the centers of the nodes. The beam longerons are composed entirely of A struts. The B struts form a continuous helical chain that runs along the beam lateral faces (chains may be either right or left handed). The beam length is equal to Ns. The beam contains 12 protoframes and is closed by one CE end strut at the forward end and two BE end struts at the rear end.

The end struts tie the otherwise free vertex fittings of the end PFs, and thus enable the truss to bear load. A beam assembled without end struts is called a beam segment. Such segments can be readily joined to form longer segments by connecting their left and right ends together. The same applies to square section beams.

Square Section Beam

A square section or Type S beam segment is composed of $4N$ protoframes and $2N$ internal diagonal struts (IDSs, having the same length as C struts). A complete beam has an additional IDS and four end struts (same length as A and B struts). As in the Type T beam, the centerline geometry of the Type S beam is in the form of a continuous pack of tetrahedral cells. The beam longerons are composed entirely of C struts. The A struts form two continuous helical chains, and the B struts form two similar chains of opposite sense that run along the beam lateral faces. The beam length depends on the end shape, the length of a square-ended beam being equal to $2s/(3)^{1/2}(N + 1/2)$. The incomplete beam of Fig. 5 is depicted as having 16 PFs, 8 IDSs, and two AE end struts at the right end.

Basic Assembly Process

Before discussing the robotic assembly process, we describe the manner in which the PFs and struts are assembled together to form the first bay of the Type S beam shown in Fig. 5. The PFs are designated by F m–n, where m and n are numbers that identify the order in which frames and bays are assembled. For example, F 1–1 represents the first PF of the first bay to be assembled and F 2–2 the second PF of the second bay. For Type S beams, $m = 1, 2, 3, 4$, and for Type T beams, $m = 1, 2, 3$. Assembly of end

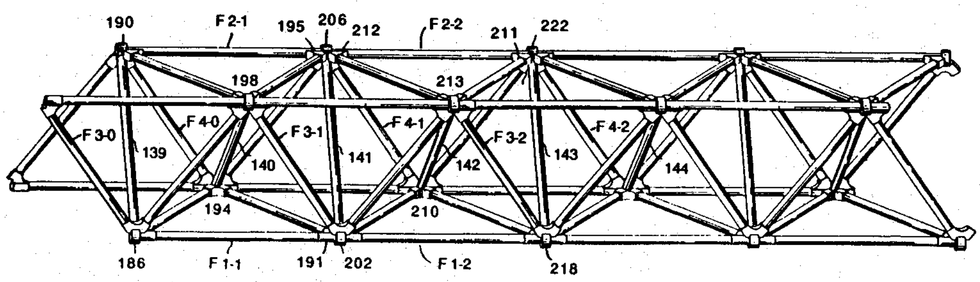

Fig. 5 Square section (type *S*) truss beam.

Table 1 Item numbers of square section beam frame entities

PF No.	PF Item No.	*FFI* No.			
		$A'\,VF$	$B'\,VF$	$C'\,VF$	Connector
*F*3–0	119	183	184	185	186
*F*4–0	120	187	188	189	190
*F*1–1	121	191	192	193	194
*F*2–1	122	195	196	197	198
*F*3–1	123	199	200	201	202
*F*4–1	124	203	204	205	206
*F*1–2	125	207	208	209	210
*F*2–2	126	211	212	213	214
*F*3–2	127	215	216	217	218
*F*4–2	128	219	220	221	222

struts is included by considering them here as parts of a nonexistent bay ($n = 0$).

Construction begins at the left end of the beam by placing end struts $F3$–0, item 119, and $F4$–0, item 120, in their assembly positions. These designations of end struts as frames is used to preserve their identity and clarify their relationship with other PFs of the beam. Each of the struts is of type BE and corresponds to a to protoframe B strut together with its associated A' and C' vertex fittings. The BE struts thus provide two A' fittings, which contain the sockets for connecting the beam nodes at connector sites 194 and 198 together, and two C' fittings for securing the B' vertices of frames $F1$–1 and $F2$–1, as well as an IDS, item 139. Next, the latter IDS is assembled to the connectors, items 186 and 190, of the C' fittings of struts $F3$–0 and $F4$–0 respectively. This is followed by assembly of frame $F1$–1 whose connecting pin of its B' fitting is passed through the hole in the C' fitting, item 185 (see Table 1), of strut $F3$–0 to which it is secured. Likewise, frame $F2$–1 is connected to the C' fitting, item 189, of strut $F4$–0. In the same action of assembling these PFs to the beam, their C' fittings, items193 and 197, are brought into nested contact with but not connected to the A' fittings, items 183 and 187, of struts $F3$–0 and F 4–0, respectively. Next, IDS 140 is brought to the assembly site and attached to the C' fitting connectors, items 194 and 198, of frames $F1$–1 and $F2$–1. This is followed by assembling frame $F3$–1, by securing the connecting pin of its B' fitting to the socket of the A' fitting of strut $F3$–0 and bringing its C' fitting into nested contact with the A' fitting of frame $F1$–1. Similarly, frame $F4$–1 is assembled to the beam, thereby completing construction of the first bay.

Additional bays of the beam are constructed in a similar manner, beginning with the attachment of IDS 141 to the C' fitting connectors of frames $F3$–1 and $F4$–1, and the beam itself is completed once the desired number of bays has been assembled and the two AE struts and final IDS attached at the right end.

Robotic Assembly System

The robotic assembly system accomplishes the following functions: 1) feeds the PFs, IDSs, and end struts from fixed sites; 2) transfers them to the assembly sites; 3) assembles and attaches them to the truss beam; 4) advances the beam upon completion of each bay; and 5) supports the base end of the beam at all times during construction.

The assembly apparatus, shown in Fig. 6, includes the robot assembler (RA), frame-holding fixture (FHF), frame feeder (FF), and internal diagonal strut feeder (IDSF). In the system considered here, one RA, four FHFs (three for Type T beams), one FF, and one IDSF are used to build a Type S beam. The functions of the RA are to pick up PFs and IDSs (one at a time) from the FF and IDSF sites, orient them properly for assembly, move them to their respective assembly sites, assemble (but not fasten) the frame and end struts, assemble and connect the IDSs to the existing beam, and help support the beam when required. The functions of the FHF are to hold an already assembled frame (or end strut) in place, fasten it to the beam, and together with the other FHFs, advance the beam a distance of one bay length upon completion of the current bay construction. The FF and IDSF, situated at fixed locations relative to the beam, store a limited quantity of PFs, and IDSs, respectively, and present them for pickup by the RA. Frames and IDSs are continuously fed to the FF and IDSF, thereby providing an uninterrupted assembly operation. The system is referenced to orthogonal axes x, y, and z, whose origin is at the base end of the truss beam at its cross-sectional center, as shown in Fig. 6. Positive directions of the axes are indicated by the arrows.

Robot Assembler

The RA shown in Fig. 6 consists of the following components: the main arm (3), protoframe assembler (4), and IDS assembler (5). The main arm has post and boom portions that comprise a low mass, rigid structure. The post (1) is coaxially mounted to a pedestal (6), which can translate in the z direction relative to a base (7), which can translate in the x direction. The arm can translate in the y direction by extending from the pedestal along the common post/pedestal centerline axis (8), which is parallel to the y axis. The central axis (9) of the boom (2) is parallel to the z axis, and in its nominal position is also coincident with it.

The frame assembler (4) comprises a column (10) and a frame gripper (11). The column is mounted with its central axis (12) perpendicular to axis (9) and can rotate about axis (9) in either direction. The column consists of a hollow cylinder (13) an internal shaft (14), and a means of moving the shaft relative to the cylinder. The shaft and cylinder are concentric with axis (12), and the shaft can translate along axis (12) in either direction. The frame gripper consists of the wrist joint (15) and gripper hand (16).

The frame gripper hand (16) shown in Fig. 7 consists of a rigid three-spoked structure (17) that is connected through a central hub to the frame assembler wrist joint (15). Gripper fingers (18) are rigidly attached to the ends of shafts that are concentric with the spokes so that the fingers can translate along their common axes (19) in either direction through equal distances or strokes. The gripper fingers are specifically shaped to conform to surface features in the fillet regions of each of the PF vertex fittings (grip receptors 20 and 21) so as to be able to engage the fittings securely and subsequently disengage from them.

When the frame gripper is in position to pick up a protoframe from the FF, the gripper fingers are in their retracted condition. The gripper engages the frame when the fingers are extended to make firm contact with the grip receptors (20), called the FA receptors (frame assembler receptors). This action results in securely holding the PF centered and perpendicular to the FA axis (12). The detail view in Fig. 7 shows a typical gripper finger occupying the FA gripper receptor. This leaves an unoccupied receptor site in the other half of the fillet thickness. The latter site is called the FHF receptor (21) and is used for holding a PF in the FHF. Summarizing the use

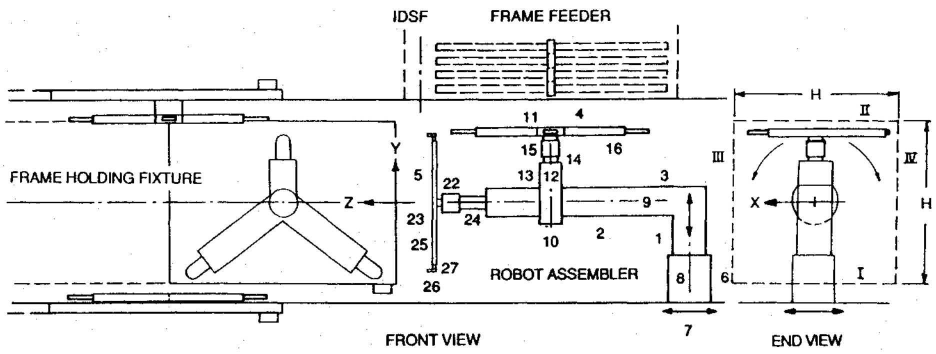

Fig. 6 Robotic assembly system apparatus.

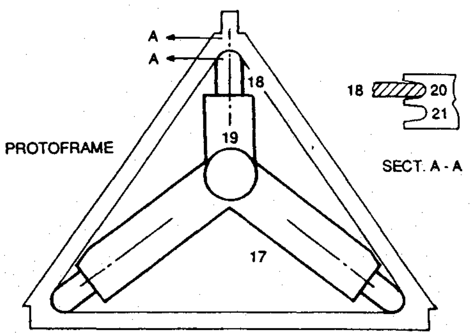

Fig. 7 Frame gripper hand (shown with protoframe).

of these receptors, the fillet region of each PF vertex fitting provides two identically shaped grip receptor sites, namely, the FA receptor used during protoframe pickup from the FF, delivery to the assembly site, fastener insertion, and release to the FHF at the assembly site; and the FHF receptor used during holding and fastening the PF in place, beam advance, and beam release.

The IDS assembler consists of a wrist joint (22) and the IDS gripper hand (23) (wrist joints 15 and 22 may have 3 deg of rotational freedom). The wrist joint (22) is connected to the boom of the main arm via a shaft (24) whose central axis lies along axis (9) and which can translate along axis (9). As shown in Fig. 6, the IDS gripper hand has a central beam (25), which supports two grippers (26) at its extremities. The basic function of the grippers is to grasp and release the IDS. The U-shaped grippers are rigidly attached to the ends of shafts (27) that are concentric with the beam and can translate along their common axis in either direction through equal distances (or strokes). The grippers are specifically shaped to conform to surface features in the IDS end connector shoulder regions.

The principal operations of the RA are as follows. The frame gripper (11) grasps the current protoframe from the FF, and with appropriate motions of the main arm (3) and frame assembler (4), delivers the frame to the assembly site. The frames in the FF stack are so positioned and oriented that appropriate translations in the $+z$ direction and $-y$ directions would bring them into coincidence with the frames in face plane II (situated at $y = H/2$, where H is the beam section edge length) shown in Fig. 6. To place frames in planes parallel to face planes I ($y = -H/2$), III ($x = H/2$), and IV ($x = -H/2$), however, requires an additional rotation about axis (9) of 180, −90, and 90 deg, respectively. This is accomplished by rotating the frame assembler about the axis (9) and then bringing axis (9) into coincidence with the z axis. Such rotation and translation positions the PFs properly for assembly to the beam at their respective places.

Prior to rotation of the frame assembler, the main arm may have to translate on the $-y$ direction to provide sufficient clearance to permit the current frame to clear the FF during its swing. Subsequent to rotation the main arm translates in the x, y, and z directions according to the requirements of the particular frame to deliver it to the beam assembly site. Additionally, the frame assembler accomplishes the insertion of the B' fitting fastener pin of the current frame into the through-hole and socket respectively of the C' and A' fittings of the associated previously assembled frames, thereby completing the assembly of the node there. The fine alignment of the current frame during the final stage of its assembly and particularly the pin insertion operation are facilitated by the robotic capabilities of the wrist joint (15), as well as those of the main arm and pedestal.

The IDS assembler operates as follows. Prior to engaging the IDS, the grippers are in their open position, in which the distance between them is greater than the distance between their corresponding mating sites on the IDS. The IDSF positions the IDS close to the nominal position: that is, with position and orientation within the mating tolerances. The orientation position error of the IDS is accommodated and corrected by means of the flared inner contour of the grippers as the IDS assembler advances toward the IDS, and the grippers encompass and finally seat against the IDS end connector pins. The grippers then move to their closed position and nest into the contours present in the end connector shoulders, and thereby move the IDS to the required centered position. During the latter movement, the IDSF transfer arm continues to hold the IDS so as to guide it and permit it to slide under the action of the IDS assembler grippers. In its final position, the IDS is centered relative to the z axis and firmly grasped near each of its ends. Subsequent y and z translations of the main arm and rotation of the wrist joint (22) by ±45 deg bring the IDS into proper alignment with and orientation about the beam centerline for attachment to the C' fittings of appropriate PFs, previously assembled to the beam. Various specific designs are possible for connecting the IDS to the vertex fittings, a preferred method involving side-entrance; that is, one in which the IDS ends engage the C' fittings as a result of a simple thrust in the z direction, with the fastening accomplished by means of quick-connect joints. However, the basic design of the IDS assembler; that is, its employment of assembly devices located near the ends of the IDS, permits consideration of other joining options.

Frame-Holding Fixture

The-four FHF units that are required in the assembly of a Type S beam are arranged about the beam cross section and equidistant from the beam central axis. Each FHF unit is parallel to and directly opposite the beam face site with which it is associated. FHF1, for example, is that particular fixture situated in a plane parallel to face I of the truss beam and external to the beam cross section; initially, it is directly opposite protoframe $F1$–1. Similarly, FHF2, FHF3, and FHF4 are situated relative to face planes II, III, and IV, respectively. The FHFs are supported on their exterior side by the workspace structure.

As shown in Fig. 8, the individual FHF consists of a baseplate (24), which supports a protoframe holder (25) and a fastening unit (26). The baseplate, as well as those of the other FHFs, is connected to the external structure via sets of tracks and keyways (27) that are parallel to the beam axis. These permit each FHF unit to translate independently of the others along the z direction. This motion is produced by the FHF actuator mechanism (28), which precisely controls the axial position of the individual FHF. For present purposes, a ball screw actuator is assumed, but other types might be more appropriate to increase assembly speed. The actuator is located on the baseplate near the C strut edge of the protoframe associated with the particular FHF. This arrangement results in less eccentricity

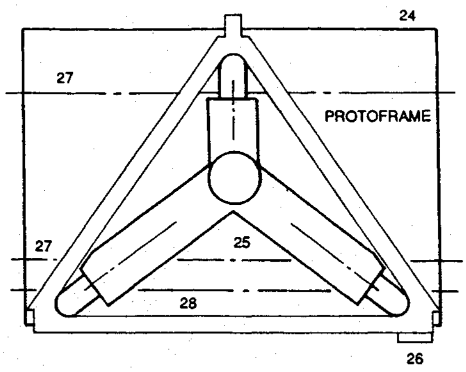

Fig. 8 Frame holding fixture (shown with protoframe).

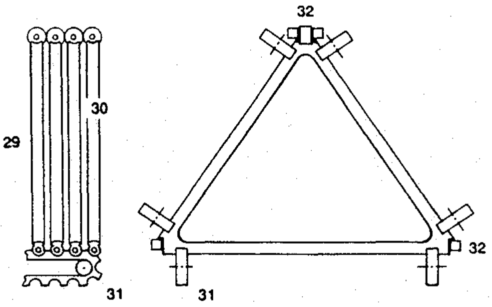

Fig. 9 Frame feeder.

between the fastener insertion force exerted by the RA and the reaction by the actuator. The frame holder is similar in design and operation to the frame gripper of the RA.

The operation of an individual FHF is as follows. Immediately prior to the delivery of a protoframe, for example $F1$–2 in Fig. 5, to the assembly site by the RA, FHF1 is holding fast to $F1$–1. Upon delivery of $F1$–2 to the assembly site, the RA inserts the fastening pin of the B' fitting of $F1$–2 into the socket of the A' fitting of $F1$–1 and holds the frame in its correct position in the beam. At this point, the fastening unit of FHF1 locks the pin in that socket. FHF1 now releases its hold on $F1$–1, strokes in the negative z direction into correct position to engage frame $F1$–2, and grips it. Once this has occurred, the RA releases its grasp of $F1$–2 and proceeds to pick up the next part to be assembled to the beam. In addition, the four FHFs act in unison to advance the beam along the z axis in the positive z direction by one bay length once construction of a bay has been completed.

It is noted that the processes of acquiring a PF from the FF by the RA frame assembler and subsequent release of the frame to and acquisition by the FHF frame holder are identical and utilize identical hardware and controls. Another important feature of these processes is that the robotic capabilities of the RA are at work during both frame transfer procedures to facilitate the various mating, release, and acquisition operations. This feature relieves the FHF frame holder of the robotic complexity that would otherwise be required of it. It also results in simplification of the system and use of common hardware, controls, and operational procedures.

Protoframe Feeder

PFs are fed to the RA frame assembler by the Frame Feeder (FF). As shown in Fig. 9, the FF consists of the frame stack (29), which is a registered pack of PFs (30) arranged in parallel alignment, feed belts and pulleys (31), and guide posts (32). A total of six belts and four guide posts are used in the system concept to support and guide the PFs in the stacked arrangement throughout the feed operation. Each edge of the PF is supported by two belts located near the associated vertex fittings. The belt thickness is deeply contoured so as to nest the outer half of the strut or vertex fitting cross section. This feature results in holding and maintaining the frames in a registered and parallel arrangement as the belts are caused to move about their associated pulleys during the feed operation. The guide posts are arranged so as to engage available contours on the external surfaces of the vertex fittings. The arrangement of belts and posts on the exterior surfaces of the PFs permits the placing of additional frames onto the inner end of the stack as frames are removed from the outer end, thereby permitting a continuous feed operation. The belts may be either free wheeling or driven.

The operation of the FF is as follows. The outermost frame of the stack is grasped by the frame gripper of the RA frame assembler in the manner described previously. To engage the frame, the frame gripper is extended into the feed stack and the gripper fingers brought into contact with the FA grip receptors. The FA then translates in the negative y direction. For a free-wheeling belt system, the outward thrust of the FA is transmitted by the frames to the belts and pulleys, thereby causing the latter to turn in unison and the frames to advance together along the stack. Thus, the RA provides the motive power to operate the feed stack. This feature results in a considerable simplification of the feed system as compared to one that utilizes driven belts. Another advantage of the free-wheeling system is easy maintenance of stack alignment during the feed operation. This is accomplished by the frame gripper, which once having grasped the outermost frame, aligns it parallel to the xz plane prior to removing it from the stack. This action serves to align the entire stack as well. Any misalignment of the stack that might ensue during the ongoing feed operation is accommodated by the FA robotics, which adjust the position of the frame gripper to engage the FA receptors.

Assembly Process for Square-Section Beams

The robotic apparatus is now applied to assemble a beam segment of the type shown in Fig. 5 (assembly of end struts described under the Basic Assembly Process is omitted for brevity).

1) Referring to Fig. 5, the RA frame assembler picks up frame $F1$–1 from the FF and delivers it to the $F1$–1 assembly site, where it transfers $F1$–1 to Frame Holding Fixture FHF1. FHF1 maintains its hold on $F1$–1, and the RA releases from frame $F1$–1. (Note: Item numbers corresponding to the various frame entities are listed in Table 1.)

2) Similarly, the RA picks up frame $F2$–1 and delivers it to its assembly site. Frame Holding Fixture FHF2, grasps frame $F2$–1 and maintains its hold on it, and the RA releases from frame F 2–1.

3) The RA picks up an IDS, Item 140, from the IDSF and moves it into place for assembly and attaches it to the connectors, Items 194 and 198, of frames $F1$–1 and $F2$–1, respectively.

4) The RA then picks up frame $F3$–1 from the FF and assembles it to the C' vertex fitting (VF), Item 197, of frame $F2$–1 and A' VF, Item 191, of frame $F1$–1. Frame Holding Fixture FHF3, grasps frame $F3$–1 and maintains its hold on it, and the RA releases from F 3–1.

5) Similarly, the RA assembles frame $F4$–1 to the A' VF, Item 195, of frame $F2$–1. Frame Holding Fixture FHF4, grasps frame $F4$–1 and maintains its hold on it, and the RA releases from $F4$–1.

6) The RA picks up another IDS, Item 141, and attaches it to connectors, Items 202 and 206, respectively, of frames $F3$–1 and $F4$–1. The RA releases its hold on Item 141.

7) The condition of the first bay of the truss beam at this point in the assembly process is as follows. Frame $F1$–1 is held fixed by FHF1 and $F2$–1 by FHF2. Frame $F3$–1, is connected to the C' VF, Item 197, of frame $F2$–1 and the A' VF, Item 191, of $F1$–1 and is held by FHF3. Frame $F4$–1 is connected to the C' VF, Item 193, of frame $F1$–1 and the A' VF, Item 195 of frame $F2$–1 and is held by FHF4. IDS, Item 140, is attached to the Connectors, Items 194 and 198, and IDS, Item 141, to Connectors, Items 202 and 206. Thus, the beam bay is rigid and held fixed relative to the workspace foundation.

8) Next, FHF1, FHF2, FHF3, and FHF4, while still maintaining their respective holds on frames $F1$–1, $F2$–1, $F3$–1, and $F4$–1, respectively, are translated (advanced) through a distance equal to one bay length.

9) When the advance is complete, the RA picks up $F1$–2 from the FF and connects it to $F1$–1 and $F3$–1. At this point, the FHF1 releases its hold on frame $F1$–1, retracts to its original position, and grasps frame, $F1$–2.

10) Next, the RA picks up frame $F2$–2 from the FF, connects its B' VF, Item 212, to frames $F2$–1 and $F4$–1, and its C' VF, Item

213, in assembly location adjacent to the A' VF, Item 199, of frame $F3$–1. FHF2 retracts to its original position and grasps frame $F2$–2 and the RA releases its hold of the same.

11) The RA picks up another IDS, Item 142, and attaches it to the connectors, Items 210 and 214 respectively of $F1$–2 and $F2$–2.

12) The RA releases its hold on Item 142 and picks up frame $F3$–2 from the FF and connects its B' VF, Item 216, to the C' VF, Item 213 of frame $F2$–2 and the A' VF, Item 199 of frame $F3$–1 and places its C' VF, Item 217 in assembly location adjacent to the A' VF, Item 207 of frame $F1$–2. FHF3 now retracts to its original position and grasps frame, $F3$–2, and the RA releases its hold of the same.

13) The RA picks up frame $F4$–2 from the FF and connects its B' VF, Item 220 to the C' VF, Item 209 of frame $F1$–2 and the A' VF, Item 203 of frame $F4$–1 and places its C' VF, Item 221 in assembly location adjacent to the A' VF, Item 211, of frame $F2$–2. FHF4 now retracts to its original position and grasps frame $F4$–2, and the RA releases its hold of the same.

14) The RA picks up another IDS, Item 143, and attaches it to the connectors, Items 218 and 222, respectively, of frames $F3$–2 and $F4$–2.

15) Similarly, additional frames and IDSs are assembled to the preceeding portion of the truss beam until the beam assembly is complete.

Conclusions

The assembly process described herein incorporates robotic devices within a basically hard automation-type system. The latter refers to the quality that, except for the dimensional variability and flexibility of the assembly parts, apparatus, and workspace structures, the truss can be assembled as a result of the programmed motions of the RA, IDSF, and FHF. It would seem that the problem of producing the three-dimensional configuration of the truss from individual parts, except perhaps for the protoframe fastening step, can be solved by a deterministic process that does not require employment of sophisticated robotic devices. Given the abovementioned practical realities, however, active robotics will be needed in various particular operations, such as the pickup of PFs and IDSs from the FF and IDSF, assembly and locking of PFs and IDSs to the beam and subsequent transfer of the frames to the FHF.

The overall process, thus, combines hard automation for performing the large translation and rotation operations and robotics for accomplishing the more intricate ones. This should obtain the higher assembly rates usually associated with hard automation for the most time consuming portions of the assembly process and ensure the accurate and reproducible connective operations that are only obtainable with robotics.

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