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Large Space Structure Automated Assembly Technique

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An erectable space structures construction concept has been developed as the basis for designing a truss frame space structure and an assembler that assembles and maintains the structure plus its subsystems, lines, and working surfaces. This concept uses programmed assembly, maintenance, and repair processes based on similar state-of-the-art industrial automated processes. The structure is progressively constructed by the assembler, which is carried through the structure at a constant velocity by means of belt transports that engage the structure at its nodes. An assembler consists of two crawlers joined by an articulated coupling. The forward crawler carries stacks of struts and nodes as well as the assembler arms that assemble the structure. The rear crawler houses most of the control, spares, power, and communication subsystems, and is essential for the truss junction construction process.

General

THE Large Space Structure Automated Assembly Technique (LSAT) concept was developed to provide a starting point for a feasibility examination of fully mechanized space structures assembly and maintenance. The LSAT concept is applicable to structures ranging in size from hundreds to tens of thousands of meters. The truss size and assembler configuration can be scaled up and down to meet specific space structure requirements. Also, the assembly can be reconfigured to meet specific needs such as solar blanket installation, but still using basically the same control, power, transport, and assembly arm subsystems.

In developing the concept, the following general requirements and goals were pursued and found to be achievable:

1) Man-in-the-loop and extra-vehicular activity (EVA) are kept to a minimum.

2) Only available technology is used.

3) The structural system and the assembler are designed for maximum self-repair, maintainability, and malfunction correction.

4) The erection concept is extendable to assembling on-board subsystems, components, lines (electrical and microwave), and working surfaces such as solar blankets and reflectors.

5) Required positioning accuracies and response characteristics of robots and other servocontrolled systems are within the state-of-the-art.

6) Structural efficiency, including strength, stiffness and resonant frequency, are kept as high as possible. Nonoptimum material in the structure is minimized.

7) Ground fit-up is possible for assembly checkout.

8) Construction material is graphite composite or aluminum.

9) Power requirements for assembly is minimized.

The developed concept, generally based on these goals, is used to identify the major problems and critical areas that will influence concept implementation. As the identified design challenges seem to be space extensions of Earth applications of similar state-of-the-art technology, further definitive study is suggested to evaluate the concept's cost effectiveness for specific large space structure applications.

Structural Arrangement

A generic structural arrangement (Fig. 1) is identified as capable of systematic assembly using struts and nodes as the basic construction elements. It consists of trusses that terminate on truss junctions to form triangulated planar truss frames joined by normal and diagonal trusses. Dodecahedral, tetrahedral, and similar truss arrangements could be substituted here. Platforms could also be constructed of side-by-side trusses with common intermediary truss planes.

A typical truss configuration, constructed of struts and nodes, is shown in Fig. 2. The struts can be tapered columns (as shown) or constant cross-section members. A truss is a sequentially repetitive assembly of longitudinal, diagonal, and cross struts. The relative orientations of these three struts are identical on the three faces of the truss structure.

The truss junction construction (Fig. 3) provides fixity, or structural continuity, and internal passageway between

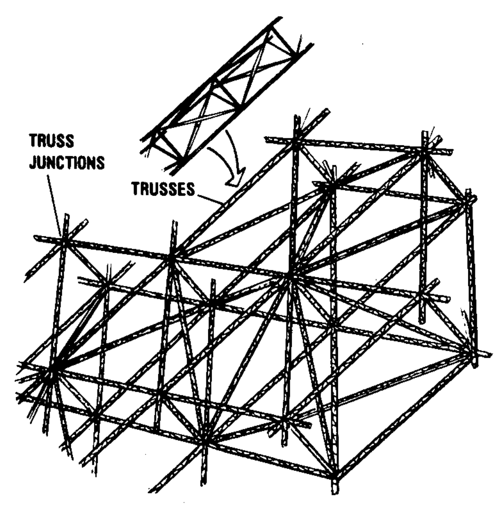

Fig. 1 Truss arrangement.

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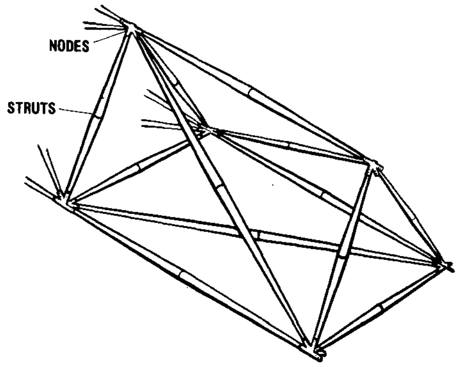


Fig. 2 Truss construction.

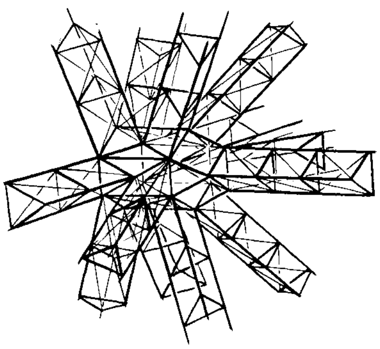


Fig. 3 Truss junction construction.

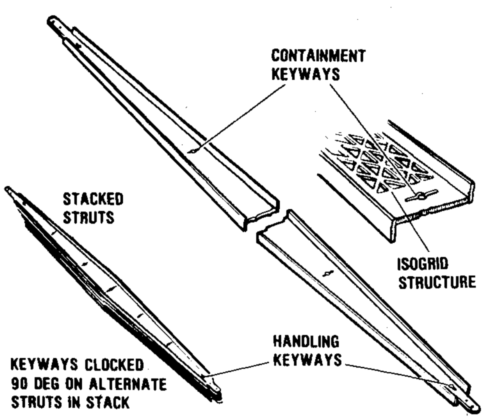


Fig. 4 Fixed-geometry strut.

trusses. The latter feature is exploited in the structure erection process to be described.

Struts

A typical fixed-geometry strut (Fig. 4) is shown as a tapered 2-4 mm thick Z-section open isogrid column which can be nested normal to its longitudinal axis. The open isogrid contributes to maximizing the percentage of see-through area and hence minimizes the thermal gradients in the structure. Other fixed and variable geometry strut configurations are possible. Closed, more efficient strut cross sections can be obtained with laterally stackable, variable-geometry (deployable) structures. Fixed-geometry closed-cross-section struts may also be used, if the available stowing volume is adequate and the allowable strut packaging density can be low. The forward crawler can hold enough nested tapered Z-section columns to build 1400 times the length of one longitudinal strut.

The ends of the strut are shown in Fig. 4 as bayonet blades with holes for pinning the strut to nodes. In the selected

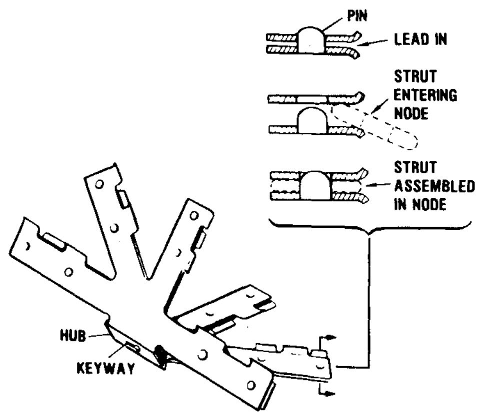


Fig. 5 Node used in truss assembly.

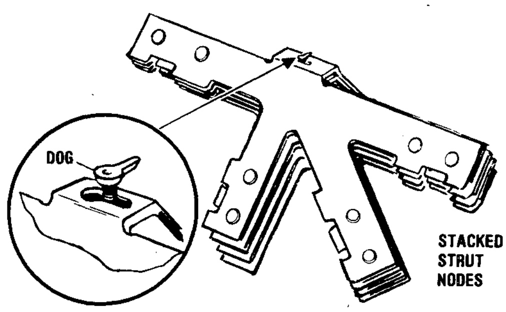


Fig. 6 Stacked nodes.

assembly approach to be described, attachment of strut ends to a node depends on lateral displacement of the strut with respect to a line between two node legs to which the strut is to be attached.

Note that the strut (Fig. 4) contains keyway slots which are used for stowing and handling the strut.

Nodes

Figure 5 shows the common nestable node used in the truss assembly (Fig. 2). This node consists of a solid hub and six springable legs, including detent pins into which the strut ends can be inserted by prying, as shown. Spotwelding, bonding, or other means may be used in place of, or in addition to the pinning, to attach the struts to the nodes. The legs include lead-ins to minimize the necessary alignment between struts and nodes at assembly.

In addition to providing structural continuity between struts, the hub is also used for reacting all inertial and assembly loads generated by the assembler or applied externally to the completed structure. Hubs are accessible for gripping from both the inside and outside of the truss and truss junction.

A keyway in the hub restrains stacked nodes. Figure 6 shows stacked nodes, including a lead screw-mounted dog used to restrain and release them one at a time.

A number of different node configurations are needed to assemble the truss junctions (Fig. 3). These can generally be as efficiently stacked as the nodes in Fig. 6 if separate stacks are used for like nodes.

Assembly Tolerance Accumulations

If the asssembly is designed for pinning between the struts and nodes, then, depending on the degree of dimensional instability (i.e., thermal gradients, etc.) developed during oribit assembly, tolerance accumulations can be partly or totally eliminated by making some or all of the strut-to-node fitups adjustable. As mentioned previously, alternate nodes may be spotwelded, thereby providing adjustable-length struts for fitup adjustments. The effective structural size that

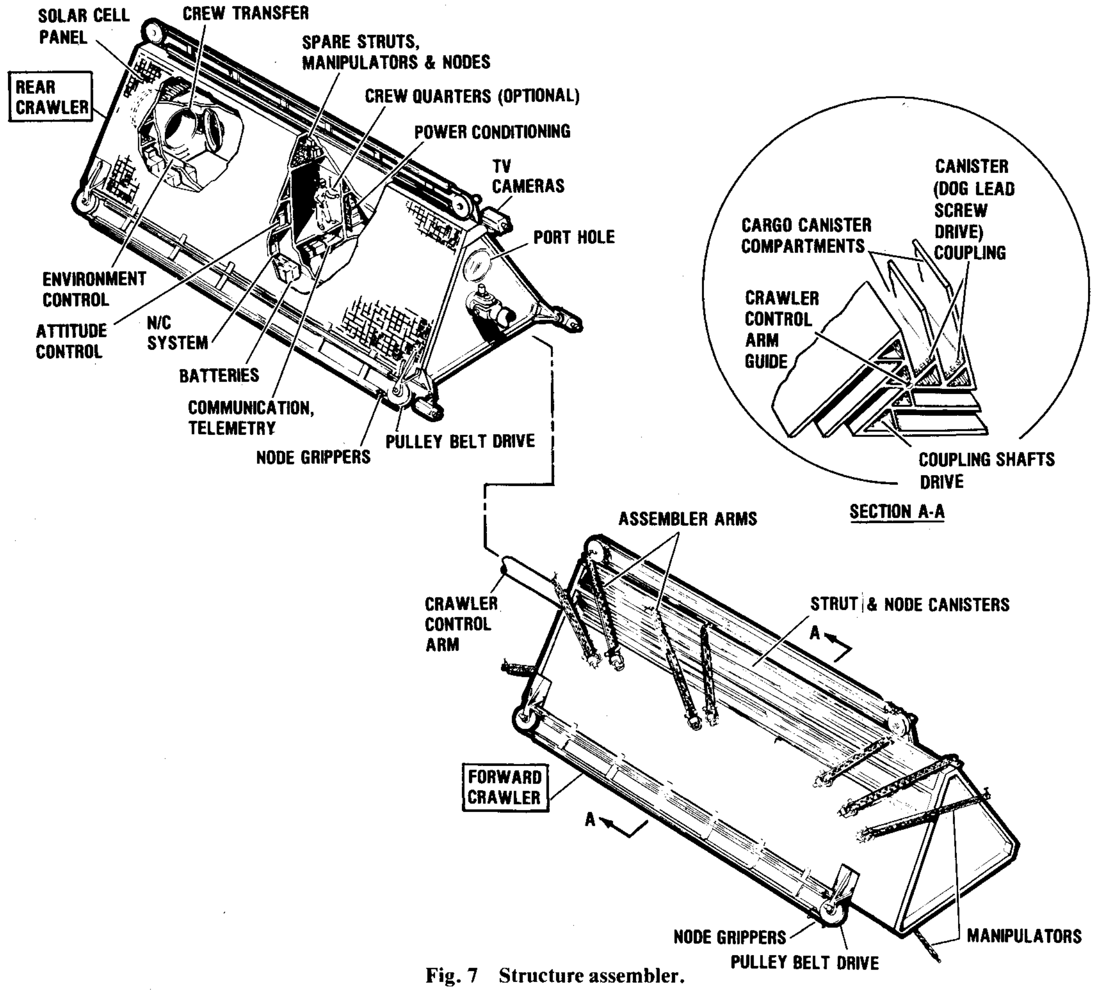


Fig. 7 Structure assembler.

can be erected would then be a function of the piece-part manufacturing tolerances and the capacity of the fitup adjustments to compromise these tolerances. Both the tolerance and adjustment problems seem to be easily solved in this concept.

The Structure Assembler

The structure assembler (Fig. 7) consists of a forward and a rear crawler joined by an articulated control arm.

Forward Crawler

The three faces of the forward crawler are identical. Each face carries two canisters containing stacked struts and nodes. Each face also has a set of seven assembler arms. Although the forward crawler tasks could be handled by as few as three arms per face, preliminary tradeoffs suggest that seven would produce a better system design. Each arm is assigned to handle a node or one end of a strut. Therefore, since a truss is composed of sequentially assembled repeating longitudinal, diagonal, and cross struts, each of these strut ends (plus the node) is assigned to separate assembler arms. In this way the necessary reach, programming complexity, power consumption, and queuing time associated with each arm are minimized. The arm designs are essentially identical, with some differences in arm segment lengths and angular excursions.

Rear Crawler

The forward and rear crawlers are equipped with controlled pulley-driven belts along their three longitudinal edges. As will be explained further, these belts and the node grippers that are mounted on them are the primary fixturing means for assembling the trusses and moving the assembler along the structure after assembly.

The rear crawler can be a duplicate of the forward crawler or, as shown, can carry support systems such as controllers, power supplies (i.e., solar cell arrays), power conditioning, communication equipment, stabilization and attitude control systems, TV cameras for monitoring assembly operations, and, if size permits, an optional crew and their life support system.

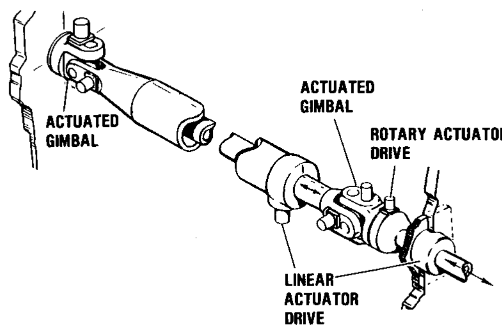


Fig. 8 Crawler control arm.

Crawler Control Arm

The crawler control arm (Fig. 8) is a servocontrolled linkage between the forward and rear crawlers. It includes linear-extensional and rotary actuators with which the forward and rear crawlers can be variably separated up to almost triple their minimum separation. The two crawlers also can be universally tilted with respect to each other, such that the crawlers' longitudinal axes can be anywhere from parallel to

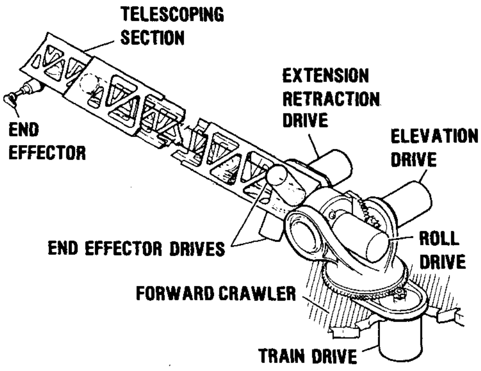


Fig. 9 Assembler arm.

perpendicular to the crawler-coupler-arm axis. These capabilities are adequate for assembling the structure in Fig. 1. The crawler control arm capabilities are used during truss and truss junction construction operation as well as in postconstruction and auxiliary assembly operations.

Assembler Arm

Figure 9 shows the general arrangement of an assembler arm consisting of: triangular cross-section telescoping sleeve and guide sections; a dog-disk end effector actuated through a differential timing belt system by drives located at the assembler arm shoulder; shoulder-mounted train, elevation, roll, and extension-retraction drives.

The arm's kinematic characteristics were selected to give it the dexterity needed to move the end effector into engagement with stacked struts and nodes, and to deliver and assemble them in their final positions. The actuated dog-disk end effector is used to remove struts and nodes from the cargo canisters, and to release them when delivered and installed in their proper assembly positions.

All assembler arms are quickly releasable and mutually removable from the forward crawler in case of failure. The assembler arms on cooperating assemblers are designed and programmed for mutual removal and replacement of a defective arm. The store of spare parts in the rear crawler of one assembler is made accessible (i.e., backed up) to the forward crawler of an assembler needing a spare assembler arm. Replacement by the Shuttle RMS or EVA is also possible.

Note that the end effector could pick up and use a spot-welding head for weld-attaching struts to nodes.

Note Gripper

The node gripper (Fig. 10) consists of a set of actuated tongtype jaws carried by a guided timing belt. Fiber-reinforced timing belts run along the edges and entire lengths of the forward and rear crawlers. The jaws are sprung open by cam action between a follower (operating the actuation mechanism) and a linear cam in the belt guide. They are then closed by a preset release. Triggering the preset release would occur when a node moves into position for engagement by the grippers. All of these functions can also be powered by separate drives to avoid dependence on belt motion for actuation.

The gripper jaws are opened to release the nodes as the nodes approach the aft timing belt pulleys. At this point, the nodes are already assembled into the structure and therefore can be released.

It is possible for the jaws to engage a node before or after they have passed around the forward timing pulley.

There are two node grippers per timing belt. They are equally spaced (at the basic strut length L) along the developed length of the belt.

The node gripper functions, as shown in Fig. 10, are to engage and hold a node from either the structure's inside or outside. When released from the node, the jaws completely withdraw to avoid interference with the assembled structure.

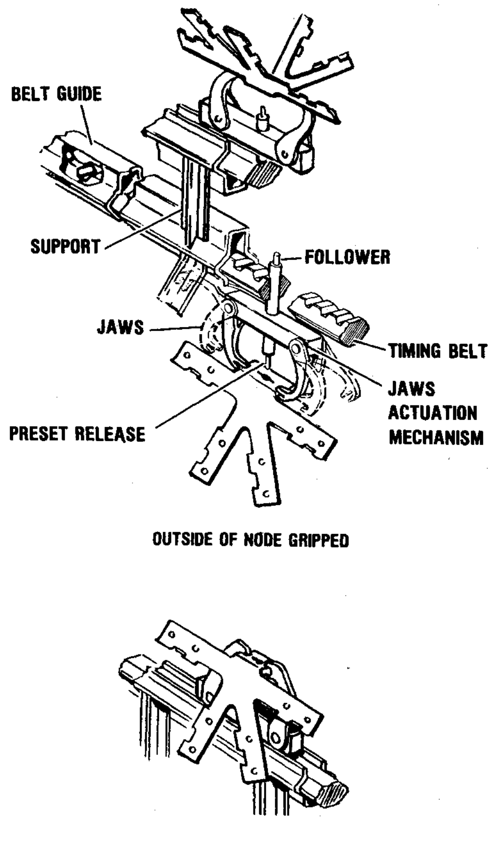


Fig. 10 Node gripper.

Forward Crawler Construction

The cross section of the forward crawler structure (section A-A of Fig. 7) is supported between the triangular endplate structures. This construction creates cargo canister compartments and a guide for the forward extension of the crawler control arm.

Separately actuated canister drive couplings are found at the bottoms of the canister compartments. When a canister is inserted into a compartment, it is latched in and engaged with the couplings.

Cargo Canister

The cargo canister and the manner in which nodes and struts are stowed in it are illustrated in Fig. 11. The canister is shown containing the three different strut lengths used in the truss structure construction. Not all struts in any one of the three indicated stacks need have the same length.

The selection of stacks in which specific struts are included is a function of strut lengths and assembly sequences.

The stacks of struts and nodes are retained in the canister bay by lead screw-mounted dogs. The lead screws pass through keyways in the struts and nodes. Keyways are clocked 90 deg between the successively stacked struts and nodes. To release one of these, the dogs are rotated to align with the long dimension of their keyways. The top strut or node can then be moved, but the next one in the stack is prevented from release because its keyway is clocked to interfere with the dog. Before a strut is released, it is first gripped at its two ends by the dog-disk working ends of two assembler arms, which then deliver the strut to an assembly position.

Before a node is released, the dog on the operative assembler arm is brought into alignment with the dog retaining the node stack from which the node is to be released.

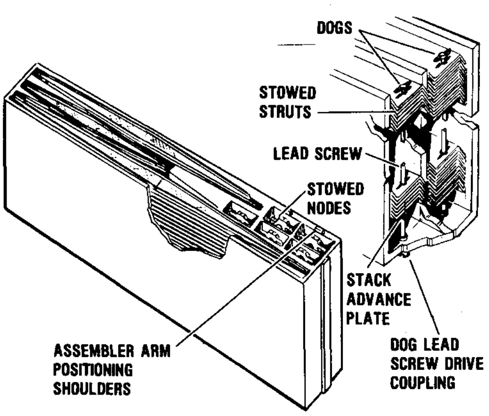


Fig. 11 Cargo canister.

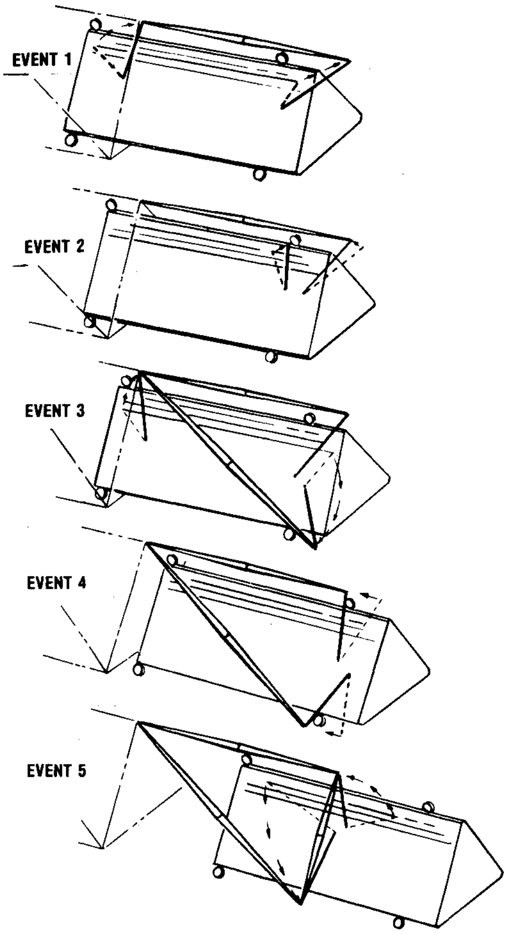
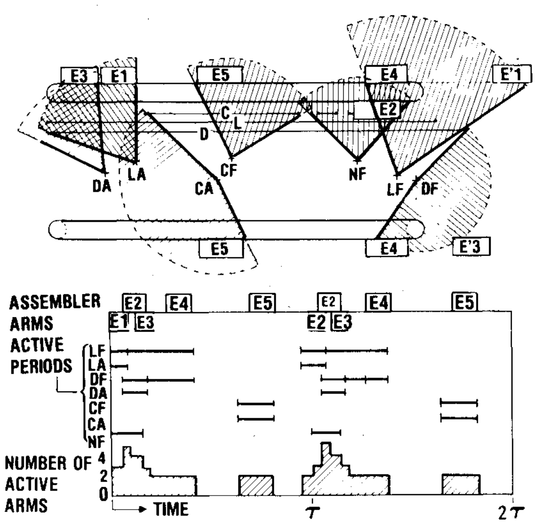


Fig. 12 Truss assembly sequences.



LA = LONGITUDINAL STRUT ASSEMBLER ARM AFT
LF = LONTIGUDINAL STRUT ASSEMBLER ARM FORWARD
DA = DIAGONAL STRUT ASSEMBLER ARM AFT
DF = DIAGONAL STRUT ASSEMBLER ARM FORWARD
CA = CROSS STRUT ASSEMBLER ARM AFT
CF = CROSS STRUT ASSEMBLER ARM FORWARD
NF = NODE ASSEMBLER ARM FORWARD

NORMAL OPERATION EVENT

E1 = LA ASSEMBLES STRUT IN AFT NODE
E'1 = LF PROPERLY POSITIONS FORWARD END OF STRUT
E2 = NF PLACES MODE IN FORWARD GRIPPER
E3 = DA ASSEMBLES STRUT IN AFT NODE
E'3 = DF PROPERLY POSITIONS FORWARD END OF STRUT
E4 = LF AND DF ASSEMBLE STRUTS IN FORWARD NODES
E5 = CA AND CF ASSEMBLE CROSS STRUT IN FORWARD NODES

START UP OPERATIONS EVENT SEQUENCES:
E2, E5, E1, E'1, E2, E3, E'3, E4, E5

Fig. 13 Assembler arm time lines.

The assembler arm and canister dogs are aligned and simultaneously clocked to allow the subsequently released node to pass onto the assembler arm dog. When this has happened, the assembler arm dog is clocked 90 deg to engage the node. The assembler arm then delivers the node to its assembly position.

Figure 11 indicates positioning shoulders on the canister near the nodes and strut ends. The shoulders serve to guide the dogs to their final engagement positions and to thereby minimize the required assembler arm positioning accuracy. This is accomplished as follows: A follower extending from the dog-disk drive housing on the end of an assembler arm engages a shoulder. In this condition, the dog is moved normal to the plane of the stowed strut, as well as in a direction parallel to this plane and perpendicular to the strut axis. If necessary, hunting maneuvers in these two directions can then ensure movement of the dog into its final position.

Stack advanced plates acting on the strut bottoms and node stacks engage with the lead screws. The plates are advanced by the successive unidirectional rotations of the lead screws. The incremental advances are equal to the strut or node stacked thickness.

When a canister is loaded into the forward crawler, the lead screw drive couplings on the lower part of the canister engage mating couplings in the canister compartments. Actuation and control functions for the canister derive from subsystems incorporated in the assembler.

After a cargo canister has been depleted, it is released and removed from its compartment by the assembler arms, and is either returned to the shuttle or used as a structural member.

Battery packs may be included in canisters to provide some or all of the onboard power.

Truss Structure Assembly Sequence

Truss structure assembly operations are performed while the crawler moves forward at a constant velocity in the direction of truss construction. This reduces assembly time requirements by orders of magnitude over what they would be if start/stop motion between the assembler and assembled structure were required for each assembly operation. Because of the resultant inertial reactions, the following would also be significantly greater: 1) assembler and structure tumbling excitations, 2) all drive power requirements, 3) structural strength and, therefore, 4) overall system weight and complexity.

Figures 12 and 13 describe the operation sequence carried out by the forward crawler.

The truss assembly sequence consists of five cyclic events.

Event 1 nominally starts with a partially assembled truss structure engaged by the grippers in an aft position on the forward crawler. During this event, two longitudinal strut assembler arms remove a longitudinal strut from a canister and transport it to its assembly position (designated by areas E1 and E'1 in Fig. 13). The strut aft end is just to the right of the rear pully, but the strut forward end is a greater distance from the right of the forward pulley. (This is caused by the belt's developed length being equal to two longitudinal strut lengths; hence the pulley center distance is shorter than the longitudinal node-to-node spacing to account for pulley belt wrap.) The two arms synchronize their trajectories with the belt motion, and event 1 is complete when the aft end of the longitudinal strut is assembled in the aft node. During this assembly, the forward strut end is held in the compliant mode (e.g., with reduced servogains), allowing the aft assembler arm to manipulate the end fitting without fighting forces caused by mismatches in assembler arm trajectory guidance.

During event 2, which overlaps events 1 and 3, installer arms simultaneously install nodes on the three synchronously positioned grippers at each corner of the forward crawler. The assembler arms first remove nodes from canisters and then place them on grippers when the grippers, transported by the crawler timing belts, are near the node stacks. That is, grippers receive nodes before being carried around the forward belt drive pulleys. Since the grippers are moving when the nodes are emplaced, the movements of the assembler arms must be coordinated with this motion. The nodes are engaged by the gripper from the inside, as shown in Fig. 10.

Event 3 is similar to event 1, except that the diagonal strut is emplaced. During events 1, 2, and 3, as seen in Figs. 12 and 13, interference between assembler arms is avoided. Consider the two largest operating envelope overlaps, viz. the aft longitudinal and diagonal arms (LA, DA) and the node and forward longitudinal arms (NF, LF). In the first case, note that the longitudinal strut aft end can be picked up first with the aft diagonal arm swung counter-clockwise to clear the aft longitudinal arms. Similarly, after event 1 the aft longitudinal arm can be swung slightly clockwise to provide clearance for event 3. In the second case, when the node is emplaced (event 2), the forward longitudinal arm (LF) must hold the end of the strut in an area slightly to the left of E'1; hence, there is no interference.

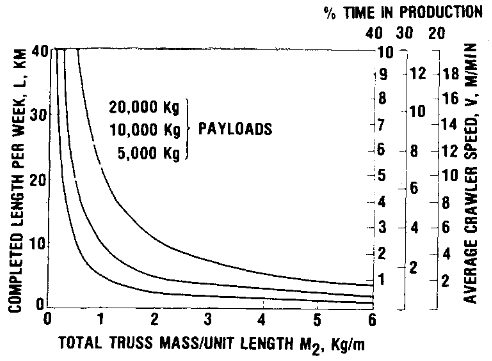
Event 4 begins when the forward node clears the forward pulley. During this event, the forward ends of the longitudinal and diagonal struts are assembled into the forward nodes.

Event 5 (Fig. 12) is the installation of cross (or batten) strut. Two assembler arms on one face remove a cross strut from a canister and transport it into assembly between the two previously assembled forward nodes. As in all assembly operations, small fore and aft and side-to-side shaking forces may be applied to jog possible incompletely assembled joints into full assembly.

Between completions of events 3 and 4, the forward crawler is only attached to the truss structure by a set of its forward arms. This attachment is reinforced and stabilized during this period by the rear crawler through the crawler control arm.

Assembly Speeds

As indicated in the timeline shown in Fig. 12, three events take place close together, leading to the question: Is there sufficient time to do all the tasks? Therefore, consideration is given to expected assembly rates, and a corresponding assembly period τ. As an approximation, for large structures in the near future, shuttle resupply once per week of a 20,000-kg payload is assumed. Further, assume that of the 10,080 minutes per week, 4000 minutes (40%) are available for truss construction. The remaining 60% is used for resupply, truss junction construction, and contingency. A set of parametric curves of completed truss length vs total truss mass per unit length can be constructed, as shown in Fig. 14. Also, based on



EXAMPLE: LSAT CAN ASSEMBLE 4 KM/WEEK OF A 2.5 KG/M TRUSS IF 10,000 KG OF TRUSS PAYLOAD IS DELIVERED PER WEEK. ALSO, IF LSAT ASSEMBLES 20% OF THE TIME, THE CRAWLER NEEDS TO AVERAGE 2 M/MIN.

Fig. 14 Truss length and required crawler speeds.

assumed percentage of production time of the crawler, the average velocity can be computed as shown. For typical truss unit weight of 2-3 kg/m and 40% production time, the average velocity will be 2 m/min or less. Hence, for an 8-m longitudinal strut, the assembly period τ would be 4.0 min or more. Thus, the time allocated for event 1 (or 3) is about 18 s, and events 2, 4, and 5 are allocated 24 s each.

The implications of such a relatively low speed are that: 1) assembler arm speeds are low and time cycles long; hence 2) arm actuator torques are not dictated by acceleration requirements but possibly by insertion or assembly forces; and 3) assembler arm power requirements will be low. Preliminary estimates for all 21 arms indicate a total power level of about 800W. This and all other required power can be supplied by body-mounted solar cell panels on the three faces of the rear crawler.

Assembler Arm Positioning Aids—Slide Rails

The timing belt guide structure (Fig. 10) includes shouldered slide rails paralleling belt motion which can be counterparts to the assembler arm positioning shoulders on the canisters. Like the shoulders, the rails are prominent features easily found by the assembler arm. During assembly operations an extension off the working end of an assembler arm is located on and biased against the rail. By sliding along the rail, the extension controls the transverse of a node, or strut-end position, with respect to the timing belt. Assembler arm motions necessary to complete an installation are facilitated by this condition. Overall assembler arm positional accuracy requirements can be more relaxed than if no slide rails were used.

Inspection of Installations

Before the working end of an assembler arm releases a node or strut, the following actions can be taken to verify correct installation: 1) the control system commands operative assembler arms to apply test forces—the feedback magnitude and phase of these forces will verify that assembly has taken place; and 2) visual sightings through rear crawler TV cameras are taken during and up to time of complete installation. In case of incomplete installation, contingency maneuvers are instituted.

Contingency Maneuvers

If installation is not correct, only small displacement overshoots will develop from the preceding test forces. Adequate time will be available to restore these displacements, and for the assembler arms to carry out corrective installation maneuvers (such as programmed axial and cross-axial jiggling of the struts by the assembler arms) while tracking the node.

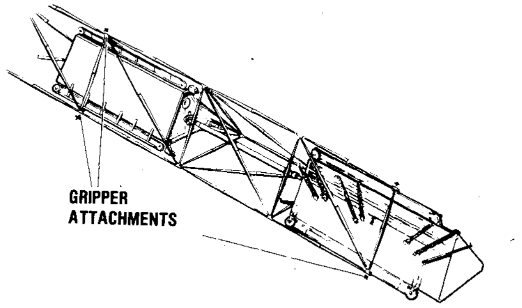


Fig. 15 Assembler in truss structure.

In case on-the-fly contingency maneuvers are not successful and/or TV observations so dictate, the assembly operations are stopped. First the end effectors are released from the members with which they are engaged if the members are fully assembled. Braking action is simultaneously applied to arrest the forward assembler movement. The stopping distance will be a minimum of three-quarters of a crawler length before rear crawler and truss structure disengagement could occur. However, actual stopping lengths should be an order of magnitude less.

The assembler crawling direction is reversed until the correct crawler-to-structure position is re-established. At this point, the released strut or node is repositioned and preprogrammed corrective contingency assembly maneuvers are initiated with or without man-in-the-loop performing a supervisory go/no-go decision function. If these fail, manual direct control and/or EVA are exercisable.

Assembler in Truss Structure

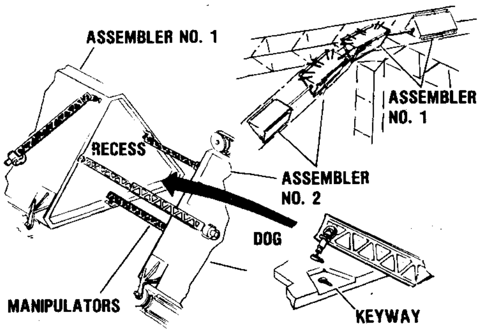
After structural assembly completion, when the assembler is crawling through a truss structure (Fig. 15), it is necessary for stability purposes that at least three grippers be engaged with strut nodes. In normal operation, six grippers (three each on the rear and forward crawlers) may be engaged with nodes. The assembler can progress from the inside to the outside of the structure through clearances built into truss junctions. It can also move between the interiors of two trusses by passing through the truss junctions.

Truss Junction Construction

Briefly, at the completion of a truss construction, the assembler is brought to a halt with the forward crawler freely extending beyond the assembled truss. The rear crawler supports the forward crawler. In this condition, the forward crawler assembler arms and coordinated articulations of the crawler control arm function to assemble the entire truss junction structure. The basic assembly process calls for some assembler arms to act as fixturing devices. Typically, one arm holds a node while other arms install struts between this node and previously assembled nodes. The grippers on the timing belts are generally not used as node holding means as they were for truss construction. When the junction construction is completed, the forward crawler commences to assemble a new truss. The direction of the new truss may be at as much as 90 deg with respect to the one in which the rear crawler is lodged.

During truss junction construction, assembler arm motions must be orchestrated to avoid interference among themselves and to minimize their operational power requirements.

One possible limitation on the truss junction construction rate is the cantilever strength of the previously assembled truss. This strength may limit the forward crawler (articulation) acceleration by the crawler control arm. It may also limit the rate at which the assembler can be brought up to full assembly speed when commencing assembly of a truss not in line with the previously assembled truss. Compensation by thrusters for these inertial effects is possible.



ALIGNMENT BETWEEN FORWARD MANIPULATORS USED FOR ALIGNING FORWARD CRAWLERS OF ASSEMBLERS NO. 1 & 2

Fig. 16 Closeout alignment between assemblers.

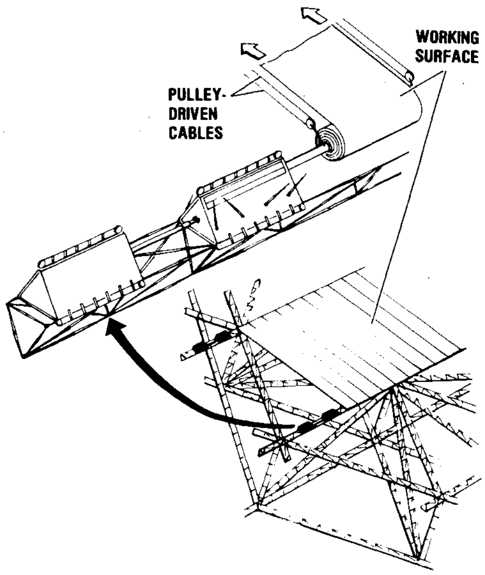


Fig. 17 Assembly of working surface.

Closeout Alignment Between Assemblers

In the overall structural assembly process, it is necessary that trusses under construction close out on previously constructed truss junctions. The manner in which final alignment can be achieved between the truss and junction is explained with the aid of Fig. 16.

Assembler 1 is positioned in an assembled junction. It is approached by assembler 2 assembling a truss. The forward assembler arms on assembler 2 act as antennae to locate and position their end effectors in the forward face recess of assembler 1. Through a series of search maneuvers, the end effectors are located and engaged in the three keyways on the indicated recessed rim. The assembler arm now aligns the two assemblers for closeout construction completion between truss and junction.

A similar closeout alignment could be used between two assemblers approaching each other while assembling the same truss.

The closeout bay length may be different from that in the basic truss structure.

Assembly of Working Surfaces and Lines

The same basic assembler or a modification of it is used to transport and assemble working surfaces. The working surfaces can typically be solar blankets and microwave and solar reflectors.

Figure 17 depicts a typical surface assembly operation by two assemblers carrying rolls of working surfaces and crawling on the outsides of parallel trusses. Clothesline-type,

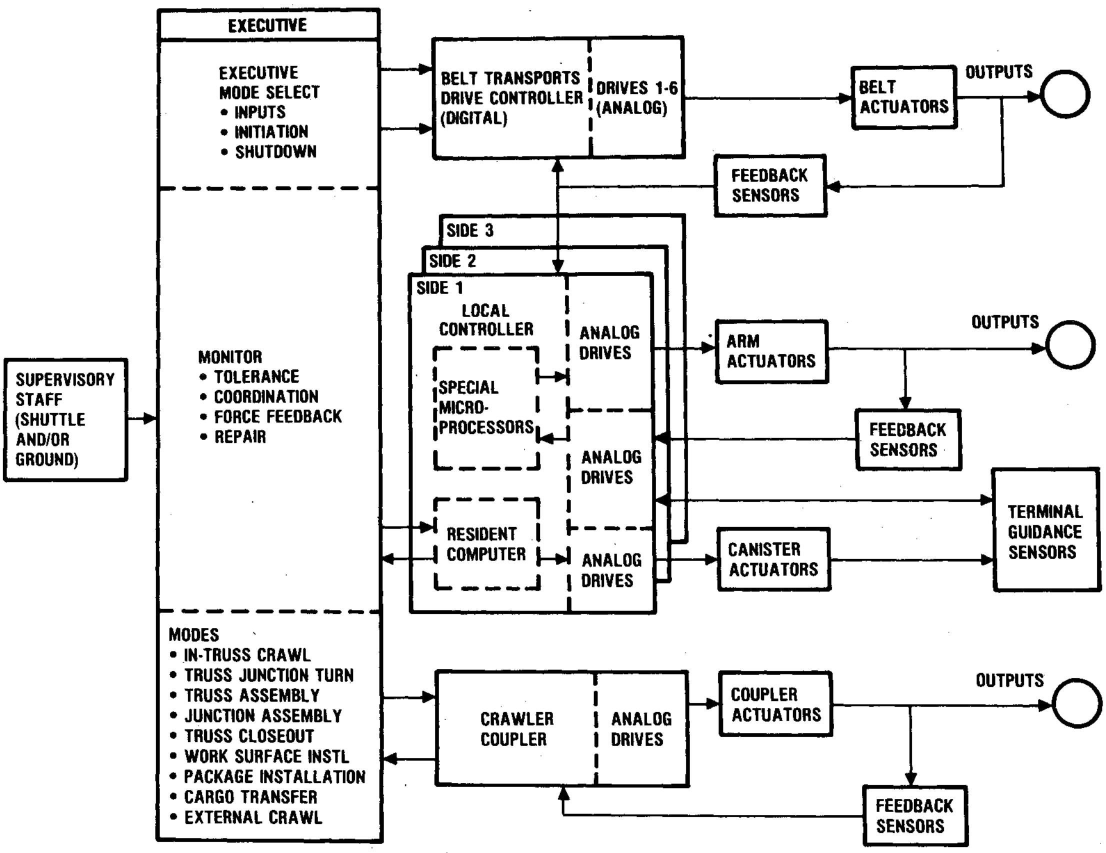


Fig. 18 Control system block diagram.

pulley-driven cables unroll the surface from one roll at a time. When the surface has been paid out, a mechanism on the pulley drive attaches the surface's four corners to four strut nodes. The assemblers then move forward repeating the process, this time by paying out a surface from the other roll.

The node attachments do not inhibit the assembler from crawling back on these nodes in the future.

After the working surface has been installed, it is accessible (by the assembler) from the inside and outside of trusses that support it.

Assembly of such lines as power, microwave, or fluid lines could be similarly carried out by making use of special-purpose adapters and the assembler's mobility and versatility.

Control System

The control system orchestrates the motion of 21 assembler arms, six belt drives, six canister drives, and the crawler control arm using preprogrammed and/or man-machine-interface-derived commands as well as motion, force, and TV sensor feedback. Sufficient computer memory will be required to carry out the different functions enumerated in Table 1. No individual task indicated in Table 1 is without existing present-day analogs either actually in use or demonstrated in the laboratory.

Figure 18 presents a suggested overall LSAT control system block diagram. The automatic control can be supervised by man with computer backup aids on the ground and/or in orbit. A central control computer exercises executive control functions. Each forward-crawler-assembly side contains its own local controller with its digital computer, analog-to-digital (A/D) and D/A converters, analog drives, compensation networks, and possibly several microprocessors. Splitting the forward crawler control functions into groups permits fast response to events needing close synchronization. The microprocessors increase reaction time; e.g., the assembly arms have a microprocessor in their direct control loops to provide reflective action for each arm.

Coordination of 21 assembler arms appears to be a complex computer problem. However, the cycle timing diagram in Fig. 13 shows little activity for most of the cycle, and one flurry in the 48-s period covering events 1, 2, and 3. Based on current computer technology, providing control functions for these events is a straightforward matter.

Table 1 LSAT control functions

Functions	Crawler state	Control state[a]
Truss construction		
Normal operation	Moving	1
Contingency	Moving	1
Contingency	Stationary	2,3
Junction construction		
Normal	Stationary	1
Contingency	Stationary	2,3
Surface, line or package emplacement		
Normal	Moving/stationary	1
Contingency	Moving/stationary	3
Logistic (resupply, equipment repair, and maintenance)		
Normal	Stationary	1
Contingency	Stationary	3
Post assembly structural repair	Stationary	2,3
Transport		
Normal	Constant velocity/ accelerating decelerating	1
Contingency	Constant velocity/ accelerating decelerating	1,2

[a] 1 = computer-preprogrammed control; 2 = man-in-the-loop supervisory control; 3 = main-in-the-loop analog control.

The LSAT concept includes the use of two assembler arms with coordinated motions for handling one strut. Unless perfectly coordinated, the arms will apply structural loads on the strut and forcing functions on each other. This is a relatively new problem for which several approaches have been considered. For example, force sensors in the end effector and/or drives could allow optimum coordination of the arms by slaving one arm so that it is partially driven by the other arm through the strut. Computer-directed change of servoposition gains is another possibility. Either scheme will limit the force levels to prevent strut damage. The problem of one arm's forces affecting the positioning of the other during insertion maneuvers will require investigation.

The LSAT concept uses lead-ins and guides to reduce position accuracy requirements. This is consistent with industrial robot practices and methods. However, if necessary for precision assembly operations, advanced robotic techniques can be employed using sensory aids to guide the end effector.

Concluding Remarks

The Large Space Structure Automated Assembly Technique (LSAT) is a concept for evolving compatible designs for an intelligent-versatile assembler and the structural system it assembles, maintains, and repairs. Its many significant features and advantages set it apart from known proposed large space construction methods. The more important of these features and advantages are that:

1) LSAT maximizes the use of automation and robotics in all space structural system construction, maintenance, and repair phases.

2) LSAT is scalable for application to structural sizes of from hundreds to tens of thousands of meters.

3) Different strut and node materials, gages, and design configurations can be used other than those shown in this paper.

4) LSAT is adaptable to many different truss frame structural arrangements including planar, ring, linear, tetrahedral, and pentahedral arrangements.

5) LSAT provides for internal and external transportation means for the assembler to carry out refurbishment, maintenance, and repair operations. This will significantly influence life-cycle costs.

6) The structure is efficient and has structural continuity in all of its parts.

7) Use of man-in-the-loop is minimized.

8) New technology breakthroughs for implementation are not anticipated.

9) Solar cell panels mounted on the three faces of the rear crawler can provide all assembler operation power requirements.

10) LSAT includes an optional canister system for handling multiple strut, node, and add-on payloads.

The following are some of the significant areas that will need study and development to implement LSAT: strut-node joints, packaging, localized spotwelding and spotwelding repair operations, assembler kinematics, specific structure and assembler baseline (point) designs, time lines, dynamics of assembler processes and assembler structure interactions, and truss junction geometry.