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A TELEROBOTIC SYSTEM FOR AUTOMATED ASSEMBLY OF LARGE SPACE STRUCTURES

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INTRODUCTION

Future space missions may require large planar platforms such as those illustrated in Figs. 1 and 2. These platforms could serve as single-mission high-altitude satellites or as mounting surfaces for multiple instrument packages that could fly in conjunction with, or be a precursor to the proposed space station. These platforms are expected to have a number of structural requirements which may include the following: (1) an accurate surface for mounting of precision instruments, (2) predictable structural response that does not adversely interact with the flight control system, (3) a moderate level of structural redundancy so that failure of a single truss member does not cause catastrophic damage to the entire flight mission.

Considerable research has been conducted in the past several years to develop hardware and construction techniques suitable for astronaut assembly of structures in space, and several studies are reported in Refs. 1 and 2. In Ref. 3, the results are reported for a successful flight experiment that demonstrated astronaut assembly of a 10 bay beam. In future flights the demands on astronauts are expected to increase and it is desirable to use their time to perform decision making tasks. Also, there are potential problems with astronaut assembly, particularly as the size of the structure (number of members) increases. These problems include: (1) the limited amount of work time available in an astronaut EVA work shift for assembly operations that may involve several thousand members; (2) the potential for fatigue; and (3) the large size of these structures may require the astronaut to perform most of the assembly away from the safe haven of the shuttle or the space station crew module.

Due to the anticipated demands on astronauts and the potential problems associated with astronaut assembly, other methods of construction are being explored at the Langley Research Center. A research program has recently been initiated to develop the technology and to demonstrate the potential for automated in-space assembly of large erectable structures. Robotics technology and the experience in structural assembly have been merged into an interdisciplinary cooperative program. Initially the program effort will be focused on automated assembly of a simple generic structural unit. As the program matures, more complex tasks and structural units will be examined. Automated assembly has a number of potential technical advantages and eliminates many of the problems associated with astronaut assembly. Automated assembly is also advantageous for operations that require a large number of repetitive operations, because much of the actual assembly will involve keeping track of the orientation, position, and location of the truss struts which is easily adapted to the computational systems associated with automation. The purpose of this paper is to describe this new facility, discuss the planned test program and truss structural hardware, and outline future tests and operations that could be conducted using the facility.

Identification of commercial products in this report is used to describe the test facility and doe not constitute official endorsement, expressed or implied, of such products by the National Aeronautics and Space Administration.

FACILITY DESCRIPTION

The automated assembly facility at the Langley Research Center is shown in schematic form in Fig. 3A. The facility is composed of the following major components: a robot arm, a planar X-Y motion base platform, and a rotating motion base. The robot arm is mounted on the planar X-Y motion base and can translate in two directions in a horizontal plane. The truss is assembled on the rotating motion base that moves about a vertical axis (θ). The struts used in truss assembly are stored in the pallets that are rack mounted behind the robot arm. As the pallets are emptied they are removed and stored in the rack beside the arm. The facility was designed around the use of existing components and fabricated from inexpensive materials so that it could be easily modified to evaluate future research tasks. In Fig. 3B, a photograph of the actual hardware is shown. The facility hardware was not designed for space qualification, but was designed as a ground based system to permit initial evaluation of in-space assembly concepts. The initial system is purposely intended to be used as a learning tool from which more sophisticated and complex procedures and operations can be developed. For example, the structural design of the transversing platform and the rotating platform were dominated by stiffness considerations to eliminate the need for tactile sensors and vision systems. However, sensor and vision systems may be incorporated after an operational data base has been established.

The system is commanded and controlled using several digital computers that are serially interfaced. The facility also has an integrated video subsystem to permit the operator to view, at close range, the operations of the robot and end-effector. System operations can be interrupted or modified by the operator at a master control panel if a malfunction is detected by either the computer or the system operator. Details of the various facility subsystems follow.

Truss Structure

The truss structure selected for initial assembly operations in the facility is a flat tetrahedral truss such as the model shown in Fig. 4. This truss configuration was chosen because it is a basic generic structural unit that has application to a number of planned and proposed space missions such as those indicated in Figs. 1 and 2. The top surface of the truss is comprised of hexagonal rings as noted in the figures. The truss assembly process begins with building the center ring by connecting individual struts to nodes. Once the center ring is completed, the second hexagonal ring is assembled by connecting additional struts and nodes to the center ring. Additional rings are formed by repeating the same assembly procedure that was used to form the second hexagonal ring. Consequently, the procedure is not controlled or modified by the size (number of rings) of the truss as long as it is composed of at least two rings. The truss has members that are all of the same length, and the nominal member length is not critical if the basic cell geometry is preserved. Also, the location of a particular strut in the truss is not critical. This feature minimizes the complexity associated with fabrication of the strut members in that a very accurate truss can be constructed using only one strut assembly/bonding fixture to maintain member length.

The tetrahedral truss has an additional feature which makes it desirable as a development tool for automated assembly. The truss has a natural set of orthogonal planes imbedded in its geometry and each member in the truss lies in one of those planes. The planes are noted in Fig. 4B and a set of orthogonal axes, one of which is normal to each plane is also shown. These orthogonal planes provide the maximum room for inserting a member in the truss at its connecting node. The strut members for the assembly test article are 2 m in length and 2.6 cm in diameter. The complete truss has 102 struts and 31 nodes. The truss is large enough to be a viable space truss unit and yet small enough that a special dedicated building is not required to house the assembly facility.

The nodes and joint connections of the truss are shown in Fig. 5. Each node must be capable of connecting nine members, six that lie in the plane of a face and three from the core which connect the top and bottom faces (illustrated in model of Fig. 4). The load path of all members intersect at the node center. The nodes for the assembly truss were machined from aluminum and anodized to provide a hard surface finish. However, for space application, they could be easily fabricated from a material with a low coefficient of thermal expansion such as titanium or invar.

The joint, shown in Fig. 5, is used to attach the strut to the node. The joint is composed of two parts. One part is the main connector mechanism of which the housing is bonded to the graphite strut, and the second part is a receptacle which is attached to the node using a threaded stud. The joint connector is locked by turning the locking nut protruding form the side which drives an internal wedge mechanism. This joint connector was modified for the robotic assembly project and the basic invention is described in the Ref. 4 patent. Joints for large space structures have a number of requirements that must be met for the completed truss to be capable of being assembled in space and have a predictable structural response. A set of joint requirements were defined at the start of the program and are outlined in the appendix. The numerical values noted in the appendix are intended to be representative and do not reflect an absolute need that is based on analysis of a particular mission. The mass of the joint including the receptacle (node excluded) is approximately 134 g (0.296 lbs). The joints were fabricated from aluminum and all of the components were treated with a teflon impregnated hard coating to reduce friction and to eliminate the potential for galling.

The strut tubes (shown in Fig. 5) are T300/934 graphite/epoxy. The interior tube diameter is 2.22 cms (0.875 in.) and the wall thickness is 2.03 mm (0.080 in.). They were fabricated on a mandrel from unidirectional prepreg tape which was preplied at +/-10 deg before being rolled on the mandrel. Laminate analysis indicates that this lay-up should have an axial elastic modulus of about 120.7 gPa (17.5 E6 lbs/sq in.). Static three-point-bending tests of all the tubes indicate that the average axial modulus of elasticity is 106.9 gigapascals (15.5 E6 lbs/sq in.), which is within 11% of the laminate analysis prediction.

The joints were bonded to the graphite tube using Epon 934 epoxy resin. All bond joints were set on the same fixture so that all struts would be of nearly identical length. The struts are anticipated to have a length variation of approximately +/-0.005 cm (+/-0.002 in.). Also shown bonded to the graphite tube in Fig. 5 is a hexagonal shaped piece with a center groove identified as an alignment and grasp adapter. This piece, and a like piece on the opposite end of the strut , are grasped by the end-effector and will be described subsequently in the discussion covering end-effector operation.

MOTION BASES

X-Y Robot Translation Motion Base

The X-Y translation bases have 6 meters of travel along each axis and are used to support and position the robot (Fig. 3B). Both of the X and Y bases are mounted on low friction linear bearings. The X base is mounted on aluminum I-beams and bolted to supports anchored in the floor. The X supports are 4.57 m (15 ft) apart and the Y supports are 0.91 m (3 ft) apart. There are two drive mechanisms that can be used to propel the motion bases, (1) a motor powered drive or (2) the wrist rotation of the robot arm. The motor drive system is designed to accelerate the positioning systems in both the X and Y directions at a rate of 0.61 m/sec/sec (24 in./sec/sec) to a velocity of 15.2 cm/sec (6 in./sec). The position of the robot can be determined by sensors mounted along both tracks to within +/- 0.05 mm (0.002 in.). The drive system for both axes use cables that are anchored at both ends of the track and the cables are wrapped around drums attached to the drive shafts. A cable drive system was selected to eliminate free-play and backlash associated with gear type systems. Brakes are used to prevent back-driving in the X or Y direction due to forces generated by the robot. The X and Y motion bases were designed to have a high stiffness restricting deflections to less than 0.25 mm (0.01 in.) at any position of the robot within the operating envelope.

Rotating Motion Base

The turntable is used to support the truss during assembly and is positioned near the end of the X Translation System. It is permanently attached to the floor so that the relative position with respect to the X-Y Motion Base remains fixed. The turntable is capable of three revolutions of travel in either direction. The table is motor driven but can also be turned by a force applied by the robot. The speed of rotation using the motor drive is 5.6 deg./sec., which will provide a circumferential speed at a 6 meter radial perimeter of the truss of 58.8 cm/sec. (23.2 in./sec.). The turntable is capable of positioning the outer ring at a radius of 6 meters at any desired circumferential location to within 0.25 mm (0.01 in.). The drive system, like that of the X-Y motion base, uses cables that are wrapped around the main drum on the turntable and the system drive shaft. The turntable is stiffness designed and fabricated using conventional welded steel construction so that deflections introduced from an unbalanced assembly or from forces applied by the robot arm at the outer ring to the truss would not adversely affect positioning accuracy. The heart of the structural support is a 0.89 m (35 in.) diameter drum that is supported at the perimeter on rollers and pivots around a center shaft. The truss is mounted to the turntable by connecting the three nodes in the truss bottom plane to the triangular frame of the turntable (Fig. 3) which is just above the drum. The turntable was accurately aligned during installation so that the truss supports would rotate without wobble around the local vertical.

Robot Arm

An extensive review of commercially available robot arms was conducted in the initial phase of the project. The review was restricted to those arms that are electrically operated because of the long distance required for field power runs along the X and Y motion bases and the greater simulation realism for space operation. An evaluation matrix was developed based on the following criteria: 1) a minimum payload capability of 89 newtons (20 lbs) and a minimum torque capability of 24.3 newton m (215 in. lbs); 2) a reach envelope in excess of 152 cm (60 in); 3) positioning repeatability of about 0.010 cm (0.004 in.); 4) dexterity provided by at least 6 axes; 5) low robot arm mass; 6) capability to adapt to a motion drive system for the X and Y motion bases; 7) program language that is user friendly; 8) low system cost and immediate availability; and 9) a favorable history of service and reliability. The MR 6260 Merlin Arm, built by the American Robotics Corp., was chosen from several robot arms capable of meeting most of the selection criteria.

Following procurement and delivery of the robot, it was assembled and checked for specification compliance by a series of tests and found to be adequate. Following these tests it was mounted on the Y motion base for operation.

Truss Strut Canister

The struts comprising the truss structure, are mounted in pallets that will be held in a rack behind the robot arm (Fig. 3). A sketch is shown in Fig. 6 of these pallets with the strut holders. The pallets are structural frames fabricated from 2.5 cm (1.0 in.) wide aluminum angle and are approximately 1.02 m (49 in.) long by 0.62 m (24.5 in.) wide. Each pallet has handles on the ends to permit the robot to pick it up and move it to the pallet storage rack which is located to the right of the robot. The same mechanism on the end effector that handles the struts will be used to pick up the pallets and will be discussed later. Each pallet will hold up to 13 struts and the nodes will be preattached to one end of selected struts before assembly begins. The struts will be placed in the pallets at preselected locations to accommodate efficient packaging. The struts will be spaced at 4.4 cm (1.75 in.) intervals across the pallet so that the entire truss will be packed within an envelope of about 0.72 cubic meters (25.5 cubic feet), which is less than 1.4% of the fully erected truss volume. The complete truss can be packaged in nine trays with several tray locations unused to accommodate selective placement of nodes in the trays. The struts will be latched to the trays by two hexagonal adapters which are bonded to the struts. This configuration is shown in Fig. 6. The adapter has a hexagonal cross-section and the flat side of the hexagon rests on the frame of the pallet. It is similar to the alignment and grasp adapter noted in Fig. 5 that is used by the end effector to pickup and position the strut. Spring loaded pin plungers in the side of the positioning pin hold the strut in the pallet and a force is required to extract each strut from its storage location.

End-Effector

The end-effector is a uniquely designed instrument that is dedicated to the task of grasping a strut positioned in the pallet, holding that strut while the robot moves it into position, inserting the connector into the joint receptacle, and then driving the lock nut to secure the strut in the truss. The end-effector is mounted to a tooling plate on the wrist axis of the robot. A sketch of the end-effector mounted to the robot is shown in Fig. 7 and a photograph of the hardware is shown in Fig. 8. The strut is grasped at the alignment and grasp adapter by the jaws of the strut gripper as shown in Fig. 9. The jaws are opened by activating an electric solenoid. The solenoid is spring loaded so that releasing power causes the jaws to close automatically locking the strut in place. This feature provides a passive lock on the strut and prevents it from being dropped or released in the event of a power failure. The fingers on each end of the end-effector grasp the joint receptacle and are seated in the groove when closed (Figs. 7A and 7B). These fingers are designed to capture the receptacle at any location within a 2.5 cm (1.0 in.) diameter by 1.5 cm (0.6 in.) long cylindrical envelope, and will force the node into the correct position for strut insertion. This feature is required in a ground-base simulation to compensate for any misalignment errors caused by gravity or bowing of the strut graphite tubes. Having grasped the receptacle, the end effector inserts the strut in the joint and a motor powered nut driver locks the strut in place. The receptacle grasping feature secures and accurately positions all components so that drag or small misalignments will not restrict the insertion operation. The end-effector is designed to permit operation either with a node preattached to the strut, or to insert a strut into nodes already assembled on the truss. The receptacle fingers and insertion platforms (Figs. 7B and 9) are operated by pneumatic cylinders to keep the mass of the end effector as low as possible. For space operation these components would likely be replaced by electric actuators. The total mass of the end-effector including electrical and pneumatic components and a strut in place is approximately 6 kg (13.4 lbs). The model is instrumented to provide the position of the insertion platforms and has 12 microswitches to monitor functional operations. Two small video cameras are mounted on the frame (Fig. 9) to permit operator viewing of end-effector functions.

Computer Control Systems

Computational System: Several computers are required to monitor and control the operations of the assembly facility. The function of these various computers is illustrated in Fig. 10. The system is controlled by an executive program executed by a microVAX workstation. The executive program communicates with the other computers by transmitting ASCII code through RS232 lines. The computers are the robot computer which is a Motrola 68000 based unit that is programmable in a modified basic language, and the motion base control computer which is an 80286 based PC that executes a commercially available software control program. Output commands are transmitted from both of these lower level systems directly to stepper drive motors and encoder position sensors. The lower level systems can be used for incremental or absolute position control. The robot computer also has the capability to handle analog and discrete input and output signals and is, therefore, used as a servo controller for the end-effector. The computer control system for the automated assembly facility uses only off-the-shelf equipment. This approach was taken to minimize problems that might delay the operational schedule of the system.

Executive Program: The assembly facility executive program, which operates on the microVAX workstation, is shown schematically in Fig. 11. The system experiment operator selects the desired assembly function from a menu of preprogrammed operations. The selected menu function is directed to the expert system which stores in memory the preceding operation and determines what changes in the current hardware configuration are required to perform the new menu selection. The hardware configuration status includes the truss struts and their location (either attached in a partially assembled truss or in the storage trays) as well as the state of the end-effector and the three motion bases. If the selected operation can be performed, the system notifies the operator and checks the facility safety interlocks for clear system operation. The expert system then generates the command sequence file required to perform the selected menu function and the commands are directed to the appropriate sublevel computer in sequential order. As the commands are executed the operator is notified by the executive program. The operator also monitors the operations as they occur by the video surveillance system which is described in the next paragraph. If a failure occurs, the operator will have some checks to perform and will be permitted to override noncritical fault indicators. Operations that are not listed in the menu can only be performed by directly accessing the sublevel computers.

Video Surveillance

Assembly facility operations are monitored by the operator using a video system that displays the output from four cameras at the control console. A schematic of the system is shown in Fig. 12. The four cameras consist of two surveillance cameras with pan and tilt drive controls, and two fixed mounted cameras that are attached to the end-effector. These end-effector cameras are aimed at the strut holders and joint connectors with one at each end so the operator can observe the strut attachment operation. The two surveillance cameras are controlled by the video tracking program which is directed by the system executive program described earlier. These two cameras are placed: 1) at the facility perimeter to give the operator a panoramic view of the entire operation and 2) directly behind the robot arm to give the operator an "over-the-shoulder" view of the robot during assembly operations and during pickup of the struts and pallet positioning.

Signals from the four cameras can be viewed on individual monitors or the signals can be partitioned to observe several cameras on a single monitor. Both video and data signals can be multiplexed over a broadband network to and from remote locations for future integration into more advanced computers and crew workstations. Although the current structural assembly is designed for automated operations, the test engineer will monitor all real time operations using the video system and can terminate or redirect operations during assembly if an error of failure is observed.

STRUCTURAL ASSEMBLY CONSIDERATIONS AND REQUIREMENTS

Much of the initial research conducted with this facility will involve the development and evaluation of assembly sequences. One preliminary assembly sequence has been developed to ensure proper system coordination during the design and checkout phase. This sequence will be used for initial assembly tests and will provide a baseline for evaluation and comparison of subsequent tests. Factors to be considered in evaluating future test sequences may include the following: whether separate drive systems are required to power the motion bases as opposed to driving them using the wrist rotation of the robot; the difficulty of continuing assembly operations when an error or failure occurs; the frequency for robot repositioning required during assembly, especially if robot power is used as the drive system; the desirability of a redundant degree of freedom in the motion base system; potential for continuing assembly or successful termination should failure occur in one axis of the robot. The above factors should provide insight into the value and capabilities of automated structural assembly using robots, and may also help to define the requirements for other space based automation systems. The development of assembly scenarios must be coordinated with limitations imposed by other considerations such as the way struts are stored in the trays and the way the trays are positioned in the canister.

For evaluation of assembly scenarios using this terrestrial based facility, consideration must be given to gravity induced deflections. Although the truss components are relatively small, stiff and of low mass, the gravity imposed deflections are not insignificant when one considers that the struts must be captured by the end effector and connected together automatically. The main contribution to position errors is the cantilever deflection of a truss face strut with a node preattached. This deflection is approximately 1.7 cm (0.7 in.) when the strut is supporting a fully populated node and has one end clamped. For the preliminary checkout scenario, only core struts will be cantilevered because they are not subjected to full gravity load. However, due to gravity imposed deflections it may be difficult to evaluate all assembly scenarios of interest.

One of the main considerations in the evaluation of astronaut assembly of space structures is the time required to complete the installation of a truss member. For automated assembly the member installation time is likely to be less important because video monitoring at the control console with operator shifts will permit assembly operations to run on a continuous basis. A major consideration for evaluation of automated assembly may be the responsiveness of the system to astronaut intervention and the ease with which assembly operations can be modified.

FUTURE RESEARCH OPPORTUNITIES

This facility offers many opportunities for evaluation of automated structural assembly operations. Among those that may be considered for evaluation are structural repair and servicing of proposed operational spacecraft. This will be particularly useful for a system that was initially assembled using automation, and requires either periodic maintenance or structural repair. Other tasks that should be considered include the installation of electrical utility cables, mounting of reflector panels for precision antennas and solar dynamic power systems, and the installation of payloads and instrumentation. Most of these components are required in operational spacecraft and, therefore, complete satellite assembly may be a desirable goal for any focused effort in automated assembly.

Telerobotic operation has been a major focus of research efforts in the past and is likely to continue to receive much attention. This facility could be a valuable tool in support of telerobotic operations especially using components that were designed for automated assembly. The facility will be useful for evaluation of circumstances where manned maneuvering and real time decisions are critical to successful operation.

The current demonstration was designed and configured for automated assembly and all components were designed by stiffness/deflection considerations. These requirements could be relaxed if the system incorporated feedback controls which were developed around a force-torque load-cell or a simple vision or ranging sensor system. These systems could be incorporated initially with limited range and accuracy and updated as the experience level improves. The use of a ranging system may eliminate the concern associated with gravity deflections of cantilevered struts and open up new options in developing assembly scenarios.

SUMMARY

Future space missions are likely to require large planar platforms as mounting surfaces for instrument packages. A research program has been initiated at the Langley Research Center to develop the technology and demonstrate the potential for automated assembly of these large planar platforms. To accomplish this task, a facility has been constructed to perform assembly studies on a two-ring-model of a regular tetrahedral truss with 2-meter-long members. The initial assembly will be accomplished using a commercial robot arm to place the struts in the truss in a totally automated manner. The robot arm is moved into the various assembly positions on an X-Y carriage that is designed to minimize positioning errors, and the truss is mounted on a rotating motion base. The struts are stored in pallets near the base of the robot and a specially designed end-effector places the struts in the truss and locks them in position. The entire system operation is driven by two computers which are serially connected and controlled by a third computer that serves as an executive system. A video surveillance system provides monitoring capability to the operator who can terminate the assembly if an error occurs.

Assembly scenarios will be evaluated using the facility and the results of these studies are expected to aid in the definition of the equipment and requirements for space based automation systems. Other tasks that may be considered for evaluation include attachment of operational instrument payloads, structural repair, and mechanical servicing and periodic maintenance of spacecraft. It is anticipated that the facility will also be a valuable tool in support and evaluation of future robotic operations.

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APPENDIX

The specific requirements joint connectors must satisfy are as follows:

1) A member must be capable of being installed or removed from a structurally redundant assembly. Therefore side entry between two nodes a fixed distance apart is mandatory.

2) The connector must apply a controlled preload to the joint of approximately 1.1-2.2 kN (250-500 lbs) to eliminate free-play and provide a linear load deflection response for reverse tension-compression load cycles across the connector.

3) To compensate for manufacturing errors or measurement errors the connector must have a shallow ramp to permit insertion of a member in the redundant truss that is apparently too long. The interference length to be no longer than 0.06 cm (0.025 in.).

4) The connector must also be capable of "picking up" the receptacle if the member is apparently too short. As in item (3) this length error is to be less than 0.06 cm (0.025 in.). The connector must be capable of exerting the joint preload of 1.1-2.2 kN (250-500 lbs) during the latching or joining process.

5) The connector must not relax the preload significantly over extended temporal operation in space due to exposure to normal environmental conditions of thermal cycling.

6) All parts of the joint connector must be contained so as not to be capable of inadvertent release in space.

7) The circumferential orientation of the node to the member axis must be set accurately (preferably by use of detent or guide) during the connecting process.

8) As the connection process is completed the connector must force the member to assume the proper axial alignment.

9) The connector must have high axial stiffness and strength, i.e., nearly the same structural stiffness and strength as the virgin wall of the strut.

10) Each connector must be permanently attached (bonded) to the wall of a thin graphite/epoxy composite tube.

11) The receptacle that attaches to the node must not be so large that it interferes with the attachment of other connectors to the node.

12) No part of any component associated with the joint or connector that is exposed so as to be accessible to an astronaut may have sharp edges or protrusions that could cut an astronaut's space suit or otherwise cause damage by collision or contact with other payloads.

13) All connectors must be capable of being joined and loaded by pressure suited astronauts in EVA using either small hand tools or without tools if possible.

14) The connector should transfer load axially without imposing a significant eccentricity that would introduce bending in the joint or strut member.

15) The connector parts must be interchangeable so as not to be specially machined or lapped as a unit.

16) The length and mass of the connector section should be minimized.

17) To reduce costs, the connector must have as few parts as possible and these parts should be simple to machine.

18) The connection to the node may be accomplished in a number of ways: (a) it may be threaded directly into an internal thread in the node, (b) it may be an interference fit to a nonthreaded hole, or (c) it may attach to a short receptacle that is a part of the joint where the receptacle is preattached to the node by way of a bolt prior to the assembly operation.

19) The connector must not undergo significant longitudinal expansion cue to thermal loading and it should be capable of being machined from a low CTE metallic material such as titanium.

20) The connecting operation must be simple, require a very limited number of special tools, and be capable of being completed in a short time. Revisiting the joint or node to complete or perform a required check of the connection is not permitted.

21) A connector for space operation must have a positive lock that will prohibit the release of the connector or a reduction in the preload due to vibration or thermal loads. It is desirable that the joints have the same features as those required for space operation. However, if this feature is an expensive or a difficult requirement, demonstrate the capability to add the feature to the design.

22) The connector must be capable of reacting the torsion load imposed by two members connected to a node at right angles to each other, in a 1-g environment. In this condition, one member has its opposite end clamped, and the second member has its opposite end free. Both members are considered to be in a horizontal plane.

Some very desirable features which should be considered for incorporation in the joint are as follows:

1) No load path through the joint or member should involve or introduce structural bending. Therefore, all load transfer should be through direct tension, compression, or shear.

2) For astronaut assembly, it is desirable that the connector incorporate a capture feature that will hold the member in place once it is inserted. (It is required, however, that the capture feature be capable of being released so that the member may be removed or replaced if damaged.)

3) The connector could attach directly into the node. The use of a receptacle attached to the node as an interface between the connector and node, or as a part of the connector is permissible, however, it may not extend far from the node surface, otherwise the receptacles will significantly reduce packaging efficiency of the nodes.

4) It is desirable to avoid complicated contours that are difficult to inspect for machining accuracy.

5) The connector should be able to tolerate small angular misalignment of the longitudinal axis of the member when the locking process is initiated.

6) The connector should be approximately the same diameter as the outer diameter of the tubular strut to which it is attached, although larger diameters are permissible, a larger diameter will significantly reduce packaging efficiency of the struts.

7) The connector should be capable of being manufactured in a range of sizes so as to be useful for a large range of structural applications and scale model studies.

8) The connector should aid in the alignment by guiding the insertion once the mating parts of the connector have been bought into close proximity to each other.

9) The connector should be capable of being visually inspected at some distance away (approximately 3 m) to determine if it is locked. The identification system used for this purpose should be visible from any circumferential angle around the member.

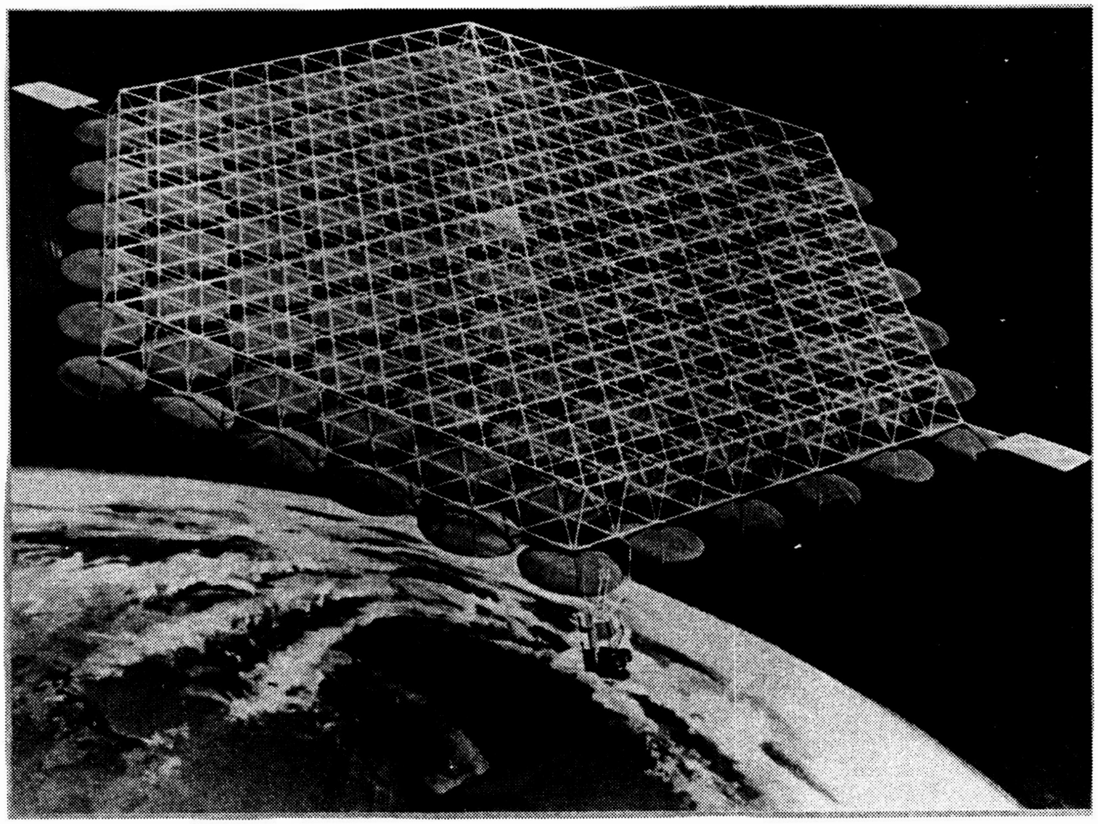

Fig. 1 - Artist Sketch of Proposed Electronic Mail Satellite.

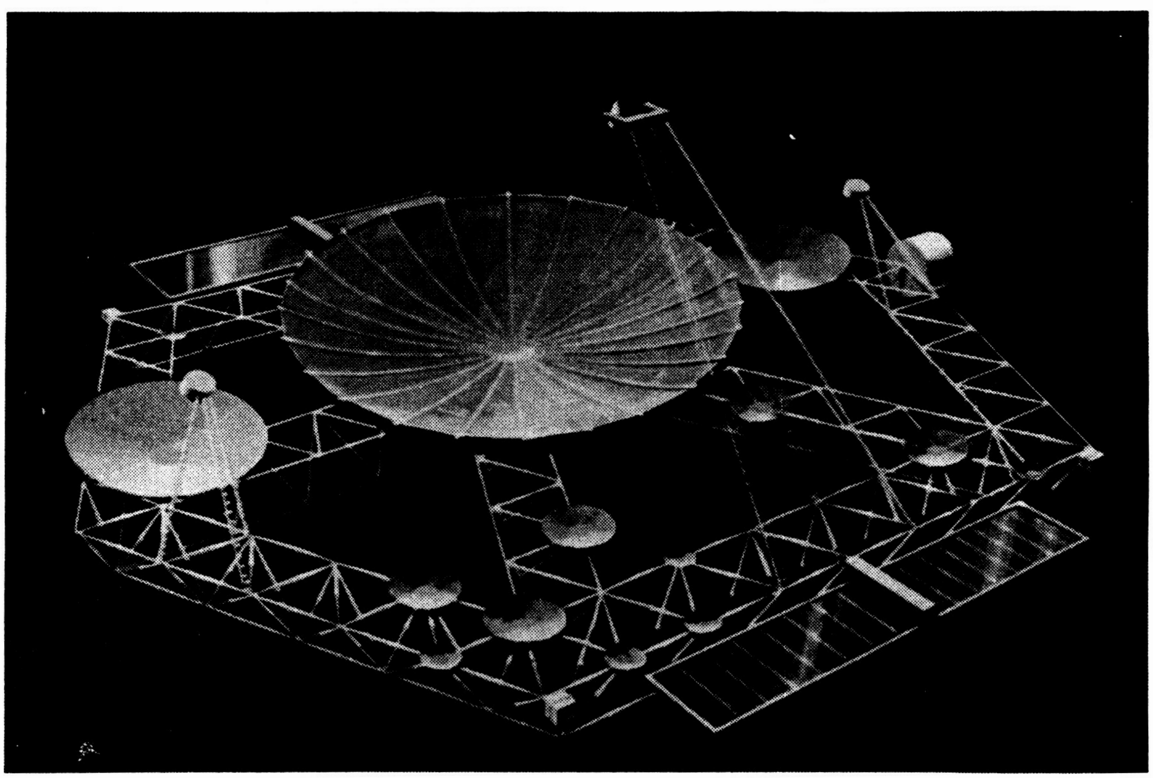

Fig. 2 - Artist sketch of Proposed Geostationary Communication Platform.

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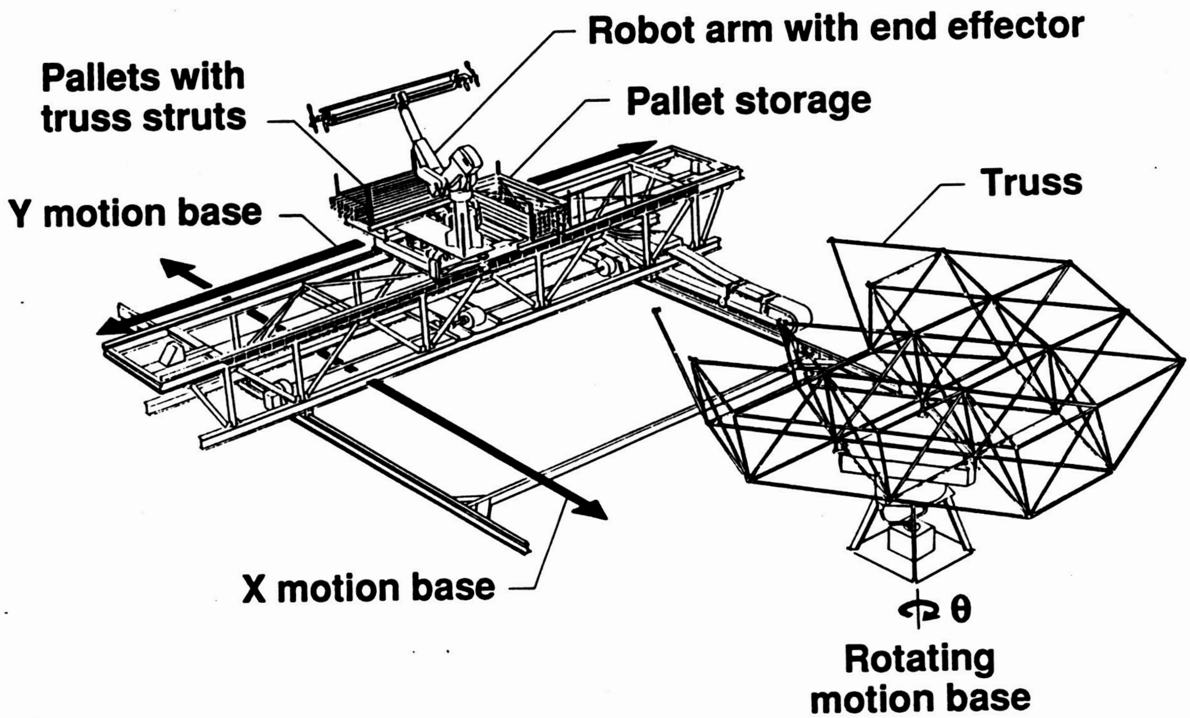

Fig. 3a - Facility for Automated Assembly of Large Truss Structures (Schematic of Facility).

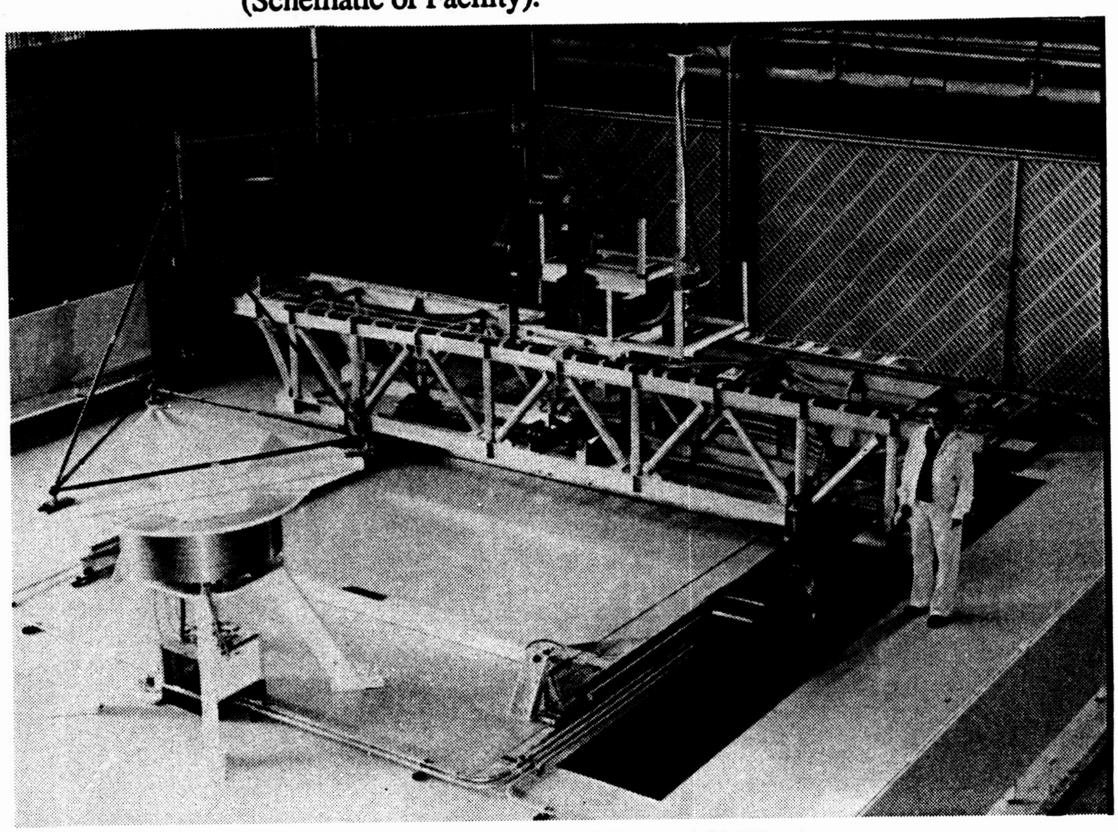

Fig. 3b - Photograph of Assembly Hardware.

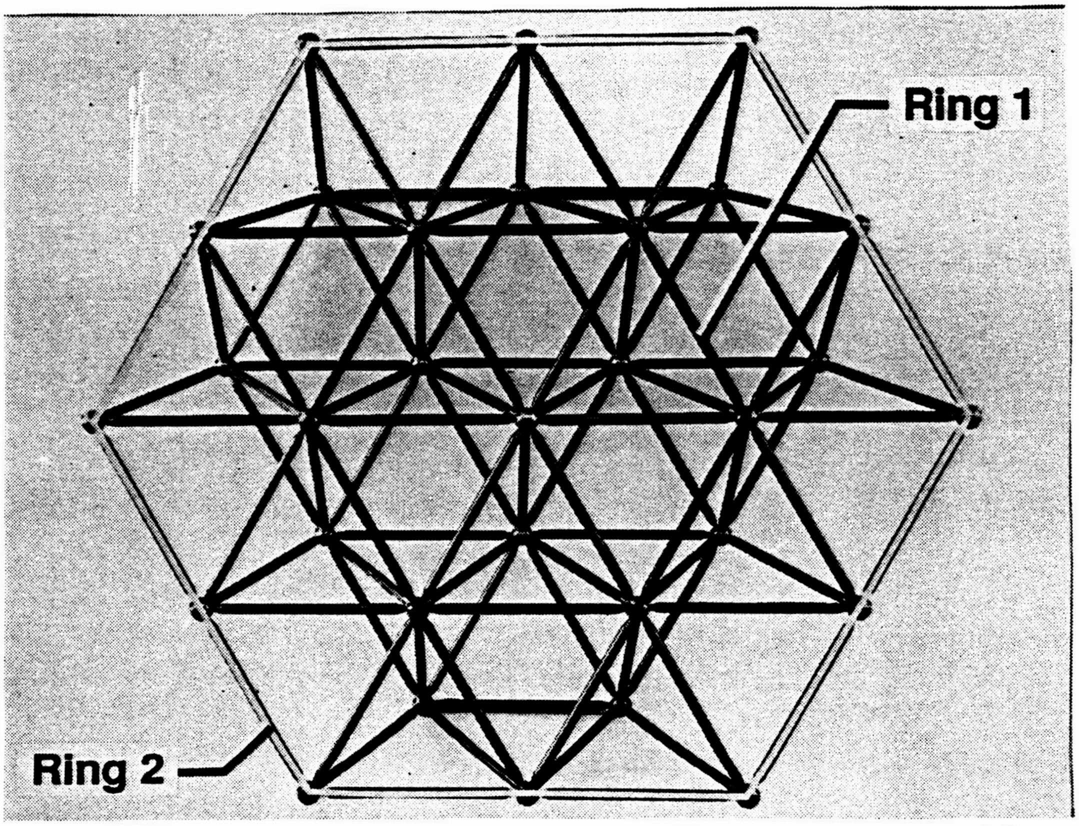

Fig. 4a - Model of Regular Tetrahedral Truss (Top View of Truss Model).

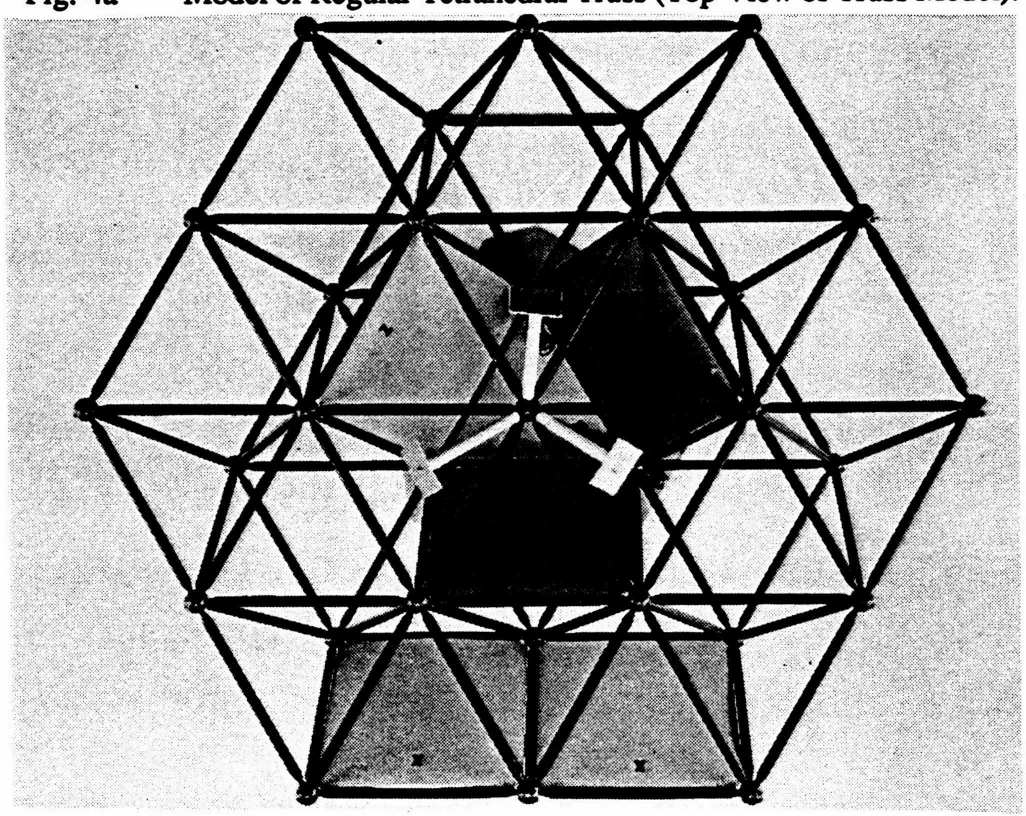
Fig. 4b - Truss Model Showing Set of Imbedded Orthogonal Planes.

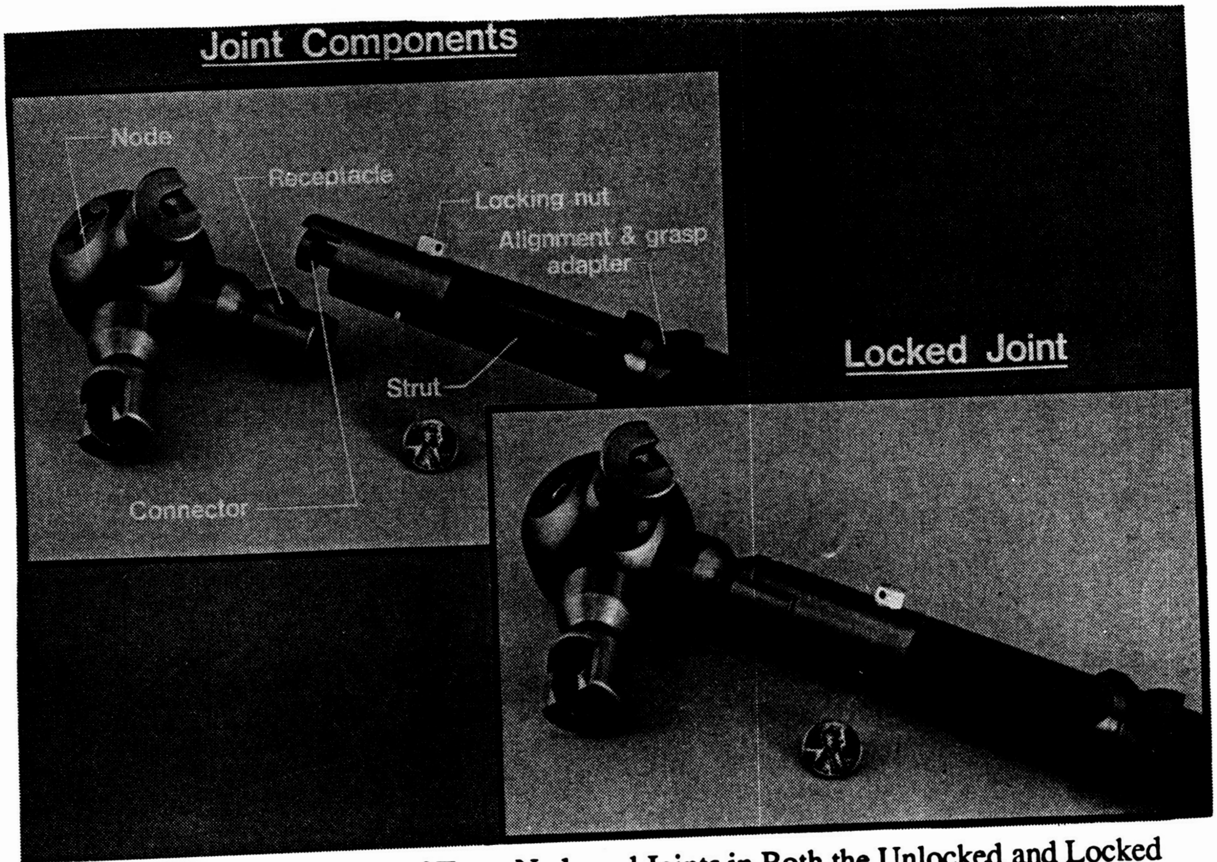

Fig. 5 - Photographs of Truss Node and Joints in Both the Unlocked and Locked Condition.

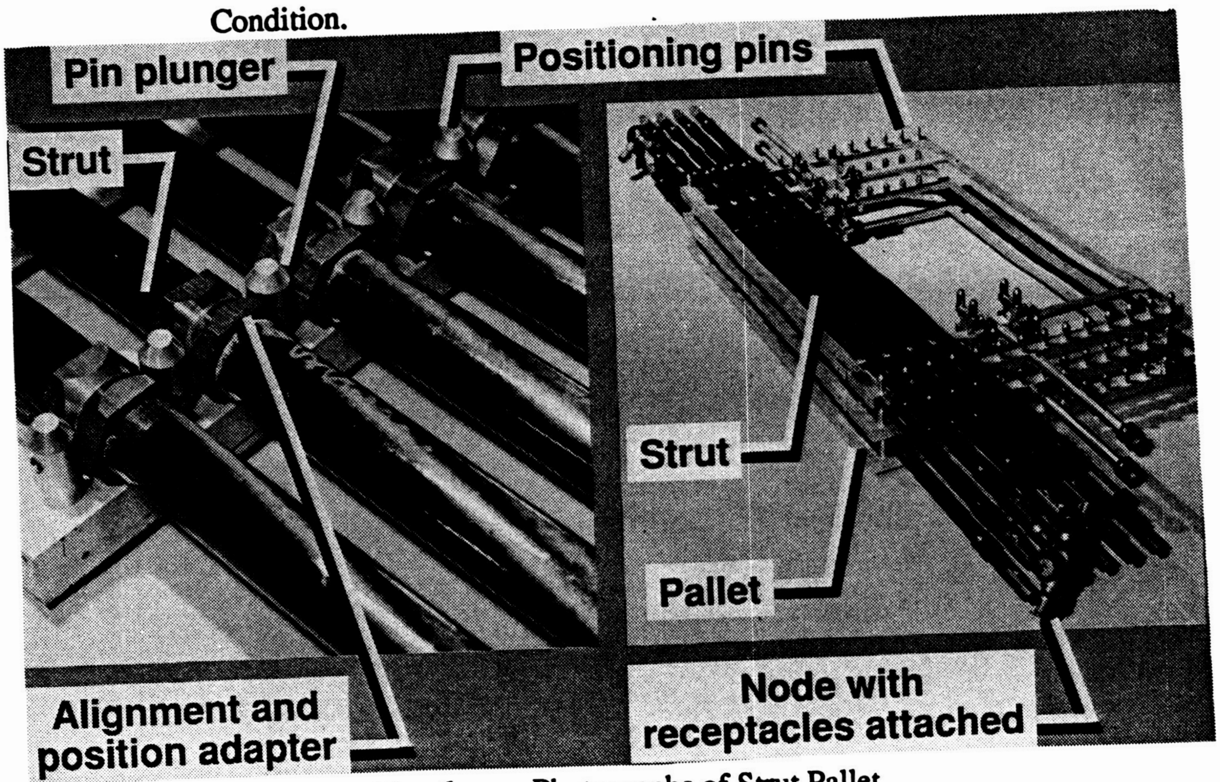

Fig. 6 - Photographs of Strut Pallet.

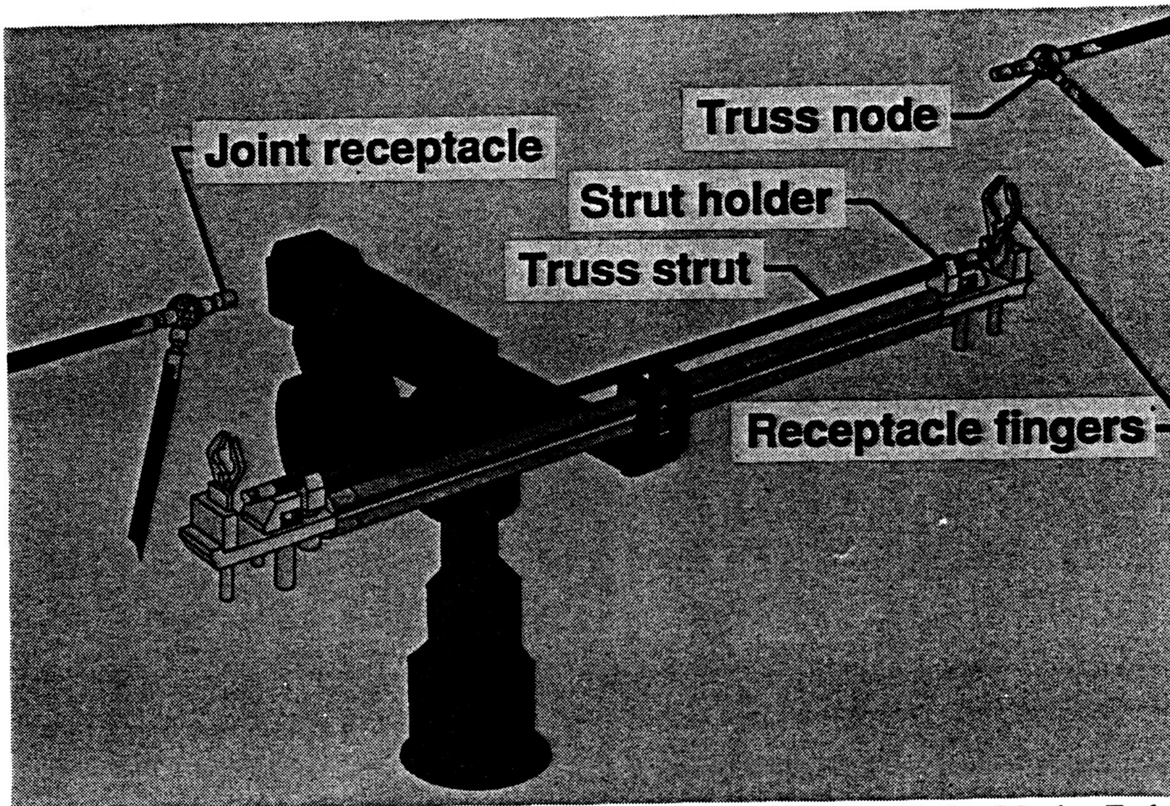

Fig. 7a - Sketch Demonstrating Operation of Robot End Effector (Robot Moving End Effector with Strut into Position to Grasp Node/Joint Receptable).

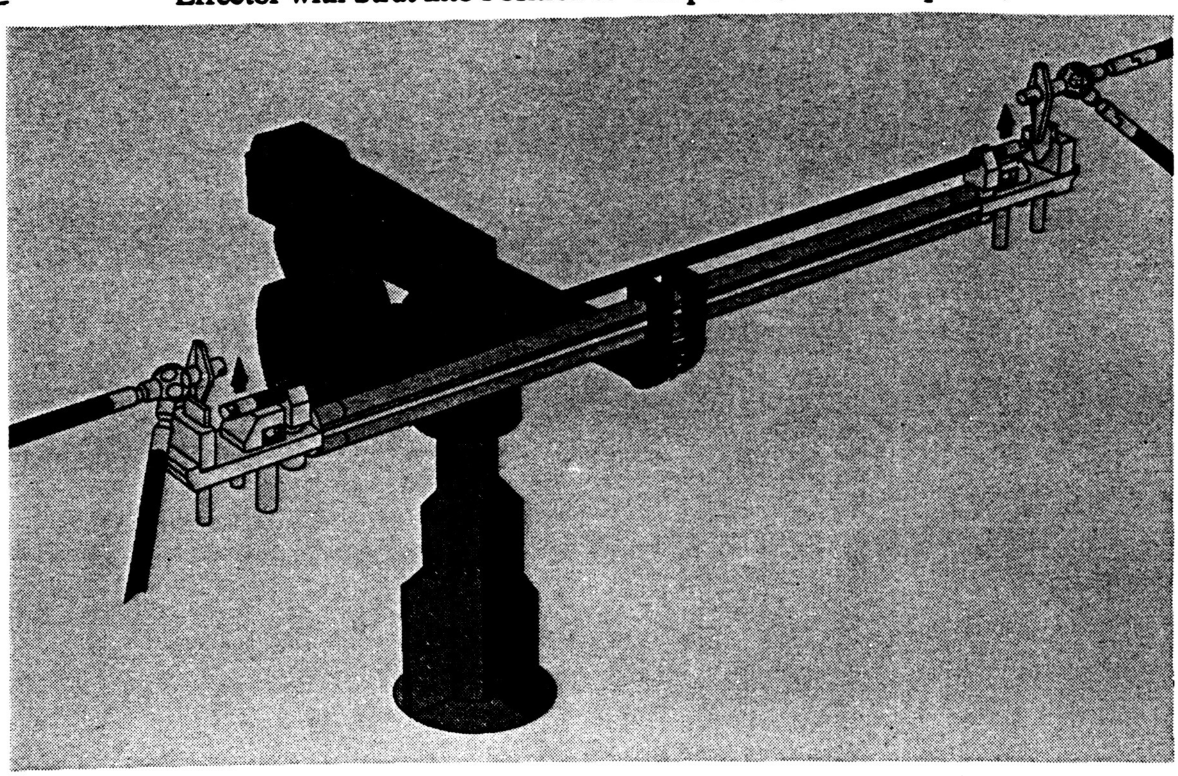

Fig. 7b - End Effector in Position to Insert Strut into Truss.

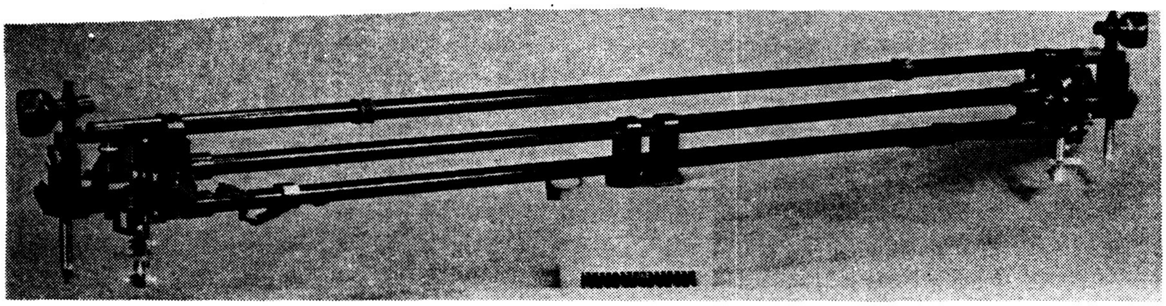

Fig. 8 - Photograph of End Effector Showing Complete Mechanical System (Sensors and Pneumatic Connectors are not Shown).

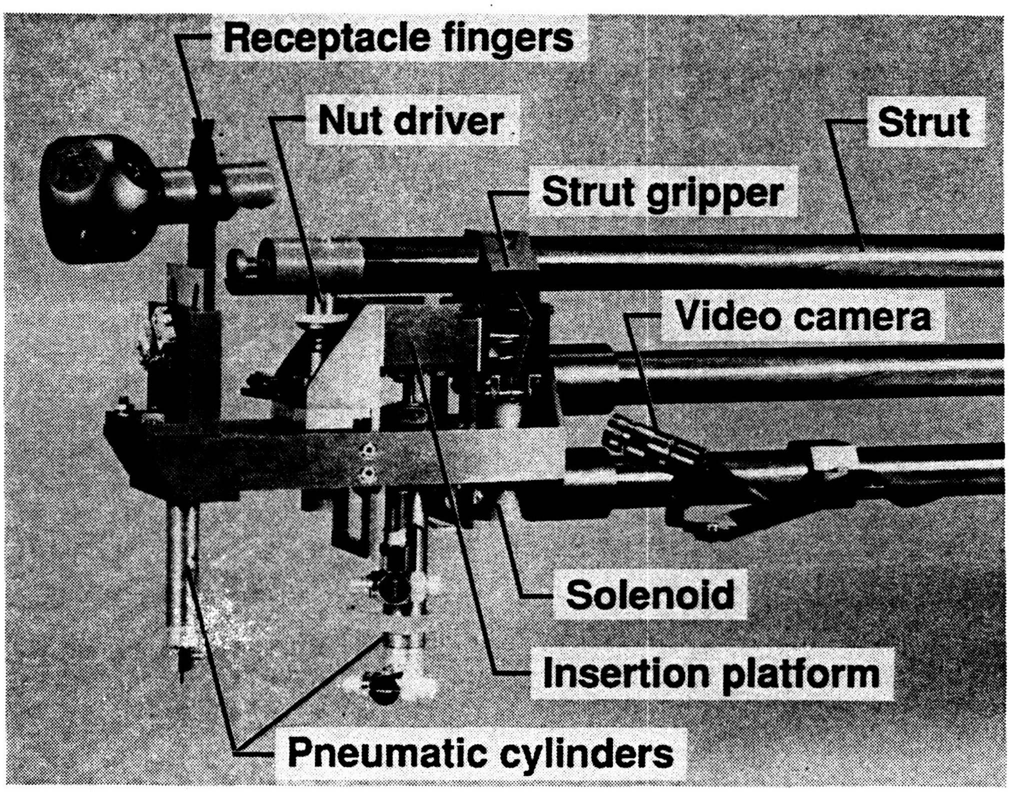

Fig. 9 - Photograph of One End of the End Effector.

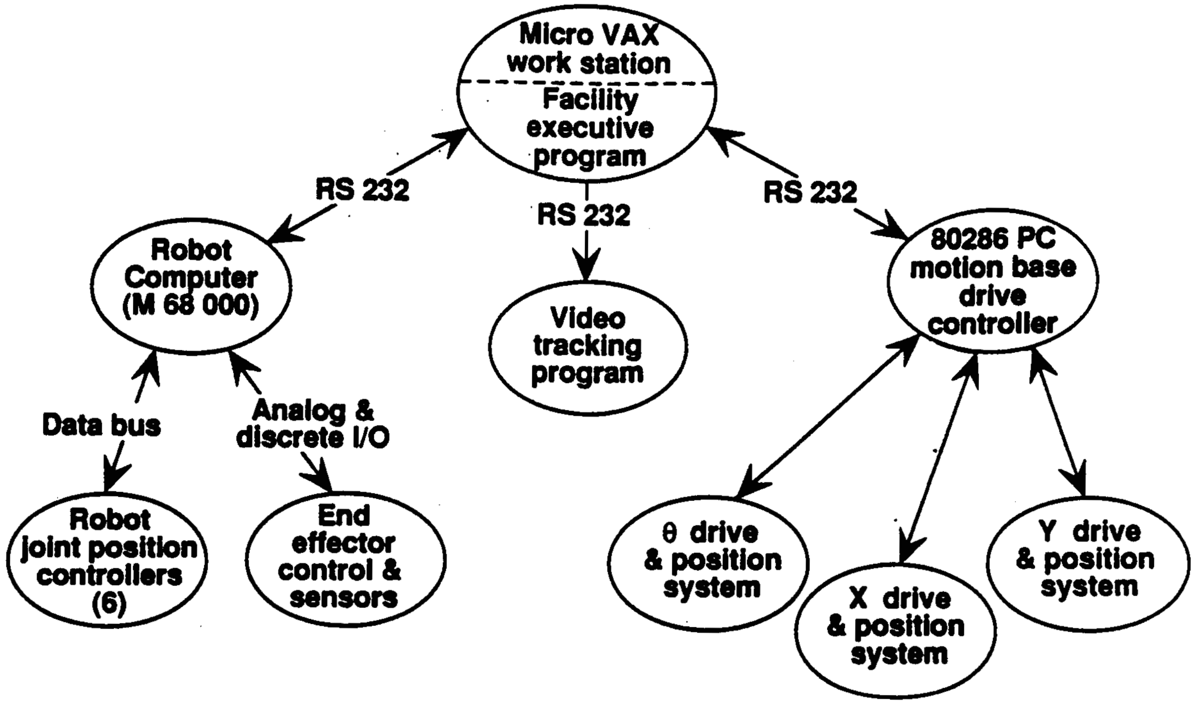

Fig. 10 - Schematic of the Facility Computer Control System.

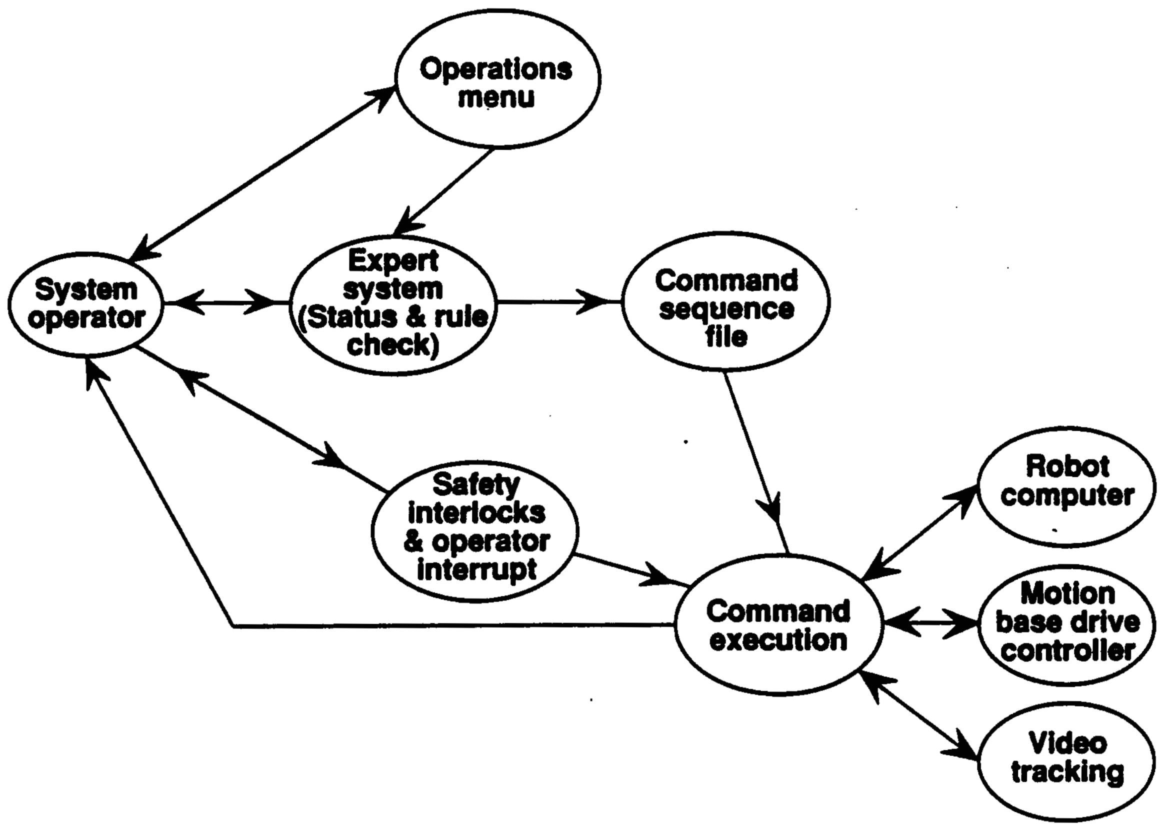

Fig. 11 - Schematic Illustrating Operation of the Computer Executive Program.

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16. Abstract

Future space missions such as polar platforms and antennas are anticipated to require large truss structures as their primary support system. During the past several years considerable research has been conducted to develop hardware and construction techniques suitable for astronaut assembly of truss structures in space. However, many potential problems associated with this assembly approach still exist and other methods of construction are being explored at the Langley Research Center. A research program has reeently been initiated to develop the technology and to demonstrate the potential for automated in-space assembly of large erectable structures. The initial effort will be focues on automated assembly of a tetrahedital truss composed of 2-meter members. The facility is designed as a ground based system to permit evaluation of assembly concepts and was not designed for space qualification. The system is intended to be used as a tool from which more sophisticated procedures and operations can be developed.

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