JOURNAL OF SPACECRAFT AND ROCKETS
Vol. 29, No. 4, July-August 1992

Mobile Transporter Concept for Extravehicular Activity Assembly of Future Spacecraft

Judith J. Watson,* Harold G. Bush,* Walter L. Heard Jr.,* and Mark S. Lake*
NASA Langley Research Center, Hampton, Virginia 23665
and
J. Kermit Jensen,† Richard E. Wallsom,‡ and James E. Phelps†
Lockheed Engineering and Sciences Company, Hampton, Virginia 23666

This paper details the ground test program for the NASA Langley Research Center mobile transporter concept. The mobile transporter would assist extravehicular activity astronauts in the assembly of the Space Station Freedom. One-*g* and simulated 0-*g* (neutral buoyancy) tests were conducted to evaluate the use of the mobile transporter. A three-bay (44 struts) orthogonal tetrahedral truss configuration with a 15-ft square cross section was repeatedly assembled by a single pair of pressure suited test subjects working from the mobile transporter astronaut positioning devices. The average unit assembly time was 28 s/strut. The results of these tests indicate that the use of a mobile transporter for extravehicular activity assembly of a space station size structure is viable and practical. Additionally, the mobile transporter could be used to construct other spacecraft such as the submillimeter astronomical laboratory, space crane, and interplanetary (i.e., Mars and lunar) spacecraft.

Introduction

THE design and construction of large space structures has been studied extensively at the NASA Langley Research Center (LaRC).[1-4] From these studies, the erectable structures concept emerged, whereby large truss structures such as platforms or curved reflectors are erected (i.e., assembled) from individual struts and nodes. Studies[5-9] have been conducted on manual assembly by astronauts in extravehicular activity (EVA), assembly by astronauts in EVA mechanically aided by a mobile work station, and fully automated assembly of large platforms. These studies have identified efficient ways of assembling structures in EVA that can be applied to the assembly of the Space Station Freedom (SSF) truss beam and other large truss structures. The SSF baseline configuration is shown in Fig. 1. The primary structure is an erectable truss beam consisting of a series of 5-m cubic segments (bays). A proposal[10,11] for on-orbit construction of the Space Station truss beam makes use of a mobile work station concept and two astronauts in EVA. This concept is called the mobile transporter (MT). LaRC has a research program to study this concept and its usefulness for construction during the SSF buildup flights, as well as for maintenance, repair, and growth activities after SSF is operational.

The objective of this paper is to present the mobile transporter ground test program, including 1-*g* and simulated 0-*g* (neutral buoyancy) tests. Results of assembly time lines will be discussed, as well as proposed uses of the mobile transporter for assembly of future spacecraft.

Received March 2, 1990; presented as Paper 90-1049 at the AIAA/ASME/ASCE/AHS/ASC 31st Structures, Structural Dynamics, and Materials Conference, Long Beach, CA, April 2-4, 1990; revision received Aug. 28, 1991; accepted for publication Aug. 31, 1991.

*Aerospace Technologist, Spacecraft Structures Branch, Mail Stop 199. Member AIAA.

†Engineer, Structures and Materials Department, 144 Research Dr.

‡Engineer, Structures and Materials Department, 144 Research Dr. Associate Fellow AIAA.

Mobile Transporter Concept

A sketch of the MT as envisioned for the assembly of the SSF is shown in Fig. 2. The MT would be folded in the Shuttle cargo bay and remotely deployed to an upright position on-orbit. The truss is assembled one bay at a time above the MT platform by two EVA astronauts. The astronauts are secured in foot restraints attached to astronaut positioning devices (APDs). After the crew has assembled a bay, the MT drawbar extends (as shown in Fig. 2) pushing the MT one bay length along the truss longitudinal axis. The next contiguous bay is then assembled, after which the drawbar is retracted to grasp the next nodal joint guide pins and then extended to move the transporter into position for assembly of the next bay. In this way, the MT "walks" along the truss as the truss is being assembled. The truss hardware is packaged in stowage canisters that are attached to the MT platform. The platform is also used to transport SSF operational equipment that requires integrated installation during the primary truss assembly. A Shuttle-type remote manipulator arm attached to the MT is envisioned to support these tasks. Utility trays that would house the electrical and utility lines of SSF would be attached inside of the primary truss structure. A scenario to be discussed later would allow the trays to be deployed and then attached directly to the truss nodes during truss assembly.

Test Program

Test Hardware

Mobile Transporter Test Article

In Fig. 3, the MT test article is shown. This test article was used in simulations for construction of the space station truss conducted in 1 *g* at LaRC and in neutral buoyancy at the Marshall Space Flight Center's Neutral Buoyancy Simulator (NBS). The MT test article was supported on a tower and remained stationary during the tests. The truss structure was assembled one bay at a time under the transporter. When a bay was completed, it was moved out of the work area by the drawbar, thus producing the relative motion between the truss and MT to simulate the MT walking along the completed truss structure. A remote manipulator arm was not required nor used for these tests.

The APDs could be moved one bay length forward or aft as indicated by the arrows in the sketch as well as in a 360-deg motion providing the astronauts adequate positioning capabil-

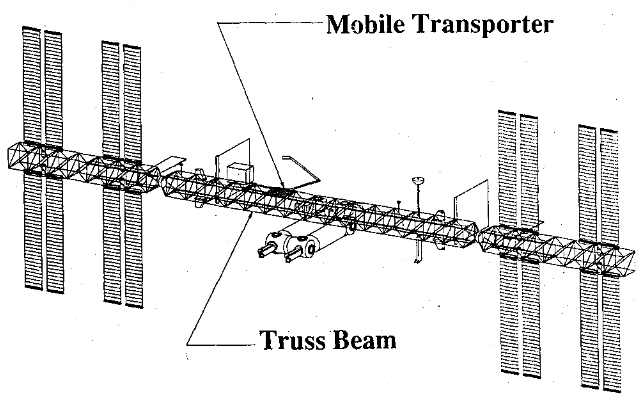

Fig. 1 Space Station Freedom baseline configuration.

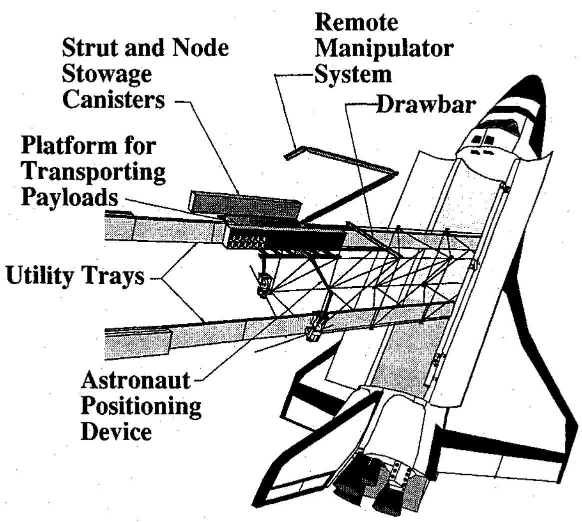

Fig. 2 EVA/mobile transporter concept for assembly of Space Station Freedom.

ity for assembly. As indicated in Fig. 2, the preferred position for the EVA astronauts is with their heads pointing away from the MT. This orientation provides the best visibility and least obstructed work area. However, for comfort and safety reasons, the test subjects were positioned with their heads pointing toward the MT (vertical) during the 1-g and neutral buoyancy tests.

The two rectangular canisters shown attached to the top of the MT are for stowage of truss struts and nodes. Although the size of the NBS test facility limited the amount of truss that could be assembled to only three bays (44 struts and 16 nodes), the canisters were sized to hold enough struts and nodes for assembly of 10 bays (135 struts and 48 nodes) of truss. Struts could be removed by the test subjects from any location along the canister. The nodes were stowed in compartments in the canisters. The compartments were sized to hold two nodes at a time, although only one node was stowed in a given compartment for the present tests. There were 12 node compartments (24-node capacity) located at one end of each canister. To minimize the required number of trips to the stowage canisters by the test subjects during truss assembly, temporary stowage of two struts and two nodes was provided at each APD foot restraint.

The APDs, drawbar, and node latches on the drawbar were hydraulically powered. The controls were located at two remote consoles. Each console was operated by one test engineer who could view the activity. The coarse movements of the test subjects to the strut/node canister and then to the vicinity of a work site were easily performed by the console operators following simple voice commands from the test subjects of "ready" when ready to move, or "stop" when appropriate. The rate of motion for the test subjects and drawbar was approximately 1 ft/s. If desired, vernier adjustments could be requested by the test subjects through additional voice commands until the test subject was satisfied with his working position.

Truss Configuration and Hardware

An orthogonal tetrahedral truss (OTT) (Fig. 4) was used for the tests discussed in this paper primarily because of the operational benefits it exhibits over the Warren-type truss[12] currently baselined for the SSF. The MT can be used to assemble either truss configuration; however, the OTT geometry simplifies the logistics of component stowage, the assembly procedures that must be followed by the test subjects, and the installation of utility trays. The truss tested in the present study had a 15-ft square cross section. In order to meet MT design and fabrication scheduling requirements, the cross-sectional dimensions had to be selected early, before NASA selected the 5-m (16.4-ft) truss for the SSF baseline configuration.

The truss hardware consists of struts (termed longerons, battens, and diagonals, as indicated in Fig. 4) and nodes. Guide pins attached to the truss nodes form the interface

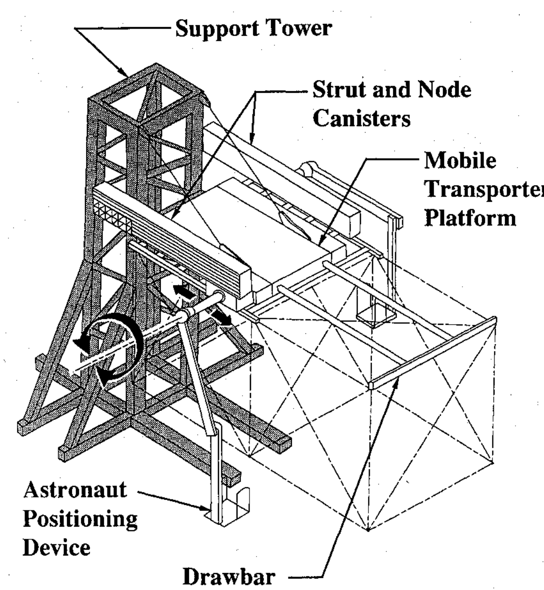

Fig. 3 Sketch of mobile transporter test article.

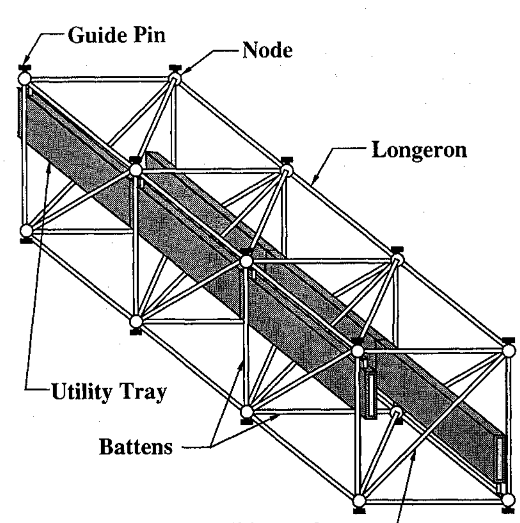

Fig. 4 Truss configuration with utility trays.

between the MT guide rails and the truss structure. The struts were 2-in.-diam aluminum tubes with a fitting at each end to permit side insertion into the mating node fitting during truss assembly. For the 1-*g* tests, the struts were fabricated from thin-wall 7075 aluminum tubing to minimize their weight. The struts for the neutral buoyancy tests consisted of welded sections of 6061 aluminum tubing with a ⅛-in. wall thickness. The welded sections contained internal airtight chambers for positive buoyancy and flooded chambers to which lead shot could be added or removed for neutral buoyancy adjustment.

A typical truss node is shown in Figs. 5. The nodes (Fig. 5a) were modified spheres to which up to 26 fittings could be attached for accommodating strut and payload connections. The joint used was designed at NASA LaRC to facilitate EVA assembly while retaining structural efficiency.[13] A pattern was painted on the strut and node fittings to provide a highly visible lock position indicator. Figure 5b shows the pattern when the strut locking collar is positioned for insertion into mating node fitting. Figure 5c shows the pattern when the strut is captured in the node fitting. With the locking collar in this position, the strut-to-node joint is secure but will not provide the design structural stiffness. By manually rotating the locking collar 45 deg, the locking pattern becomes a wide bar (Fig. 5d) and the joint is locked into its design preloaded condition. The nodes could not be made neutrally buoyant without adding external flotation. Thus, following assembly of a given bay, and before the truss was moved by the draw-bar, flotation was attached by scuba divers to each of the lower nodes on each side of the truss to neutrally buoy it and the node directly above it. In this way the truss neutral buoyancy is maintained.

a)
b)
c)
d)

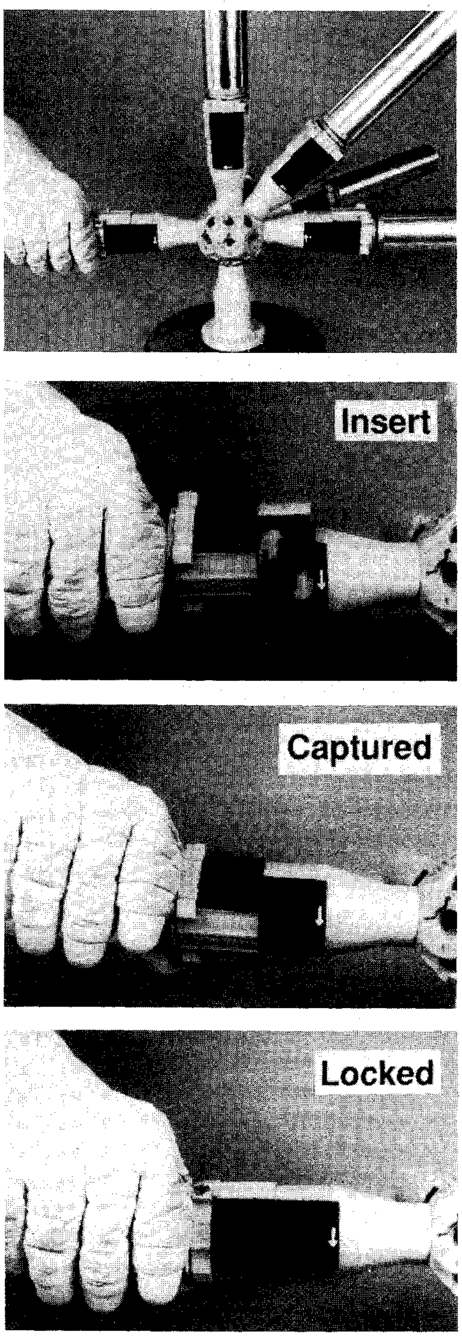

Fig. 5 Attachment of strut to node.

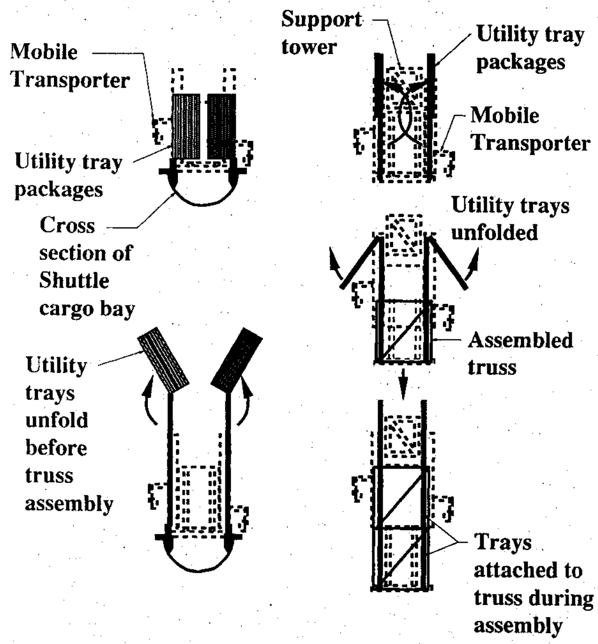

Fig. 6 Utility tray deployment: a) concept for space station utility tray deployment; b) utility tray deployment in neutral buoyancy.

Utility Trays

A major concern associated with SSF construction is installation of the utility system that is vital to the SSF operation. This utility system will consist of electrical and fluid utility lines housed in protective trays that are attached to the inside of the primary truss structure (Fig. 4). Although electrical and fluid line connections were beyond the scope of this investigation, a scenario for integrated installation of the utility trays during truss assembly was addressed. This scenario permits folded bay-length packages of tray segments to deploy automatically to their proper positions prior to assembly of the supporting bay of the truss, as shown in Fig. 6a. The deployed tray segments can then be attached directly to the truss nodes during truss assembly. This procedure, by minimizing astronaut handling, is designed to have a minimal impact on truss assembly times.

The integrated utility trays were installed only in neutral buoyancy tests. Two neutrally buoyant tray systems were provided, one for each side of the three-bay truss (Fig. 4). An individual tray was nominally a 3 × 15 × 0.5 ft aluminum box. Three trays were linked together with simple hinges to form the utility tray system for one side of the truss. The utility trays had tubular members attached at intervals along the tray edge corresponding to truss node locations. These tubular members had end fittings identical to the strut end fittings (Fig. 5) that attached the trays to the truss nodes during assembly. Figure 6b shows the method used to install the trays during assembly of the truss (the MT and the MT support tower are represented by dashed lines). Since the MT support tower would interfere with the initial inward unfolding of the utility tray packages, the packages were predeployed one bay length. The two partially unfolded tray packages were then supported in place on the support tower, simulating the temporary tray support system in the Shuttle cargo bay. The neutral buoyancy tests began with assembly of the initial truss bay and attachment of the first tray to two of the nodes. The pins used to secure the second and third trays in the folded configuration were then pulled and the trays unfolded with the aid of scuba divers (simulating springs) as the drawbar extended to move the completed bay out of the work area. The remaining bays of truss were assembled in sequence, and the utility trays were attached at the appropriate node locations.

Assembly Tests

Assembly tests were conducted both in 1-*g* and in neutral buoyancy. The 1-*g* tests were performed with the test subjects in street clothes. The neutral buoyancy tests were performed with the test subjects in scuba and also with the test subjects in pressure suits [extravehicular mobility units (EMUs)]. These tests were conducted in an attempt to isolate the effects of water drag and pressure suit encumbrance on assembly times. Because of the effects of gravity, the assembly procedures developed for the 1-*g* tests were necessarily somewhat different from those used for the 0-*g* tests. However, the 1-*g* assembly procedure, though not as efficient as the neutral buoyancy procedure, was duplicated in some of the scuba neutral buoyancy tests for comparison of assembly times. The dimensions

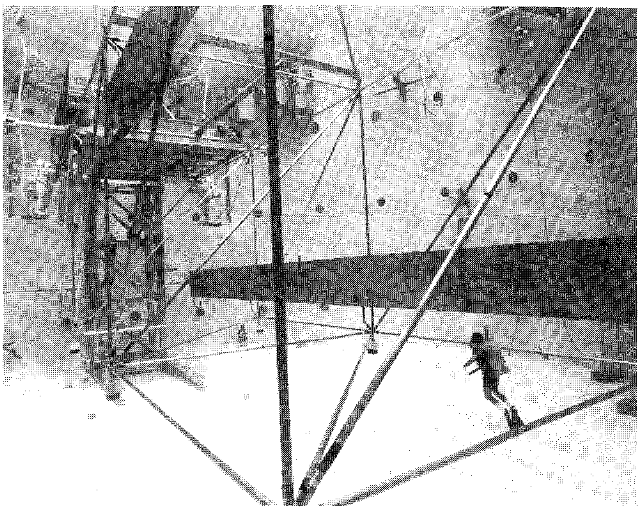

Fig. 9 Simulated 0-*g* truss assembly and integration of utility trays.

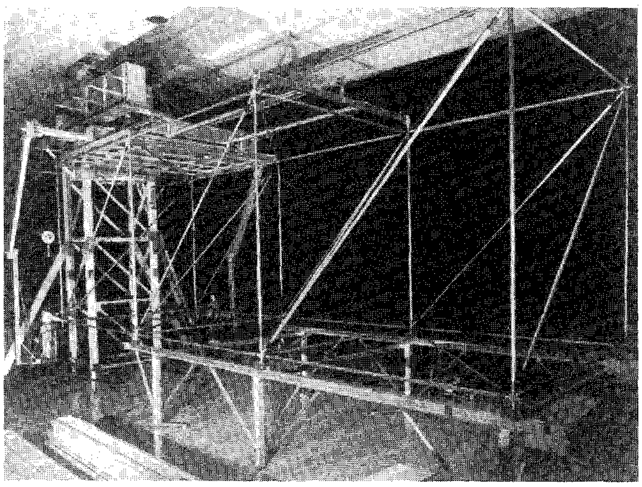

Fig. 7 Three-bay space station truss assembly in 1-*g* with mobile transporter.

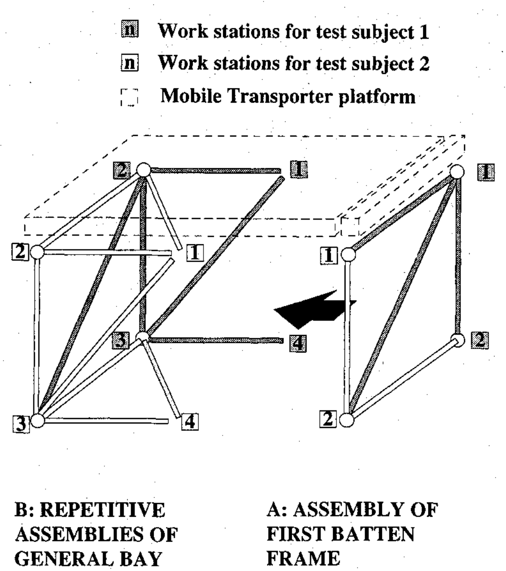

Fig. 8 Assembly procedure for neutral buoyancy tests.

of the NBS test facility (75 ft in diameter and 40 ft deep) limited the amount of truss that could be continuously assembled to only three bays. Complete or partial truss disassembly was accomplished by scuba divers between assemblies during a given test.

The assembly procedures used for the pressure suited neutral buoyancy tests were also duplicated in scuba tests. The differences in assembly times were assumed to be attributable to pressure suit encumbrance. The following three scenarios were used for the pressure suited assembly tests: 1) consecutive three-bay truss assemblies without integrated installation of utility trays (with associated scuba disassemblies), 2) consecutive three-bay truss assemblies with integrated installation of utility trays (with associated scuba disassemblies), and 3) an initial three-bay truss assembly with integrated utility trays followed by consecutive two-bay assemblies (with associated scuba disassemblies of two bays). During the scuba disassemblies, the test subjects were idle. The duration of a test was limited to approximately 2 h by NBS safety rules, which permitted only one decompression stop for the test subjects when being brought to the surface. The test scenarios were developed in order to build as much truss structure as possible in the limited time available for a given test. Tethering of the hardware was not addressed in these tests.

1-g Tests

Figure 7 shows an assembled three-bay truss in 1-*g*. The truss support frame, shown at the lower right, was used in the 1-*g* tests to carry the weight of the truss after assembly. To facilitate handling by the test subjects, it was necessary to develop unique assembly procedures for the 1-*g* tests because of gravity effects. A short bracket attached to the tower was used as a prop to help support the upper truss struts as they were being passed from the test subject on the far side of the truss to the test subject on the near side. When a lower truss member was being passed across the truss, an engineer on the floor assisted by manually supporting the free end of the strut.

Numerous truss assemblies were performed in 1-*g* by a number of different subjects, including two NASA astronauts, in order to check out the hardware, develop efficient procedures, and to train test subjects and console operators. Following these preliminary tests, four timed tests were performed in which well-trained engineers were used as test subjects and console operators. A three-bay truss was assembled for each of these tests.

Neutral Buoyancy Tests

Figure 8 is a schematic showing the assembly sequence used for the neutral buoyancy tests. After the first batten frame was assembled, all remaining bays were assembled identically fol-

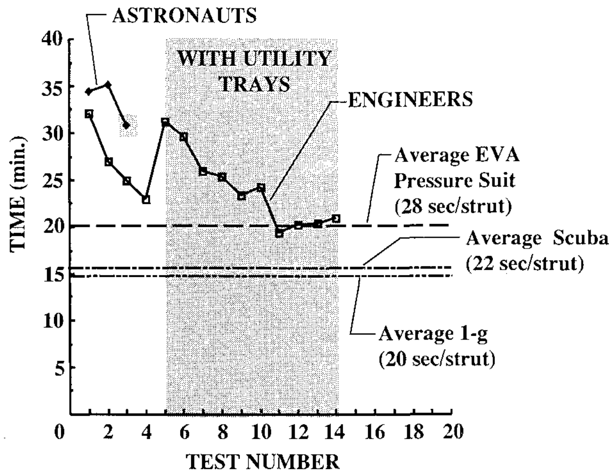

Fig. 10 Summary of three-bay truss assembly rates.

lowing a very simple and easily memorized routine. Test subject 1 always moves in a counterclockwise direction, whereas test subject 2 always moves in a clockwise direction. Struts and nodes were removed from the stowage canister and temporarily stowed on the APD foot restraint handrails when the test subjects passed the canisters so that no long distance translations are required for material resupply.

Figure 9 shows a neutral buoyancy test in progress with integrated installation of utility trays. As with the 1-*g* tests, numerous assemblies for hardware checkout, procedural development, and personnel training were performed in scuba. Several additional pressure suit tests were also performed to verify the test setup. Two different pairs of test subjects were used in these tests as well as two pairs of console operators. Scuba personnel assisted in safety and in disassembly of the truss structure. Fourteen timed assembly tests were performed, during which a total of 46 bays of truss (tests 1–13 were three-bay assemblies only, whereas test 14 was a three-bay assembly followed by two consecutive two-bay assemblies) were assembled by a pair each of trained engineer test subjects and console operators. In the last ten of these tests 34 bays of truss were assembled with integrated installation of utility trays. Three additional tests were performed by a pair of NASA astronauts to provide them with some hands-on experience with the assembly procedures and hardware and to solicit their comments for consideration.

Test Results

Figure 10 presents the total assembly rates for three-bay truss assembly times as a function of test number. In this section, the assembly times are discussed for trained engineer and astronaut test subjects. As shown in the figure, the assembly times generally decreased as the test subjects and the console operators became more experienced. An increase in assembly rate occurs when the utility trays are integrated into the assembly procedure; however, as the test subjects became more experienced and developed their techniques, the assembly times with utility trays became faster than the assembly times without utility trays. The astronaut assembly times were somewhat greater than those from the first few tests of the experienced test subjects and significantly greater than the times realized in the latter tests. One of these astronauts had no pervious experience with the MT or the truss hardware and relatively few hours of neutral buoyancy experience in the pressure suit. The other astronaut had performed several 1-*g* assemblies with the MT using the same truss hardware, but different assembly procedures. However, the astronaut times also show a generally downward trend as experience is gained. The average assembly time for the three-bay truss assembly with integrated utility trays was 20 min (28 s/strut) in neutral buoyancy with EVA pressure suits. This average is taken from the last four three-bay build sequences at which time the engineers were considered to be fully trained on the assembly procedures and hardware operation. These results demonstrate the importance of using well-trained test subjects to verify assembly times and evaluate hardware or concepts.

Figure 10 also shows a comparison of the average of three-bay truss assembly rates performed in 1-*g* with the test subjects in street clothes, and in neutral buoyancy with the tests subjects in either scuba or pressure suits. The averaged rates were obtained from tests using the same pair of trained engineer test subjects and the same pair of trained console operators in order to isolate the effects of water drag and pressure suit encumbrance on assembly time. The neutral buoyancy tests in scuba included integrated installation of utility trays, whereas utility tray installation was not possible with the 1-*g* test setup. The average assembly time for the three-bay truss without utility trays was approximately 15 min (20 s/strut) in 1-*g* and 16 min (22 s/strut) in scuba. Because these assembly times are so close and the scuba and 1-*g* test procedures differed, realistic conclusions cannot be drawn on the effects of water drag.

The results from the scuba and pressure suit neutral buoyancy tests can be used to estimate the effects of pressure suit encumbrance because these tests were essentially idential except for the test subjects' attire. The average assembly time for a three-bay truss was approximately 4 min longer in pressure suits than in scuba. These results suggest that, with the particular assembly concept studied, a 5–6-s/strut penalty in assembly time is directly attributable to the current pressure suit (EMU) and glove design.

Mobile Transporter Versatility for Future Spacecraft

The SSF is anticipated to become an orbiting construction site for various spacecraft that cannot be launched preassembled into space. The MT promises to be a powerful tool, if not a necessary one, for the EVA capability and productivity of astronauts at this in-space construction facility. In this section, the MT operational capabilities are applied to the assembly of future spacecraft.

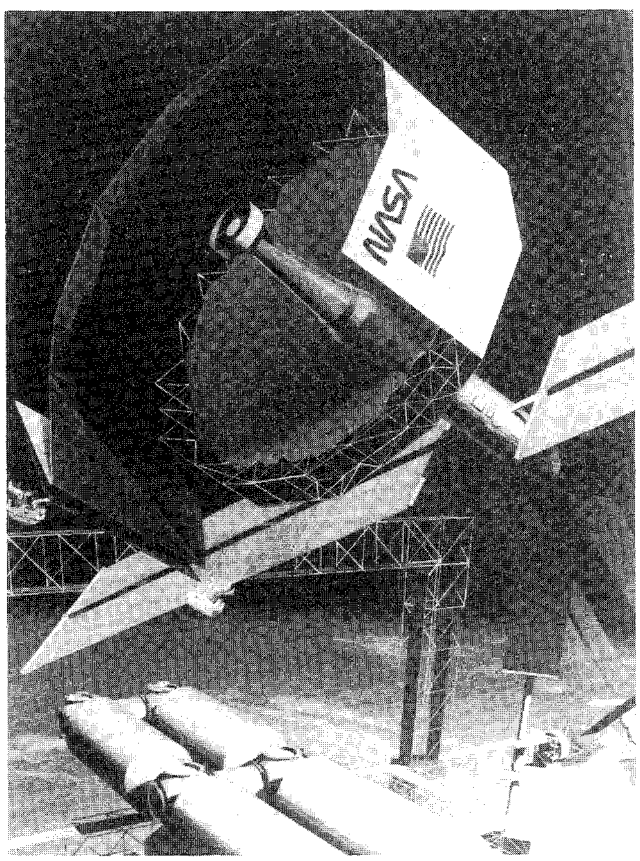

Fig. 11 Proposed Large Submillimeter Astronomical Laboratory.

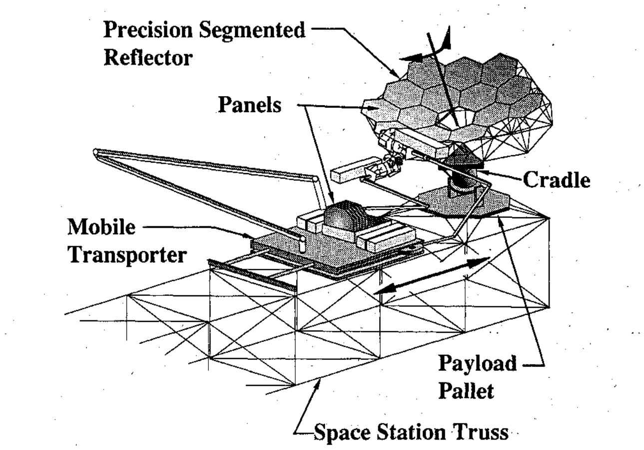

Fig. 12 Construction of precision segmented reflector from mobile transporter.

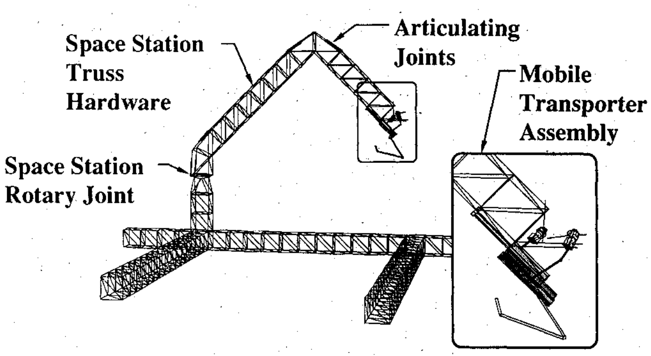

Fig. 13 Space crane assembled with mobile transporter and space station components.

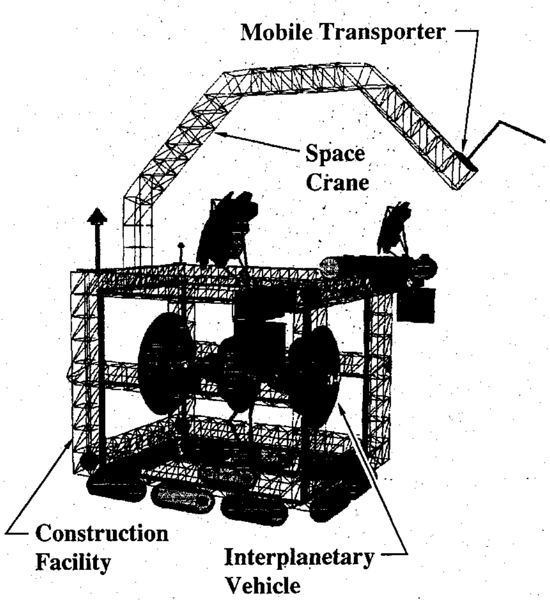

Fig. 14 Interplanetary spacecraft assembly using the mobile transporter and space crane.

Submillimeter Astronomical Laboratory

A potential early candidate for assembly from the station is the submillimeter astronomical laboratory shown in Fig. 11. This device incorporates a near optical quality precision segmented reflector (PSR)[14] made up of precise panels, each of which is actively controlled to maintain overall accuracy. The active control system requires an accurate, stable, and stiff foundation, which is achievable through use of a truss structure. The MT with EVA astronauts could be used to assemble this kind of structure and attach the panels that comprise the PSR. In Fig. 12, a PSR assembly concept is shown on SSF. The payload pallet provides the structural interface between the cradle and SSF. The cradle provides tilt, as well as rotation, to the reflector to maintain the construction site within reach of the MT and astronauts. The MT serves as a movable base, supporting and positioning astronauts to enable the assembly of struts, nodes, and panels, a supply of which is positioned nearby on the MT. As each "ring" of panels and supporting truss is added to the rotating assembly, the MT translates radially outward from the rotating cradle to permit the installation of the next ring. The astronaut positioning capability of the MT is essential to efficiently assemble components of the reflector.

Space Crane and Interplanetary Spacecraft Assembly

Although SSF can be used as a construction facility for large spacecraft, construction activities may interfere with other research functions of the station. A large integrated in-space construction facility[15] could serve as an alternative construction base. This facility would be erected on-orbit using space station truss hardware with an MT. An important feature of this facility is the highly maneuverable space crane shown in Fig. 13. The space crane[15,16] would also be built with the MT from space station truss components. A space station rotary joint and articulating joints would provide for the crane's manueverability while the MT with its remote manipulator system (RMS) would serve as an end effector. This space crane would be used to transfer and position spacecraft components and material from the Shuttle cargo bay into the construction site for final assembly into a large interplanetary (i.e., Mars or lunar) spacecraft, as shown in Fig. 14.

Aerobrakes, ranging in size from 90 to 120 ft in diameter, are anticipated components of the interplanetary spacecraft that will have to be constucted on-orbit before assembly into the spacecraft. One concept for these aerobrake structures[17] describes the structure as consisting of two major components: a tetrahedral support truss and a heat shield composed of individual hexagonal panels. Again, the MT could be a valuable tool in the assembly of these components. The MT can be used to assist the astronauts assembling the aerobrake support truss as described with the PSR support truss structure. However, some special handling aids may be required due to the size of the struts required for the aerobrake. Figure 15 shows how the space crane's MT can assist in placing the heat-shield panels on the aerobrake truss structure.

Assembly Rates for Future Truss Structures

A previous construction experiment,[9] the Assembly Concept for Construction of Erectable Space Structure (ACCESS), demonstrated that simulated 0-g tests are good indicators for on-orbit assembly rates. ACCESS was a 45-ft truss consisting of 93 struts and 33 nodes built on-orbit during a Shuttle flight (STS-61B) in November 1985. Simulated 0-g tests indicated the structure could be built by EVA astronauts in 22 min. On-orbit, the assembly time for the truss was 26 min. Because of this good correlation of simulation to flight data, assembly rates for the future spacecraft truss structures

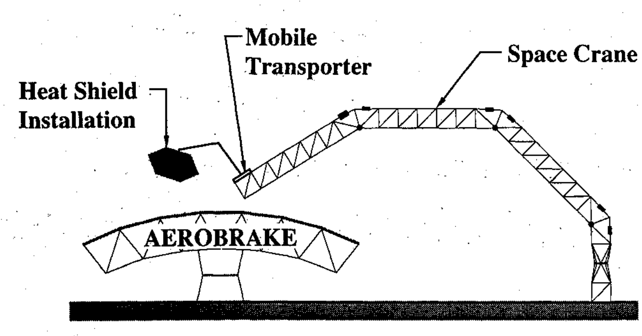

Fig. 15 Assembly of aerobrake using the space crane.

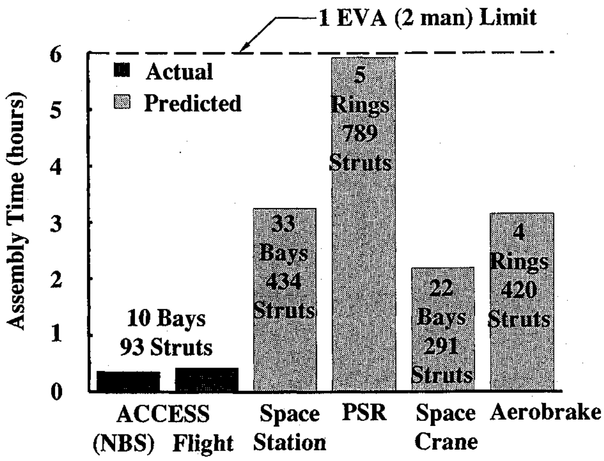

Fig. 16 Assembly times for various spacecraft truss structures using the mobile transporter.

discussed in this paper can be approximated using the assembly rate data from the MT 0-*g* simulation tests. Figure 16 shows the ACCESS assembly rates both for simulated 0-*g* tests and the flight assembly test. The truss structure assembly times predicted for various spacecraft discussed in this paper are also shown. These assembly times are based on a two-man EVA crew, and an MT assembly rate of 28 s/strut. (Since the PSR, space crane, and aerobrake structures are relatively new concepts for EVA assembly, further study and definition of assembly procedures should be required for more accurate assembly times.) Note that for all of the truss structures listed, the predicted assembly time is within the time limit of 6 h for a single two-man EVA.

Concluding Remarks

The NASA Langley mobile transporter concept has been presented for the assembly of large space structures. A test article was designed to closely simulate the outward appearance and functions of a flight version for the construction of the Space Station Freedom truss structure. Assembly tests were conducted both in 1-*g* and in neutral buoyancy. Initial assembly tests were performed to check out the hardware, develop efficient procedures, and train test subjects and console operators. Eight timed neutral buoyancy tests were conducted to evaluate the use of a mobile transporter concept in conjunction with EVA astronauts. A three-bay orthogonal tetrahedral truss configuration (consisting of 44 2-in.-diam aluminum struts) with a 15-ft square cross section was repeatedly assembled by a single pair of trained pressure suited test subjects working from the mobile transporter astronaut positioning devices. The test subjects were translated to various work sites at the approximate rate of 1 ft/s. The unit assembly time averaged from the last four assemblies of the three-bay truss (44 struts) was 28 s/strut, or 6 min/bay, which includes integrated installation of utility trays. Tethering of the hardware was not addressed in these tests.

The results of these tests indicate that EVA assembly of a space station size structure by using a mobile transporter equipped with astronaut positioning devices is viable and practical. Rapid assembly times can be expected and are dependent primarily on the rate of translation permissible for on-orbit operations. The concept used to demonstrate integrated installation of utility trays requires minimal EVA handling and, consequently, as the results show, has little impact on overall assembly times. Additionally, a discussion has been presented on application of the MT to the construction of many spacecraft whose assembly appears very impractical without an MT to support astronaut EVA. Preliminary assembly times for these spacecraft truss structures indicate that the structures could be built within a single two-man EVA. Clearly, the test results indicate that a mobile transporter with features described herein is the necessary versatile component that makes orbital spacecraft assembly both possible and practical.

References

[1]Bush, H. G., and Mikulas, M. M., Jr., "A Nestable Tapered Column Concept for Large Space Structures," NASA TM X-73927, July 1976.

[2]Mikulas, M. M., Jr., Bush, H. G., and Card, M. F., "Structural Stiffness, Strength, and Dynamic Characteristics of Large Tetrahedral Space Truss Structures," NASA TM X-74001, March 1977.

[3]Bush, H. G., Mikulas, M. M., Jr., and Heard, W. L., Jr., "Some Design Considerations for Large Space Structures," *AIAA Journal,* Vol. 16, No. 4, 1978, pp. 352–359; also, AIAA Paper 77-395, March 1977.

[4]Heard, W. L., Jr., Bush, H. G., Walz, J. E., and Rehder, J. J., "Structural Sizing Considerations for Large Space Platforms," *Journal of Spacecraft and Rockets,* Vol. 18, No. 6, 1981, pp. 556–564; also, AIAA Paper 80-0680, May 1980.

[5]Jacquemin, G. G., Bluck, R. M., Grotbeck, G. H., and Johnson, R. R., "Development of Assembly and Joint Concepts for Erectable Space Structures," NASA CR-3131, Dec. 1980.

[6]Bement, L. J., Bush, H. G., Heard, W. L., Jr., and Stokes, J. W., Jr., "EVA Assembly of a Large Space Structure Element," NASA TP-1872, June 1981.

[7]Heard, W. L., Jr., Bush, H. G., Wallsom, R. E., and Jensen, J. K., "A Mobile Work Station Concept for Mechanically Aided Astronaut Assembly of Large Space Trusses," NASA TP-2108, March 1983.

[8]Watson, J. J., Heard, W. L., Jr., and Jensen, J. K., "Swing-Arm Beam Erector (SABER) Concept for Single Astronaut Asssembly of Space Structure," NASA TP-2379, March 1985.

[9]Heard, W. L., Jr., Watson, J. J., Ross, J. L., Spring, S. C., and Cleave, M. L., "Results of the ACCESS Space Construction Shuttle Flight Experiment," AIAA Paper 86-1186, June 1986.

[10]Mikulas, M. M., Jr., Bush, H. G., Wallsom, R. E., Dorsey, J. T., and Rhodes, M. D., "A Manned-Machine Space Station Construction Concept," NASA TM 85762, Feb. 1984.

[11]Bush, H. G., Mikulas, M. M., Jr., Wallsom, R. E., and Jensen, J. K., "Conceptual Design of a Mobile Remote Mainpulator System," NASA TM 86262, July 1984.

[12]Sutter, T. R., and Bush, H. G., "A Comparison of Two Trusses for the Space Station Structure," NASA TM 4093, March 1989.

[13]Heard, W. L., Jr., Bush, H. G., Watson, J. J., Spring, S. C., and Ross, J. L., "Astronaut/EVA Construction of Space Station," AIAA Paper 88-2454, April 1988.

[14]Pawlik, E., Lin, R., and Fichter, W., "NASA's Precision Segmented Reflectors (PSR) Project," *Active Telescope Systems,* edited by François J. Roddier, Proc. SPIE, Vol. 1114, Society of Photo-Optical Instrumentation Engineers, Bellingham, WA, March 1989, pp. 374–386.

[15]Mikulas, M. M., Jr., and Dorsey, J. T., "An Integrated In-Space Construction Facility for the 21st Century," NASA TM-101515, Nov. 1988.

[16]Sutter, T. R., Bush, H. G., and Wallsom, R. E., "An Articulated-Truss Space Crane Concept," AIAA Paper 90-0994, April 1990.

[17]Dorsey, J. T., and Mikulas, M. M., Jr., "Preliminary Design of a Large Tetrahedral Truss/Hexagonal Heatshield Panel Aerobrake," NASA TM 101612, Sept. 1989.

Kerry T. Nock
Associate Editor