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OPERATIONAL EXPERIENCE AND DESIGN RECOMMENDATIONS FOR TELEOPERATED FLIGHT HARDWARE*

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ABSTRACT

Teleoperation (remote manipulation) will someday supplement/minimize astronaut extravehicular activity in space to perform such tasks as satellite servicing and repair, and space station construction and servicing. This technology is being investigated by NASA with teleoperation of two space-related tasks having been demonstrated at the Oak Ridge National Laboratory (ORNL). This paper discusses the teleoperator experiments conducted at ORNL for the Langley Research Center and summarizes the results of these experiments and the related equipment design recommendations. A general discussion of equipment design for teleoperation is also included.

INTRODUCTION

The level of man's activity in space is increasing at a very high rate and is accompanied by an accelerating requirement for more and more astronaut extravehicular activity (EVA) to deploy, repair, service, and resupply orbiting facilities. A possible alternative to EVA is to use automated and teleoperated manipulators, but both types have unresolved issues. Automated devices operate extremely well if the tasks are very precise, well defined, pre-programmed, and repetitive,but they do not perform well in an unstructured environment.

Teleoperation, having direct human control, is not dependent on structured environments, but will require a high level of manipulator dexterity and controllability for realistic space tasks. One of the difficulties in deciding where and how to apply teleoperators has resulted from not having a confident knowledge of their dexterous capabilities to perform complex tasks or of how long they will take to accomplish such tasks. The objective of this paper is to address these issues by employing a teleoperated manipulator controlled by highly skilled, experienced operators to accomplish typical tasks already accomplished by astronauts. This would demonstrate both the successful application of this technology as well as establish a data base of task completion times. The tasks chosen were the Fairchild satellite refueling coupling and the Assembly Concept for the Construction of Erectable Space Structures (ACCESS) I assembly. The Central Research Laboratories' (CRL) model M-2 teleoperator at ORNL was selected to perform these experiments.

TELEOPERATOR FACILITIES

The model M-2 teleoperator is part of ORNL's Remote Operation and Maintenance Demonstration (ROMD) facility. The ROMD facility was developed by the U.S. Department of Energy's Consolidated Fuel Reprocessing Program to demonstrate

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remote maintenance techniques for advanced nuclear fuel reprocessing equipment.[1] The model M-2 is a dual-arm, bilateral force reflecting, master-slave system developed jointly by CRL and ORNL and represents the state of the art in commercially available teleoperated manipulators.[2] The model M-2, in operation since FY 1983, incorporates a distributed, microprocessor-based digital control system. Two major assemblies comprise the M-2: (1) the slave package shown in Fig. 1 and (2) the master control station shown in Fig. 2. The slave performs "man-like" handling tasks in the remote environment. This package consists of a pair of arms, three television viewing cameras, lighting, and a 230-kg (500-lb) capacity auxiliary hoist. Each slave arm has a 23-kg (50-lb) continuous capacity, a 46-kg (100-lb) time-limited (peak) capacity, six degrees-of-freedom (D.F.), and a tong-type end effector. The slave is transported by a three-axis positioning system consisting of an overhead gantry bridge and trolley and telescoping tube assembly. A motorized joint at the telescoping tube interface provides 520 degrees of slave rotation in the horizontal plane.

Control of the slave is performed by a single operator from the master control station which consists of a pair of master arms, three 19-inch color television monitors, and an operator console. The master arms are kinematic replicas of the slave arms; each has a peak capacity of 25 lb. The handle on the master is a pistol grip and trigger type that provides slave tong control. The operator interfaces with the control system for other functions primarily through a CRT and touch-screen mounted in the operator console. Operating mode selection, force-reflection ratio selection, camera-lighting control, and system status diagnostics are available through this interface. Master-to-slave arm control is in real time with slave arm tip velocity capabilities up to 152 cm (60 in.) per second. The minimum slave arm loading which can be detected or "felt" at the master control arm is on the order of 1 lb or 1% of peak capacity.

Operator viewing of the remote work site is provided by the cameras mounted on the slave package. These include two boom-mounted cameras with four positioning D.F. (pan, tilt, boom extend-retract, and boom pivot) and motorized lens controls (zoom, focus, and iris) and one fixed camera mounted between the slave arms. The two boom-mounted cameras, one on each side, provide orthogonal views for depth information and viewing flexibility. The lower camera produces a wide angle view of the work site from a fixed position to give additional viewing information and information concerning master-to-slave arm spacial relationships. These camera views are commonly supplemented with facility and transporter mounted cameras. Camera and auxiliary hoist controls are also on the operator console. A joystick is used for overhead camera positioning, while rotary potentiometers provide camera lens zoom, focus, and iris control.

SATELLITE REFUELING COUPLING TELEOPERATION

Satellite refueling operations have been identified by NASA as a potential candidate for development as a remote operation. The refueling coupling, shown in Fig. 3, was developed by Johnson Space Center for manual operation by EVA astronauts. It was successfully demonstrated on the space shuttle by astronaut Sullivan.

This coupling was also operated using the model M-2 teleoperator. The coupling operation required the dexterous manipulation of both arms. This task was more intricate than those normally encountered in fuel reprocessing applications for which the design of the M-2 was optimized. The M-2 has a 100-lb capacity per arm, and the coupling weighed less than 7 lb; therefore, the operators were urged to use the utmost care during handling. This undoubtedly increased the amount of time required to complete the task. The bayonet-type mount on the coupling halves was engaged and disengaged without incident. The valves used to start and stop flow were operated using a standard-type ratchet wrench that had not been modified for the remote handling operation. Proper seating of the valves was remotely determined using the force reflecting feature of the M-2 teleoperator. Valve torques as low as 30 in./lb could be detected. Operation of the relatively fragile mechanical lockout device that prevents inadvertent opening of the fuel valves was also accomplished without incident.

Complete operation of the coupling was successfully demonstrated in accordance with NASA criteria and without modification for remote handling operation. Task time was about 35 min for the M-2 and about 15 min for the suited astronaut — a time factor of about 2:1. A complete video recording was produced to compare directly with suited astronaut operation.

As a result of the teleoperation of the refueling coupling, several comments and recommendations can be made relative to its design suitability for remote handling. On the positive side, it is somewhat self-aligning, has no loose parts, and has relatively short, simple motions to operate. On the negative, the gross alignment could be readily improved, the round handles were difficult to hold (for the astronaut as well), and there was poor access to the valves. The lockout mechanism which guards the fuel valves should not require two hands to operate, and the valves should be replaced with some that do not require as many revolutions. In general, the device was too delicate and should be considerably more rugged.

ACCESS I TRUSS ASSEMBLY TELEOPERATION

Truss assembly may be quite time consuming in the construction of the Space Station and has been identified as a task potentially well suited for teleoperation. The ACCESS I is an existing truss design which was developed and tested by NASA both in water tank simulation and in Space Transportation System (STS) experiments. Although the ACCESS I had no design considerations for remote handling, experimentation with this truss assembly provided information about the capabilities of teleoperator systems as well as the design considerations applicable to remotely serviced equipment. Since flight testing of the ACCESS I had been completed, astronaut and teleoperator performance could be compared.

ACCESS I Flight Experiment

The ACCESS I was a structural assembly flight experiment intended to study and verify the ability of astronauts to assemble in space a repetitive truss structure representative of the type likely to become a part of the Space Station. It was conducted in November 1985 as a part of the Shuttle Mission STS-61b (Fig. 4).

The truss was assembled from basic hardware which consisted of interchangeable, aluminum nodes and columns which can be snapped together to form connected bays of structure with a triangular cross section as shown in Fig. 5. The horizontal batten and vertical longeron members were 1.4 m (4.5 ft) long and the diagonals 2.0 m (6.4 ft) long (about 1/4 the anticipated size for the Space Station) with a two position locking sleeve on each end of each member. Each node had six nubs to which the columns could be attached. The columns were mated to a node by sliding back the sleeve on the column's end. Finally, the sleeve was slid back over the joint to make it secure.

Figure 5 shows the equipment and general setup for the flight task with the astronauts in their designated places (Nos. 1 & 2). The nodes and columns were supplied from the canisters (Nos. 3, 4, & 5), which were located so that the astronauts did not have to leave their stations to build the truss. They used the assembly fixture (No. 6) as a frame on which to place and hold parts as the truss sections were being put together. Nodes were slid up the guide rails (No. 7) from the bottom to latching positions on the fixture. The columns were attached to these to form a finished bay which was subsequently released and slid up along the guide rails to a new latched location to make room for the assembly of an additional bay on the lower half of the fixture where the raised bay had been.

ACCESS I Teleoperation Experiments

Two separate experiments were conducted at ORNL; the first demonstrated the assembly and disassembly of the truss by teleoperator alone, while the second experiment included the addition of a person at the test site working in concert with the teleoperator in order to duplicate standard NASA procedures (requiring a two-person team) and provide data for comparison with assembly by astronauts. Results of the second experiment have been previously reported by NASA.[3] Data recorded for both experiments included video recordings of operations, task and subtask completion times, task performance errors (e.g., hardware damage or drops), and test personnel observations and recommendations.

Experiment I Scope and Procedure

The purpose of the first remote handling experiment was to investigate the feasibility of remotely performing selected ACCESS I assembly and disassembly tasks. The selected operations investigated included the construction and disassembly of two truss bays and operations required in set-up of the assembly fixture guide rails. This was performed without making any modification to the ACCESS equipment or the model M-2 teleoperator, or by the use of any special tools.

Remote handling operations were performed by a two-person operator team from the remote control room. One person operated the model M-2 master control arms, and the second person operated the transport system and the model M-2 and facility cameras. The ORNL operators were very experienced at operating the model M-2, and each operator received approximately ten hours of experience assembling the truss remotely prior to any data collection for the purpose of developing procedures. Operators were usually exchanged between each series of task runs to minimize fatigue. Most tasks required dual-arm operations in support of positioning and connecting the truss struts to the nodes.

The ACCESS I assembly and disassembly procedures were modified to better suit operations using a teleoperator system since the standard NASA procedures were intended for a two-person astronaut team. Modifications were made primarily in the order of procedure steps. Only one of the two strut storage canisters was used and positioned upright on the facility floor in front of the ACCESS where the struts could be vertically extracted using the M-2 slave as shown in Fig. 6.

To assemble the first bay, operators installed nodes on each of the three assembly fixture guide rails (Fig. 7), and then installed the diagonal, longeron, and batten struts of the three bay faces around the lower section of the fixture. The upper battens were then installed and the upper end of the diagonal and longeron struts were connected to the nodes. The assembled bay was then moved to the upper position on the assembly fixture by releasing a securing latch at one of the mid-position nodes and raising the bay using the teleoperator and transport system.

Assembly of the second bay was essentially the same procedure used for the first bay except the upper batten struts were already in place from assembly of the first bay. The two bays were disassembled in reverse order of the assembly procedures.

To raise and latch a guide rail, the lower link and vertical links of the rail were raised and locked in position by inserting a captured detent-type pin at the link between the two joints. This procedure was reversed to lower the rail.

Experiment I Results

Each of the assembly-disassembly tasks discussed in the procedure section was successfully completed. Because of time and schedule constraints, the decision was made to concentrate efforts on the truss assembly tasks. Operators completely assembled the two truss bays eight times each and completed the disassembly and guide rail tasks twice per operator.

Combined task completion times for the primary truss assembly tasks stabilized after approximately five trials as shown in Fig. 8. The figure exhibits typical learning curve characteristics experienced in remote handling operations. Complete assembly of two bays by the operators required approximately 60 to 75 min. The average time to complete each task trial per operator is listed below.

Task	Completion Time (min.) Operator 1	Operator 2
1. Assemble first truss bay	35.6[a]	50.5[a]
2. Raise assembled bay	0.5[a]	0.7[a]
3. Assemble second bay	23.0[a]	26.9[a]
4. Disassemble lower bay	19.8	33.4
5. Lower upper bay	0.5	0.8
6. Disassemble remaining bay	30.6	54.4
7. Release and lower a mast guide rail	2.6	6.1
8. Raise and latch a mast guide rail	1.0	3.0

[a] - Average taken of final three trials for each operator.

Recognizing that a significant amount of time was required for retrieval and transport of task components relative to the time required to make the component connections, subtask completion times were recorded for several of the truss assembly trials. Task completion times were divided into component retrieval-transport time, and component alignment-install time. Strut and node alignment-install time started when the strut or node was in proximity (within approximately six to eight inches) to the connection point(s) and ended when the required connection(s) was completed and the tong grips were released. The remaining time was recorded as transport-retrieval time.

Subtask completion data were reduced for three of the final Task 1 trials completed by each operator which consisted of nine node installations and 27 strut installations per operator. On the average, 121 sec were required to install a node and 80% of this time was required simply in retrieval and transport. Struts required 146 sec to install and 65% of this time was required for retrieval and transport. As suspected, a significant portion of each component's total installation time was required in simply getting the component to the approximate location of installation.

Of the three types of struts handled, the batten (horizontally oriented) struts were generally the most difficult to install. This was due to the pivoting action of the node around the guide rail for the batten connection points which are orthogonal to the guide rail axis. The other connection points were much less prone to pivot when making the strut-to-node connection. The pivoting of the node made proper alignment of the strut difficult and, many times, required that the node be held secure with the teleoperator which further complicated the task.

Truss struts and nodes were occasionally dropped. The majority of the drops that occurred were an accidental release of a strut or node during withdrawal from the storage canister because of resistance to removal caused by misalignment. The struts were vertically stored in individual tubular cavities and would bind if not removed straight along the longitudinal axis (Fig. 9). The nodes were stored on pins and, like the struts, would bind on removal if pulled at an angle to the pin's axis. Binding occasionally resulted in a release of the component, allowing it to fall back into the storage canister. This type of release was recorded separately from releases that occurred after removal from storage since it is a different type of error in comparison to a free-space drop and may not result in the loss of the component. On the average, 2% of the struts handled were dropped and 6% were released during removal from the storage canister. Of the total nodes handled, 6% were dropped and 4% were released during removal from the storage canister.

Recommendations

Recommendations for design modifications to the ACCESS truss for improved remote handling based on Experiment I are summarized below.

- Strut-to-node connections should be simplified in operation. Ideally, the connections should be self-aligning and connect with a simple push-type motion once the strut is roughly aligned with the node. This type of design should also improve performance by suited astronauts.

- All lockout and latch mechanisms could be improved for operation by manipulator. Most of the ACCESS mechanisms were better suited for hands-on operation than for operation by teleoperator and end effector.

- Strut and node designs should include grip points for teleoperator end effector.

- Nodes should be designed for increased self-alignment to the guide rails. The brackets between the node connection points and node body were occasionally bent out of alignment when making strut connections and should be more rigid in design. The tolerance in the pivoting action of the nodes around the guide rails should be reduced to minimize difficulties in aligning and installing the batten struts.

- Storage of the struts and nodes should be closer to the installation locations on the assembly fixture so that teleoperator arm range is sufficient to retrieve and install the components without transporter motion. This will significantly reduce the time required for assembly.

Experiment II Scope and Procedure

The first experiment successfully demonstrated the ability to remotely assemble and disassemble the ACCESS I truss. It also provided data for evaluating these tasks but did not provide data which could be easily compared to performance by more conventional methods since assembly procedures were modified. The purpose of the second experiment was to investigate remote assembly of the truss by standard procedures so a more direct comparison to other assembly methods could be made.

The second experiment investigated assembly of two bays by a two-person team; one person performing assembly tasks using the M-2 teleoperator while working in cooperation with a person stationed at the ACCESS site. The M-2 operator and ACCESS site operator alternated between the two truss assembly stations to provide data for remote operations at each of these stations. Positioning of the teleoperator and the man at each of these stations is shown in Figs. 10 and 11. Two-way communication was provided for the teleoperator and ACCESS site operators by transmitter-receiver headsets which allowed hands-free operation.

Once positioned for operations at a station, the model M-2 slave and closed-circuit television (CCTV) cameras did not require repositioning. This allowed the M-2 operator to concentrate on the strut handling tasks which required near continuous operation of both arms and eliminated the need for transporter motion. All remote operations were performed by the M-2 operator without assistance from another control room operator.

From Station 1, operators installed the nodes and struts assembled around the lower section of the assembly fixture. This accounted for approximately 70% of the operations required. A single bay face was assembled at one time in cooperation with operations at Station 2. First, a node was installed on the guide rail while a diagonal strut was being placed in position from Station 2. The lower connection point of the diagonal was then made from Station 1. The lower batten and longeron struts of the respective bay face were then installed, the assembly mast rotated, and the process repeated until all three faces had been assembled. All assembly mast rotations were performed from Station 1.

From Station 2, the diagonal struts were positioned and the upper connections made for each bay face. For the first bay, the upper batten struts were installed and for all bays the upper connection of the longeron struts was made while the lower batten struts of the bay face were being installed from Station 1. Raising of the assembled bay was performed from Station 2.

Experiment II Results

The truss assembly tasks were successfully performed from both Stations 1 and 2. Eight repetitions per manipulator operator and station were obtained (a total of 64 bays assembled). The quality of task performance was comparable to Experiment I, and completion times were reduced by a factor of three. The average completion time of the final three task trials per operator and station are listed below. The combined task completion time (tasks 1 and 2) versus task trial for each of the operators is shown in Figs. 12 and 13, respectively.

	Task	Completion Time (min.) Operator 1 STA 1	Operator 1 STA 2	Operator 2 STA 1	Operator 2 STA 2
1	Assemble First Bay	9.7	7.9	13.6	11.5
2	Assemble Second Bay	7.9	3.0	12.0	3.1
	Total	17.6	10.9	25.6	14.6

Station 1 consistently resulted in the longest task completion time since the majority of the truss assembly tasks (approximately 70%) are performed from this station. Assembly of the first bay required more time than the second since it included more strut connections and also included raising the assembled bay. Assembly of the second bay from Station 2 did not require the installation of any horizontal struts, only the diagonals, and consistently required the least task completion time since it required the least number of operations.

The effects of learning and practice were not as pronounced in Experiment II in comparison to Experiment I. This becomes evident when comparing the straight line profiles of Figs. 12 and 13 to the exponential profile of Fig. 8. This is attributable to operators having learned truss component handling techniques during Experiment I and the very repetitive, production-like operation of Experiment II.

Task completion times varied more from trial to trial during Experiment II than Experiment I primarily because of two factors. First, operator fatigue was greater during Experiment II because handling operations were essentially continuous at the model M-2 control station; in Experiment I, operations were divided between two operators and tended to produce breaks for an operator while the other was performing his tasks. Frequently, the second task trial completion time increased for an operator because of this effect. Secondly, the M-2 was moved from one station to the other after a few task trials per operator were completed to spread any learning and practice effects to both stations evenly. This, however, prevented operators from smoothly stabilizing at either station.

In addition, the slopes of Figs. 12 and 13 show that task completion times had not quite stabilized for either operator after eight trials each. Undoubtedly, completion times would have decreased with more experience, but significant improvements are unlikely. Practical time and schedule constraints did not permit more testing, and further testing was not deemed cost effective.

There was no detectable damage to the truss components or manipulator during the task trials of Experiment II. As in Experiment I, nodes occasionally required straightening to ensure optimum alignment with the struts so movement of the assembled bay on the guide rails was as smooth as possible. Dropping of truss components was the only error committed with any frequency during Experiment II. The majority of the struts dropped were accidental releases which occurred because of binding with the storage canister during vertical extraction at Station 2. Fatigue during Experiment II was significant and certainly was a factor in errors committed. On the average, less than 1% of the struts handled at Station 1 were dropped and 12% of the nodes handled were dropped. At Station 2, less than 1% of the struts handled were dropped, but 4% were accidentally released during removal from the storage container.

The M-2 slave positioning at each of the two stations was generally a compromise from ideal task positions for separate tasks in order to perform all of the tasks at each station without having to reposition using the transporter system. The objective was to save time by eliminating transporter operation, but the ease of performing all tasks was sacrificed. This, in turn, increased the error rate and fatigue factor.

Comparison to Other Assembly Methods

The primary purpose of the second experiment was to acquire assembly time data which could be directly compared to assembly by other means. The bar graph of Fig. 14 presents a comparison for assembly by a variety of means including (1) shirt sleeves, (2) ground-based water immersion simulation with pressure suits, (3) Shuttle Mission STS-61b, and (4) teleoperator assembly at ORNL. All data are normalized to the completion of two bays. The teleoperator assembly time shown is an averaged figure computed from the last three runs of both M-2 operators (a total of twelve runs). The value for the water immersion facility is an average of times from Johnson Space Center's Weightless Environment Training Facility and Marshall Space Center's Neutral Buoyancy Simulator and includes some results from development tests with untrained subjects. The teleoperator assembly took about three times as long as did the pressure-suited astronauts in space to achieve the operation. The teleoperator time is very good, however, when one considers that neither the hardware being assembled nor the manipulator itself had been designed to accommodate this task. Historically in the nuclear industry, tasks completed by teleoperators such as the model M-2 or through-the-wall mechanical master-slave systems typically take eight times as long (on the average) to perform a task compared to hands-on operation. The five-to-one time factor achieved for shirt-sleeve comparison indicates that this task is well suited for remote handling. An average time computed from the two very best runs made at each of the two stations was only about two and one half times as long as for the astronauts.

In reality, the total time, including preparation and recovery, required for a human to perform a task directly must be considered. For example, in the case of EVA, the time required to suit up, depressurize, and pressurize must be included since it is necessary in order to perform a task directly and involves a significant amount of time. Of course, one must also consider personnel hazards eliminated through remote handling when analyzing the advantages and disadvantages of remote handling versus direct handling. This is frequently a more important consideration than performance time.

GENERAL DESIGN PHILOSOPHY FOR REMOTELY HANDLED EQUIPMENT

When designing flight equipment for remote handling (RH), several general principles are recommended. First and foremost, the equipment designers must be cognizant of the RH system that will be used on their equipment. This must be known before design can begin. Features of the teleoperator system such as reach and motion capabilities, operating envelope, lifting capacities, force threshold, and positioning accuracy will all affect the design of the equipment. Once these characteristics are known, the design can proceed using guidelines which are particularly important for remote handling. The most important of these are:

- Design with modular components - keep assemblies and subassemblies small and in easily handled modules. Include good contact surfaces for teleoperator grips on the module components.

- Keep the interfaces between the modules simple and self-aligning. Remote alignment using CCTV viewing can be very difficult.

- Design for the simplest motion. Pushing-pulling with a teleoperator is much easier than rotary motion.

- Standardize to the greatest practical extent, particularly fasteners and connectors. This minimizes the number of tools and spare parts required.

- Do not allow loose parts in the design which can be dropped (or float away). Use captured fasteners.

- Minimize the number of special tools or fixtures. Take advantage of the capabilities of the system.

An important point to keep in mind is that the designer must design for remote handling from the beginning. In many cases, retrofitting is virtually impossible and certainly expensive.

Design reviews are an important feature of any design process. They are particularly important when designing for remote handling. Equipment designs must satisfy handling requirements as well as functional requirements. The use of a design checklist, based on design guidelines such as those, can be a very useful tool.

The next critical area is that of development and demonstration. Never believe that designers/fabricators are perfect. Equipment should always be prototyped and complete disassembly and assembly demonstrated using the chosen teleoperator system. This may be a costly undertaking, but costs much less than being unable to repair equipment once in place.

Finally, planners must be painfully aware of the relative time efficiency achieved in performing tasks remotely. The well-established reference from extensive nuclear experience as well as many non-nuclear (not quite as extensive) applications is 8:1. Some tasks take less, as in the case for experiments discussed in this paper, but 8:1 is still the best data for planning purposes. Also keep in mind that the M-2 system is one of the most capable systems in the world. Lesser systems will certainly decrease the time efficiency. With the tremendous emphasis on robot safety for the space station, one likely outcome is for the telerobotic devices to operate very slowly (and implied safely). If this does occur, then the time efficiency will be greatly reduced. This could be an overwhelming issue for those designing and planning for telerobots in space applications.

CONCLUSIONS

The ACCESS and refueling coupling remote handling experiments have demonstrated the feasibility of performing complex, space-related tasks by teleoperation. In both experiments, operators were able to achieve, with relatively little experience and practice, repeated performance of the tasks without incident in an almost routine manner although no equipment modifications were implemented for remote handling. This demonstrates the high level of adaptability of man-in-the-loop teleoperation to unstructured tasks. Operator fatigue in the second truss experiment was significant and suggests that telerobotic (automated) assembly would be beneficial where possible. The results of both experiments support conclusions that teleoperation represents a valuable enhancement to astronaut EVA. It must be recognized that equipment must be designed differently for remote handling than for hands-on operation. This will also improve EVA performance. General guidelines do exist that have been proved in other remote applications.

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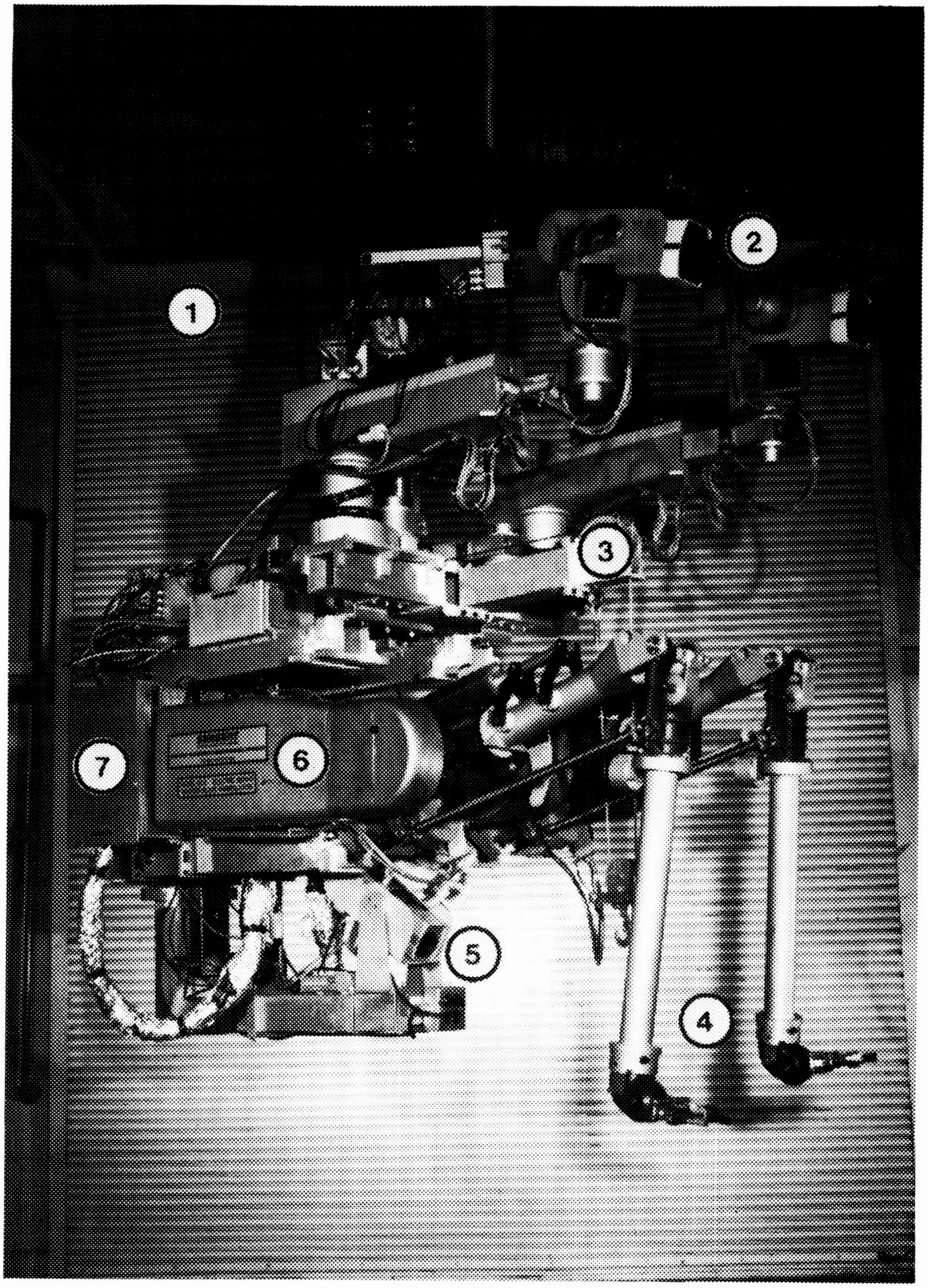

Fig. 1. The model M-2 teleoperator slave (1) transporter interface, (2) movable overhead cameras, (3) auxiliary hoist, (4) slave arms, (5) fixed lower camera, (6) servomotor housing, and (7) control electronics rack.

Fig. 2 The ROMD control room (1) model M-2 master control station, (2) teleoperator transporter and facility camera control console.

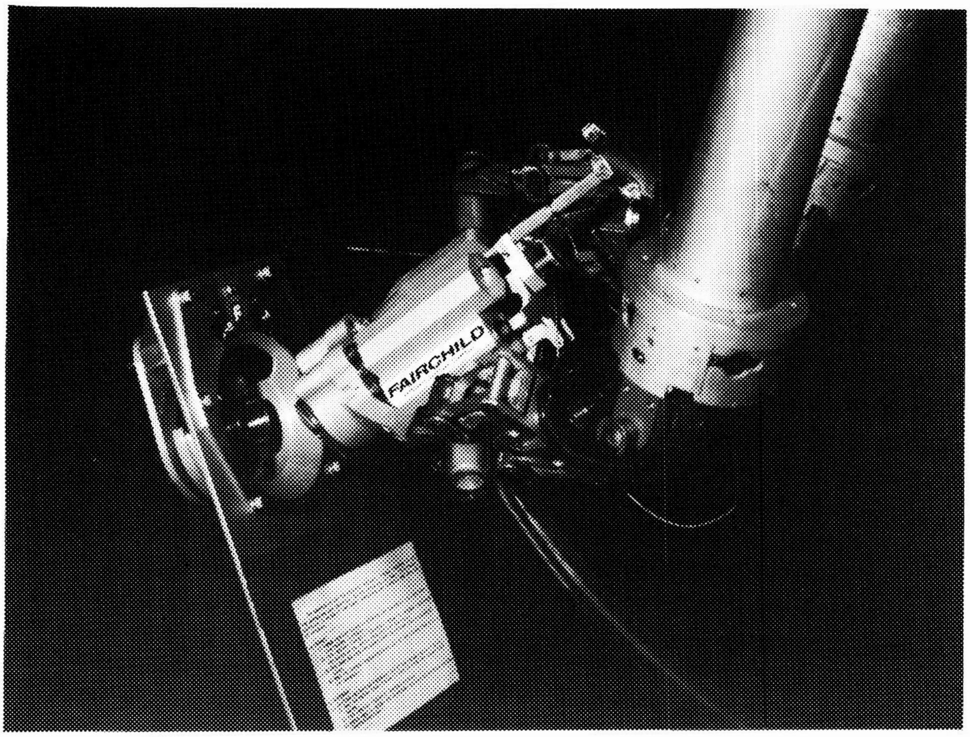

Fig. 3. Satellite refueling coupling remote handling operations.

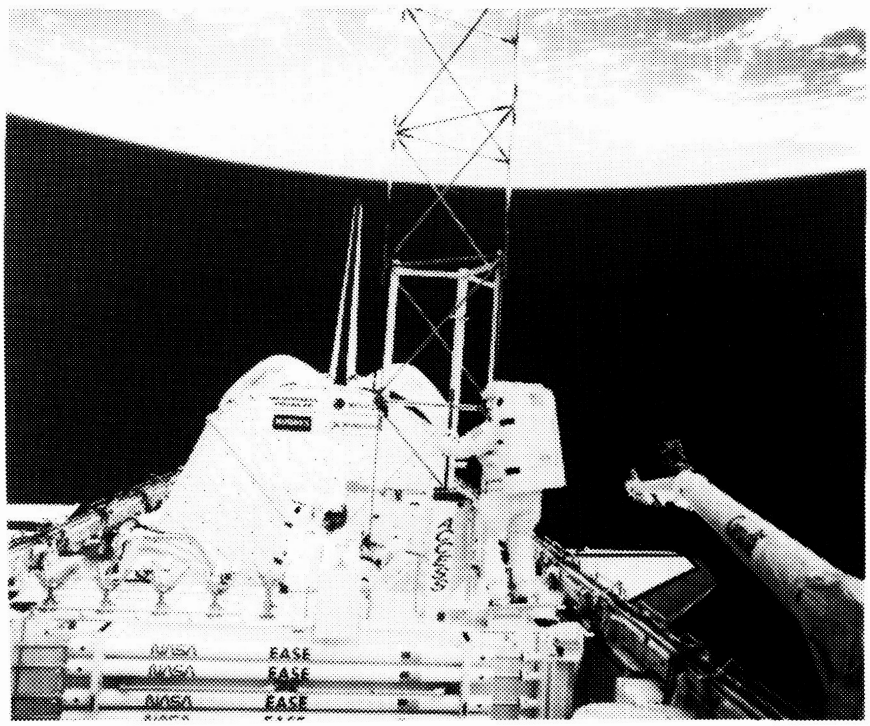

Fig. 4. ACCESS I EVA operations aboard shuttle mission STS–61b.

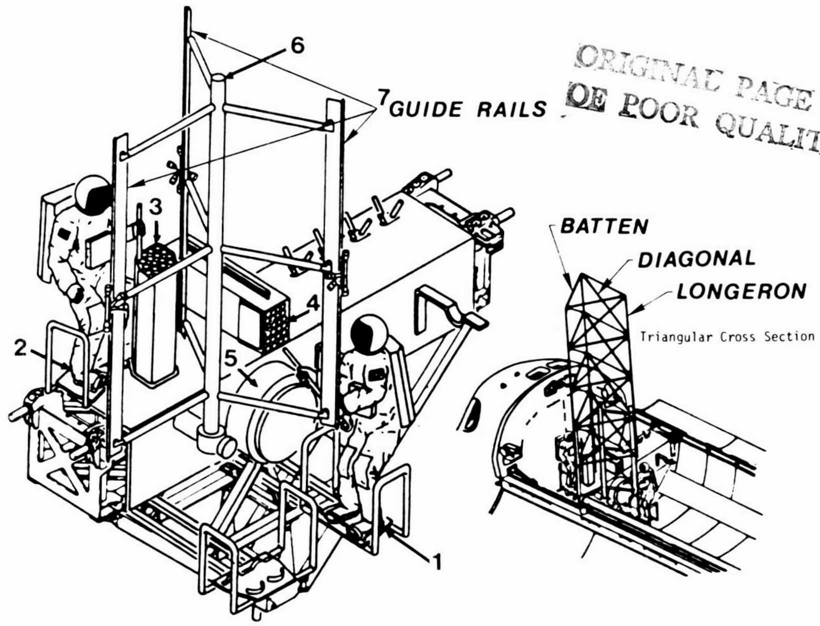

Fig. 5. Schematic showing EVA construction of ACCESS truss on assembly fixture.

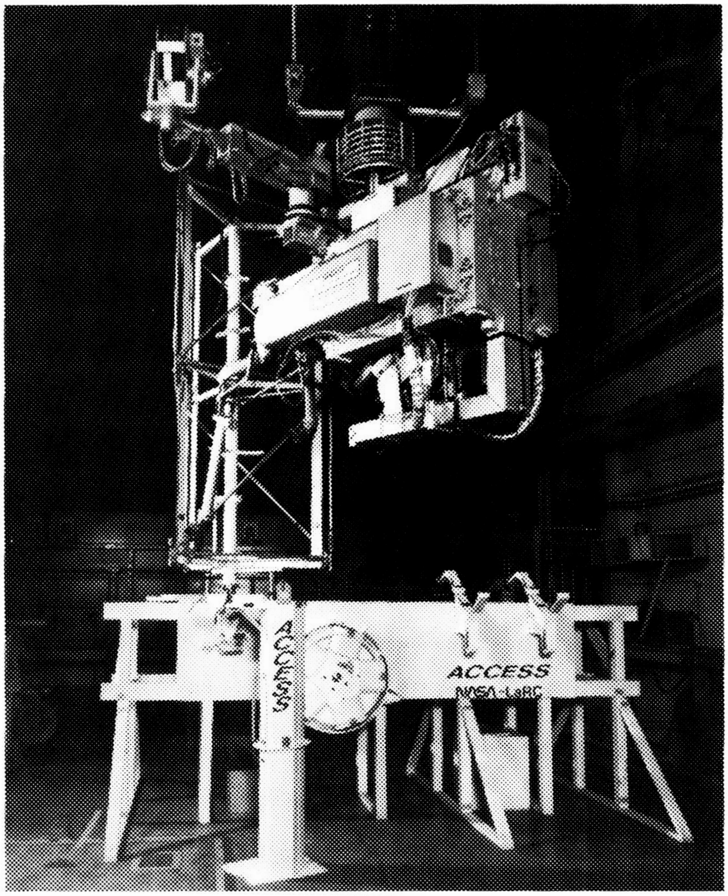

Fig. 6. ACCESS I assembly operations during Experiment I.

Fig. 7. Installing a node on a guide rail.

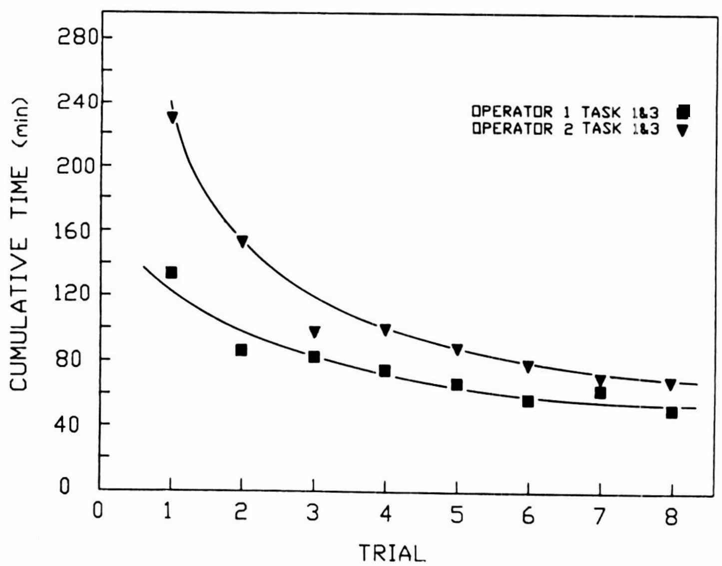

Fig. 8. Combined task completion time versus task trial for Experiment I.

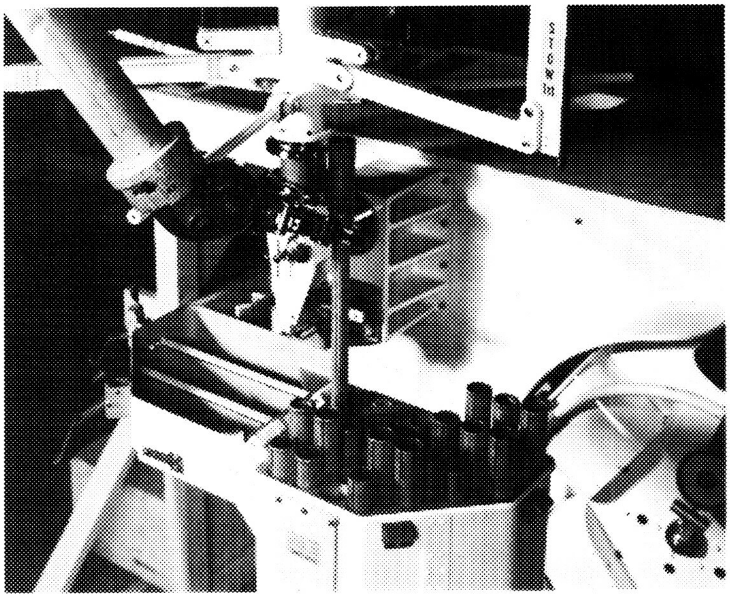

Fig. 9. Removing a strut from the storage canister.

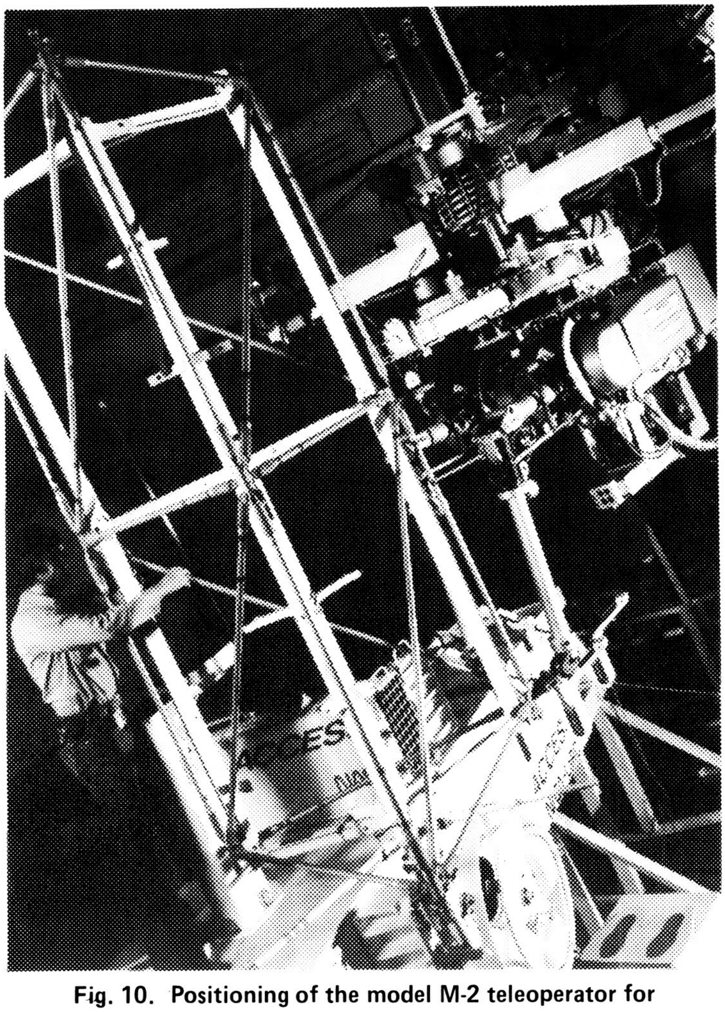

Fig. 10. Positioning of the model M-2 teleoperator for operations at Station 1.

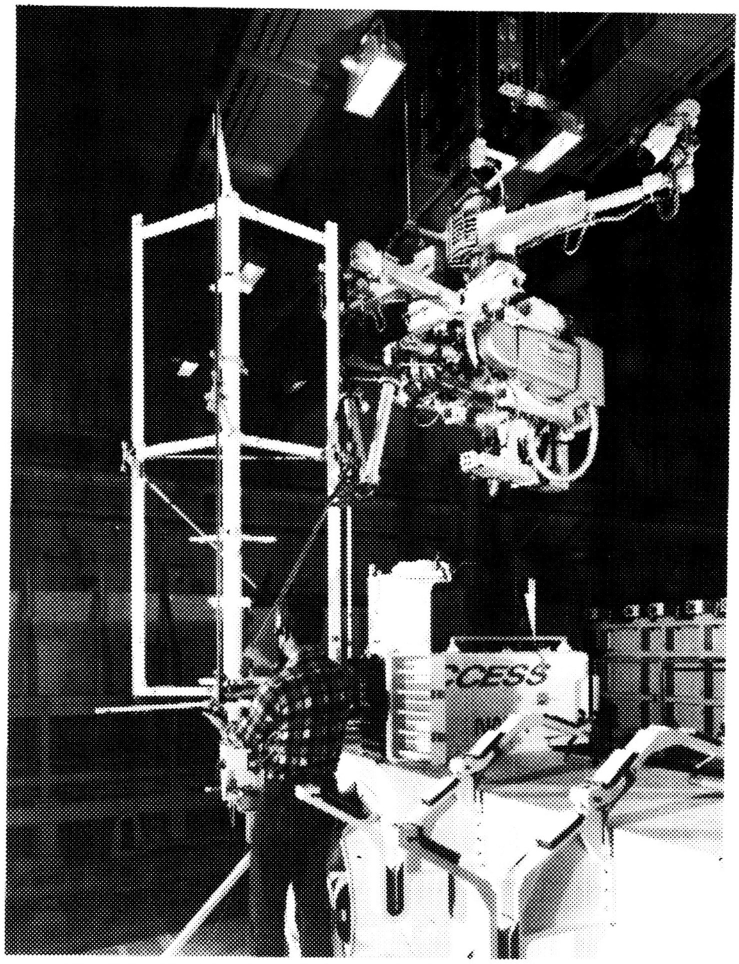

Fig. 11. Positioning of the model M-2 teleoperator for operations at Station 2.

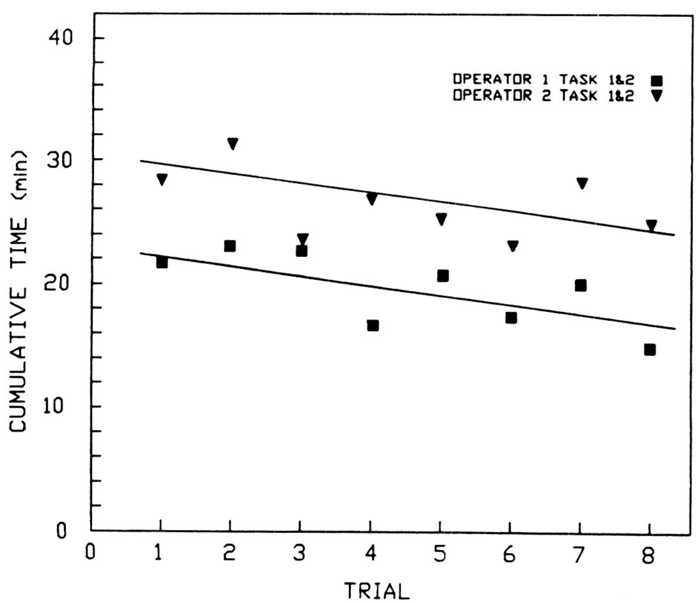

Fig. 12. Combined task completion time versus task trial for Experiment II, Station I.

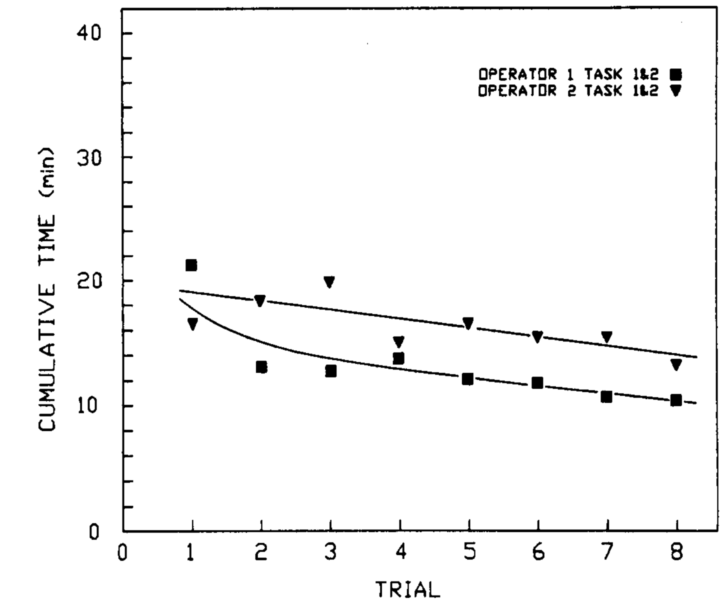

Fig. 13. Combined task completion time versus task trial for Experiment II, Station 2.

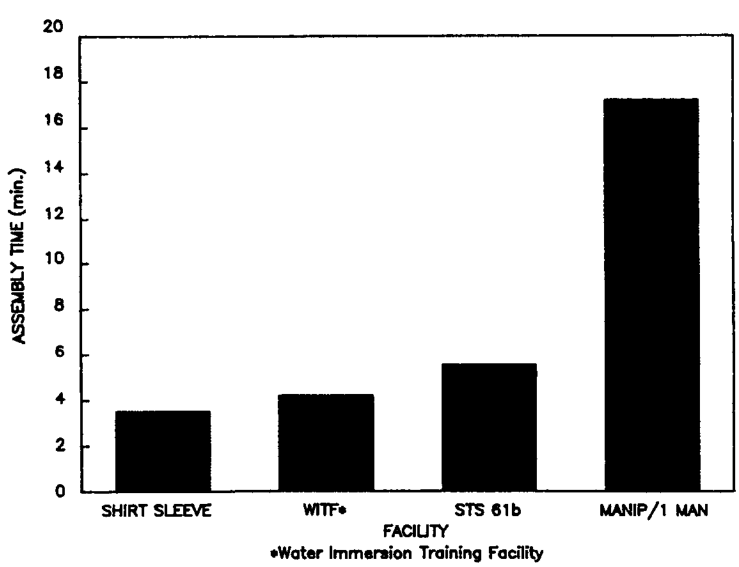

Fig. 14. Comparison of assembly time in different facilities.