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TELEROBOTIC ASSEMBLY OF SPACE STATION TRUSS STRUCTURE

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1. ABSTRACT

This paper discusses methods of assembling the Space Station's structure which only utilize telerobotic devices

- an approximately anthropormorpic telerobot with two dextrous arms
- the Shuttle Remote Manipulator System (SRMS)
- various material handling machines.

Timelines and task recommendations for autonomous operations are also included. The paper also describes some experimental results comparing two manipulator control devices.

2. INTRODUCTION:

Recent studies at Grumman have shown the feasibility of assembling the Space Station truss structure in space using only telerobotic systems. The studies investigated the use of a pair of cooperating dextrous manipulators in an anthropomorphic telerobotic system. Two types of investigations were conducted:

- Computer Aided Design (CAD) studies of the assembly of the Space Station truss structure
- Experimental tests of several subjects and control devices performing some truss assembly tasks using a pair of dextrous manipulators.

These studies were based upon the capabilities of current state-of-the art electro-mechanical devices. Although human directed telepresence control was the baseline of these investigations, the truss assembly activities described here lend themselves very nicely to autonomous (or supervised) robotic operations. This paper will present some of the results from both the CAD studies and the experimental investigations.

The CAD studies addressed the problem of assembling the entire Space Station truss structure from the Cargo Bay of the STS Orbiter, without using Extra Vehicular Activity (EVA). The studies only addressed structural connections and did not consider the installation of utility lines (fluid and electrical). Two different methods of assembly were explored. Both utilized an

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anthropomorphic machine known as SAM (Surrogate Astronaut Machine) to perform all the dextrous manipulation tasks needed in vacuum to assemble the structure. Figure 1 displays some of SAM's characteristics. The "third arm", which normally functions as a means of attaching SAM to a worksite to allow the SAM mobility aid (SRMS or MSC) to depart and perform other functions, was not utilized in this study. This paper reports the features and significant differences (including task timelines) of the two assembly methods.

A number of experimental results were obtained from a series of test subjects operating a pair of six degree-of-freedom (6 DOF) manipulator arms in a telepresence mode. Through the use of voice controlled cameras, the operators relied on video and force feedback to retrieve a "strut" and connect it to a truss node (see Figure 2). Two different control devices were used by each operator:

- A pair of 6 DOF ball type hand controllers utilized a resolved rate control law (see Figure 3). Some force feedback was provided by auditory signals. No force feedback was provided through the ball controller.

- A pair of bilateral force reflecting (BFR) replica master controllers utilized position-position error signals to produce forces in both master and slave arms (see Figure 4).

This paper reports the significant differences found in operating with both of these control systems.

3. STRUCTURE ASSEMBLY TESTS

Three struts were assembled into a node which contained strut termination fittings (see Fig. 2). The strut connections, known as the "Wendel-Wendel" joints, require that one manipulator hand hold a strut in position while the other manipulator hand translates a collar over the joint and then locks the joint by rotating the collar about half a revolution. The struts were positioned in the nodes in three orientations: vertical, diagonal and horizontal. In a gravity field, task difficulty was strongly influenced by strut orientation. The vertical strut installation was very easy to do. The horizontal strut installation was quite difficult. Task times were recorded from the start of strut removal from the vertical storage (the left zone of Fig. 2) until the visual indicator on the strut locking collar indicated a locked condition.

Figure 3 shows the two types of control devices which were utilized for these tests. The Master Controllers are 6 DOF BFR arms which have an additional DOF squeeze grip for operating parallel jaw motion end effectors on the slave arm. The master and slave arms have identical structures and kinematics (i.e., a geometry ratio of 1:1). The control laws used by this BFR replica system develop torques, at both the master and slave joints, which are proportional to the position error signal between the corresponding master and slave joints. That is, when the master elbow is displaced 30^{o} with respect to the slave elbow, the operator feels a force at the control handle (which was generated at the master elbow) which tends to drive the master arm to the same position as the slave arm. Simultaneously, the slave arm experiences a torque at its elbow which tends to drive the slave arm to the same position as the master. Thus, high forces at the slave arm are experienced by the operator as high forces on the master arm. This type of control system is known as bilateral force reflection (BFR).

The second type of manipulator controller shown in Fig. 3 is a 6 DOF ball gripper type which is under development by CAE Electronics, Ltd. This compact device, and its supporting electronics, translate operator displacement commands (+ - x, y, z, θ, ϕ, ψ) at the ball grip into slave end effector rate commands (+ - $\dot{x}$, $\dot{y}$, $\dot{z}$, $\dot{\theta}$, $\dot{\phi}$, $\dot{\psi}$) in one of two (selectable) coordinate axis systems. For these tests, the selected system fixed the slave hand x, y and z axes to the slave hand, and, when the hand grabbled a strut or collar, to the work object. Thus, ball grip input commands were in a work object coordinate system. Operator forces at the ball grip were very light (with no felt feedback from the slave arm). An auditory system supplied some indication of high forces on the slave arm. This auditory system was not very helpful for manipulator operators of this test series.

Figure 4 shows the laboratory in which these tests were conducted. The worksite region is on the right side. The operator region is on the left side. An opaque curtain was placed between these regions for these tests. The operator received all visual information from three TV monitors (see Fig. 3). These monitors received images from three fixed location comeras in the worksite region. The cameras had 3 DOF (scan, tilt, and zoom) and were controlled by manipulator operator voice commands.

One of the major objectives of this test program was to evaluate the effects of the two manipulator control systems (master vs ball controller) on task timelines and to identify benefits and problems associated with them. The results we found were:

- o 230% faster strut installation with the master controllers

  -least time difference for the vertical strut, which required the lowest cognitive workload of the ball controller tasks.

o benefits & problems	BFR-Master	rate-Ball
-speed of movement	good	too slow
-mobility (zone of wk)	good	too restricted
-single axis motion:		
o in coordinates of control system	difficult	excellent
o inclined to control coordinates	difficult	very difficult
-coordinated & constrained 2 arm motions	good	dangerous & very difficult
-operator ability with little practice	good	fair
-ability to join objects without understanding	excellent	almost impossible
-operator fatigue	very tiring	very comfortable
-control over fine (small) motions	poor	excellent

These, and other, experimental results are reported in greater detail in Reference [1.].

5. SPACE STATION ASSEMBLY STUDY

Two different methods of using telerobotic devices (SAM) for assembling the Fall 1986 Langley Task Force Space Station Design were explored. Both methods used SAM in an operator controlled telepresence mode. The major differences between the two methods were in how SAM moved around the worksite and the amount of automation used to enable SAM to obtain supplies for the construction activity.

o Method 1

-2 Telepresence controlled SAMs
-Rotating/Translating Fixture Tool for SAM
-Automatic strut & node dispensers

o Method 2

-1 telepresence controlled SAM on SRMS
-Rotating assy fixture

Figure 5 depicts a partially completed Space Station truss structure emerging from an assembly fixture at the back of the Orbiter's Cargo Bay. The truss is formed of cubical "bays" which are 5 meters long. Each face of a cube has a diagonal strut in addition to "horizontal" and "vertical" struts. Figure 6 shows more details of the support of the Truss Assembly Fixture within the Orbiter's Cargo Bay. The truss is assembled in the lower bay region by a SAM attached to a "horizontal" beam. The beam is attached to a turntable which provides 2 DOF: translation in the "vertical" (Orbiter z axis) direction and 360^{o} rotation about this "vertical" axis. These 2 DOF, and the 10 DOF within SAM, allow SAM to reach all corners of the lower bay and the storage regions for struts and nodes (which are located outside the truss at the midpoints of the lower horizontal face of the cube). When the truss element feed system canisters become empty, they are replaced with full canisters by a second SAM which is mounted on a Shuttle Remote Manipulator System (SRMS). The canisters contain mechanisms which deliver all truss elements (i.e., struts and nodes) to the same location within a canister to expedite assembly operations.

All Space Station structural assembly sub-tasks have been considered for telerobotic assembly. Reference [2.] contains a listing of these sub-tasks and our estimates for the time required for their completion. These sub-task times were grouped into major task activities and summed for the entire operation of assembling the structure of the Space Station's Transverse Boom, which required 70 hours of on-orbit time. These data are displayed on Figure 7.

We examined a second method of assembling the Space Station's Transverse Boom structure. This method only used a single SAM which remained attached to the SRMS. The partially constructed SS structure was rotated about the centerline of the assembly fixture (Orbiter z axis) to locate all teleoperations in the same region of the Orbiter. This region allowed easy access to strut and node storage areas within the Cargo Bay and allowed SRMS motion from top to bottom of the assembly fixture. Figure 8 shows part of the fixture assembly operation: the upper portion of one of the four truss supports is about to be inserted by SAM into the previously installed lower two pieces. Figure 9 depicts a node receptacle (which contains 6 nodes) installation into the assembly fixture. Figure 10 shows an assembled truss bay above four previously assembled "horizontal" truss faces within the assembly fixture. SAM is positioned to raise the completed bay to the top of the fixture where it will be held by the fixture. The second bay is completed by SAM attaching vertical and diagonal struts between the completed bay and the next "horizontal" truss face, which has to be raised up to the bottom position. During vertical face assembly, the partially completed structure is rotated 90^{o} to present SAM with a new corner of the truss. During this 90^{o} rotation, angular accelerations have been limited to 1 "g". This limits bending moments on the cantilevered diagonal struts (since they are attached at only one end during rotation) to values which are substantially below their strength. The six timelines associated with assembly Method 2 are contained in Reference [2]. The last of these is reproduced here as Figure 11. Method 2 required 72 hours of on-orbit time to assemble the Space Station's Transverse Boom structure (work began after 8 hours on orbit).

6. TASKS FOR AUTONOMOUS TELEROBOTICS

Both of the assembly methods which are discussed in this paper have assumed that all motions of the telerobot (SAM) and the SRMS have been commanded by astronauts at control stations within the Orbiter. Since telerobot operations are planned for 16 hours per day, astronauts controlling these devices may experience fatigue, even with frequent shift changes. Consequently, the reduction of astronaut workload is desireable to reduce fatigue and the concomitant probability of errors.

Selective autonomous telerobot actions can reduce astronaut fatigue by occasionally eliminating the need for an astronaut's physical effort and mental attention to details. At the completion of an autonomous robotic task, the astronaut acts like a supervisor and verifies that the autonomous task was performed properly.

Selective autonomy is stressed because of the prohibitive costs of providing a telerobot which is capable of performing all Space Station assembly tasks in an autonomous mode. Also, to perform autonomous tasks in a manner which does not impose a significant weight burden on the Space Station, a high level of machine intelligence is required. At this time, one can not predict that this machine intelligence technology will be available in time to perform the complete assembly of the Space Station.

Figures 12 and 13 list the major tasks which make up the Method 2 assembly activities. Note that some tasks are conducted only once while other tasks are conducted hundreds of times. The three highest repetition tasks use up 20 hours (which is 30%) of dextrous manipulation time. All the tasks selected as candidates for autonomy in Figure 12 represent 1/2 of the dextrous manipulation time for the assembly of Space Station structure. A similar analysis of SRMS tasks (Fig. 13) yields 13 hours (90%) of SRMS operations which lend themselves to autonomous operations.

7. CONCLUSIONS

Our work has persuaded us that the Space Station structure can be reliably assembled by telerobotic systems. We believe

- that the majority of tasks should be under astronaut control using telepresence technology,
- that selective tasks should be performed autonomously by the telerobot
- that the primary telepresence control device should be a bilateral force reflecting replica master
- that the initial Space Station structure can be assembled during 1 STS mission without EVA.

8. ACKNOWLEDGEMENTS

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I would like to thank Mr. Erik Eriksen and Dr. John O'Hara for their contributions to our test programs, and, Mr. Dan Guinan and Mr. Kirk Sneddon for their Space Station assembly studies.

9. REFERENCES

[1] O'Hara, John M., "Telerobotic Work System: Space-Station Truss-Structure Assembly Using A Two-Arm Dextrous Manipulator", Grumman Space Systems Division, Bethpage, NY, November 1986.

[2] Fischer, Grahme, "Telerobotic Work System, System Definition Study, Phase 2, Final Presentation", Grumman Space Systems Division, Bethpage, NY, January 1987.

Figure 1. ASTRONAUT CAPABILITIES WITH SAM

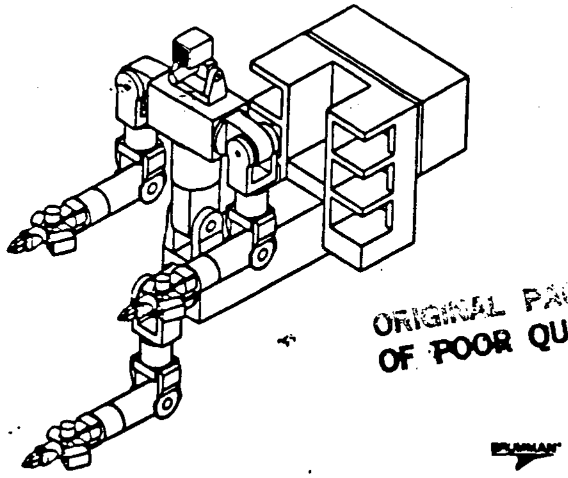

Figure 2. SS STRUCTURE ASSEMBLY TESTS

- PURPOSE —— EXPLORE USE OF TELEROBOTIC OPS FOR ASSY OF SS TRUSS STRUCTURE

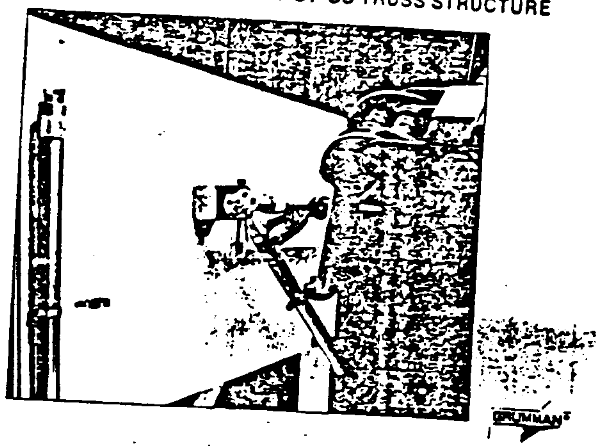

Figure 3 ... STATION

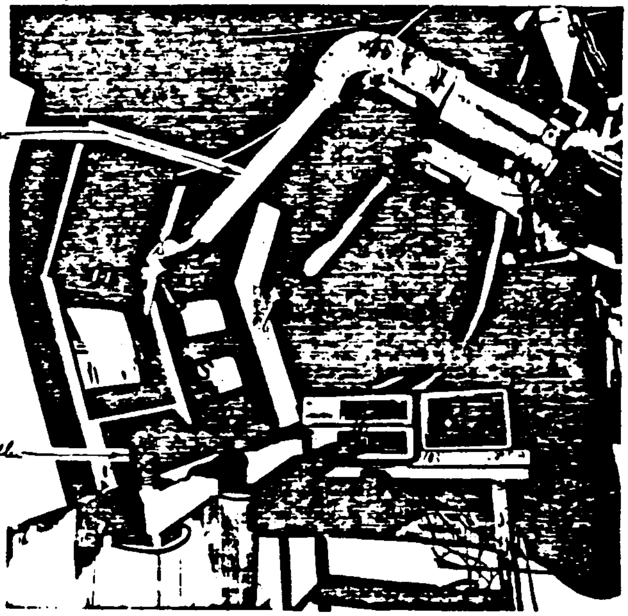

Figure 4 TEST LAB OVERVIEW

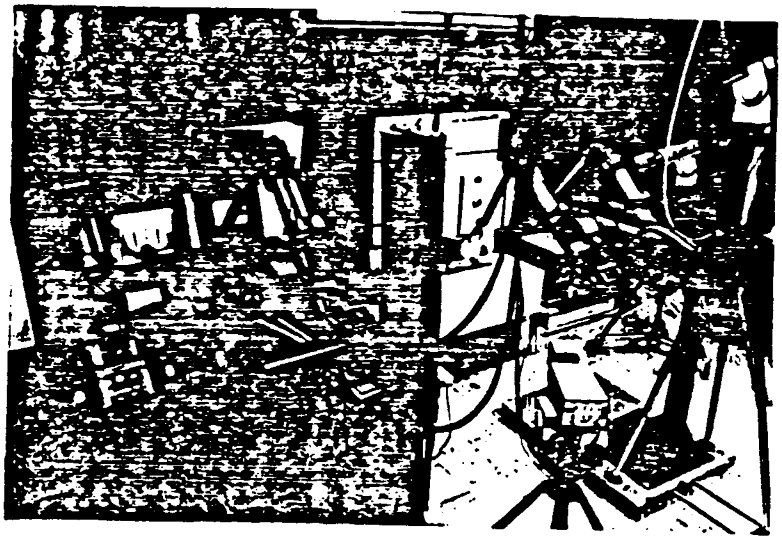

Figure 5 TRUSS ASSEMBLY FIXTURE Method 1

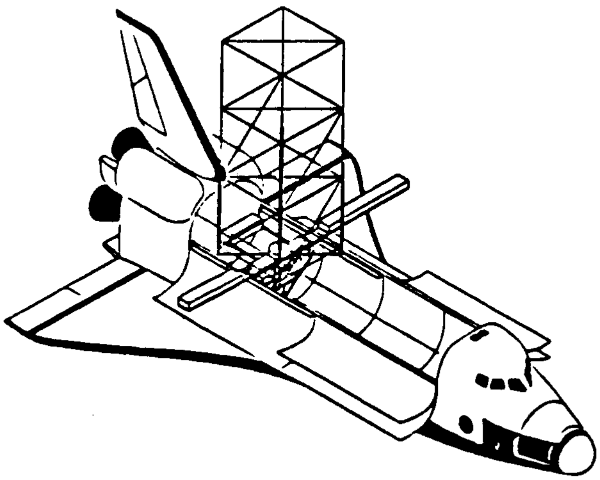

Figure 6 Method 2 TRUSS ASSEMBLY FIXTURE DETAIL

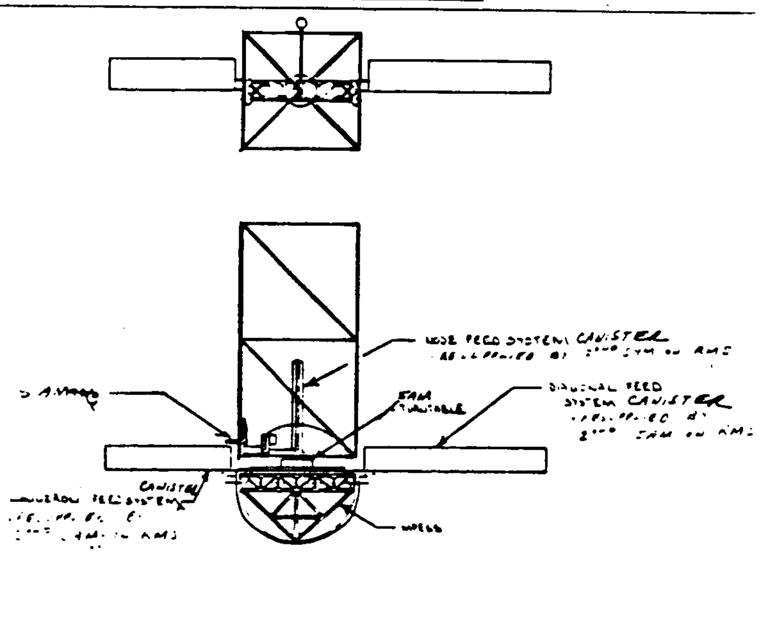

Figure 7 Combined SS Assembly / Operations Timeline: Method 1

Task	Task [illegible]	Task [illegible]	Total Time (min)
[illegible] Assembly Fixture	[illegible]	[illegible]	[illegible]
[illegible] Installation	[illegible]	4	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
ESM & Radiators	[illegible]	2	[illegible]
Alpha Joints	[illegible]	[illegible]	[illegible]
RCS Clusters	[illegible]	[illegible]	[illegible]
ACA	[illegible]	[illegible]	[illegible]
[illegible] truss and deploy	[illegible]	*	[illegible]
Retract Assembly Fixture	65	*	65
Clean up	60	*	60

$\Sigma_1 = 2509$ min

Construction of Bays

First Bay	98	1	98
Additional Bays	68	23	1564

$\Sigma_2 = 1662$ min

Assembly Time for Transverse Boom: $\Sigma_T = 4171$ minutes $= 69.51$ hrs

Figure 8 ASSY METHOD 2:

INSTALLATION OF ASSEMBLY FIXTURE

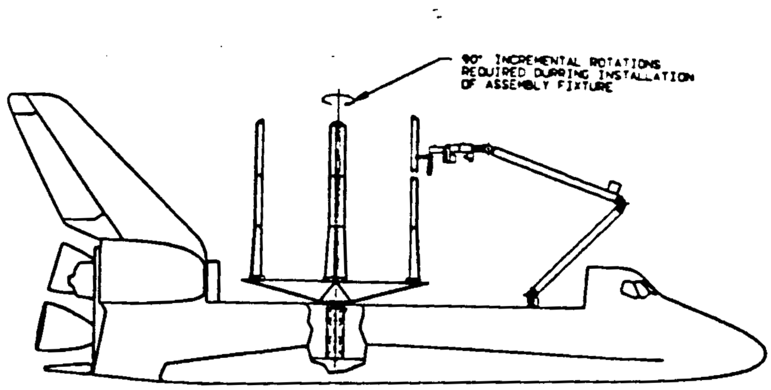

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Figure 9

INSTALLATION OF NODE RECEPTACLE DETAIL

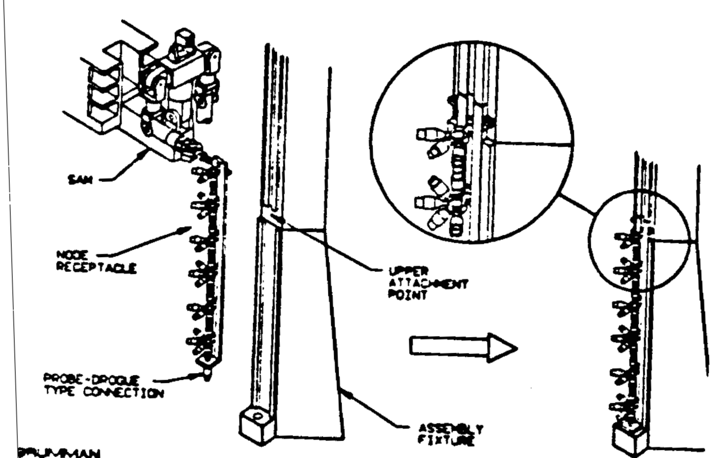

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Figure 10

INSTALLATION OF VERTICAL FACE STRUTS

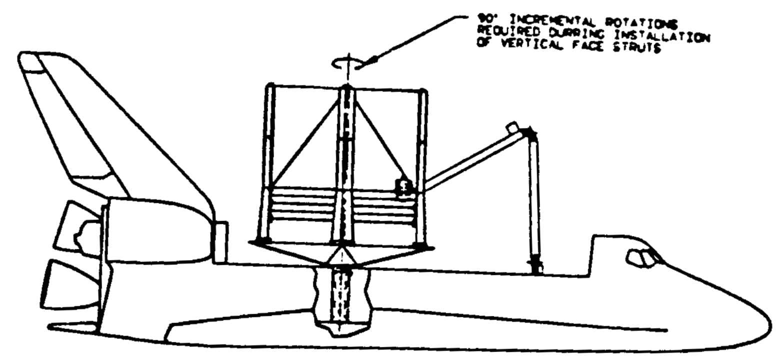

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Figure 11

TIME LINE - METHOD 2 SPACE STATION TRUSS ASSEMBLY - DAY 6

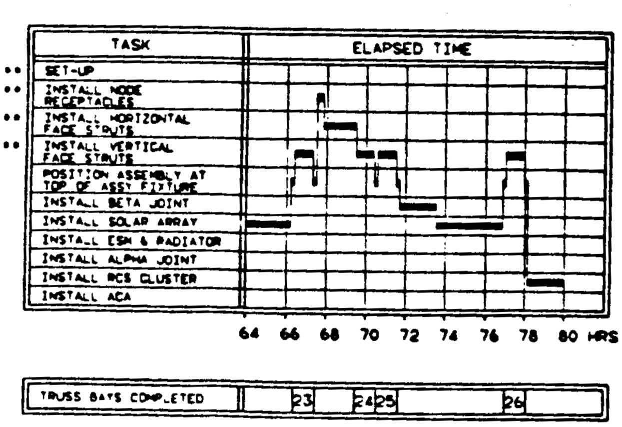

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Figure 12

DEXTEROUS MANIPULATION TASKS

DEXTEROUS MANIPULATION TASK	TASK TIME (MIN)	TASK REPE-TITION	TOTAL TASK TIME (HRS:MIN)
INSTALL FIXTURE ELEMENT ON DEPLOYABLE BASE	2.0	12	0:24
INSTALL NODE RECEPTACLE ON ASSEMBLY FIXTURE	2.0	20	0:40
* INSTALL END OF STRUT	2.0	343	11:26
* INSTALL OPPOSITE END OF STRUT	1.0	343	5:43
OBTAIN ASSY FIXTURE ELEMENT FROM CONTAINER	0.5	12	0:06
OBTAIN NODE RECEPTACLE FROM CONTAINER	0.5	20	0:10
* OBTAIN STRUT FROM CONTAINER	0.5	343	2:51
* POSITION ASSEMBLY AT TOP OF ASSY FIXTURE	10.0	33	5:30
REMOVE EMPTY NODE RECEPTACLE FROM ASSY FIXTURE	2.0	4	0:08
STOW EMPTY NODE RECEPTACLE	2.0	4	0:08
INSTALL BETA JOINT	115.0	4	7:40
* INSTALL SOLAR ARRAY	100.0	8	13:20
INSTALL ESM & RADIATOR	305.0	2	10:10
INSTALL ALPHA JOINT	115.0	2	3:50
INSTALL RCS CLUSTER	110.0	2	3:40
INSTALL ACA	115.0	1	1:55

* TASK IS CANDIDATE FOR TELEROBOTIC / AUTONOMOUS OPERATIONS

$\Sigma = 67.7$ hours

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Figure 13 NON-DEXTEROUS MANIPULATION TASKS

Σ_A = 14.2 hours

NON-DEXTEROUS MANIPULATION TASK	TASK TIME (MIN)	TASK REPE-TITION	TOTAL TASK TIME (HRS:MIN)
RMS Tasks:			
TRANSLATE TO ASSEMBLY FIXTURE CONTAINER	1.0	12	0:12
TRANSLATE TO NODE RECEPTACLE CONTAINER	1.0	20	0:20
* TRANSLATE TO DIAGONAL STRUT CONTAINER	1.0	131	2:11
* TRANSLATE TO 5 METER STRUT CONTAINER	1.0	212	3:32
TRANSL TO ASSY FIXTURE BASE WITH FIXT. ELEMENT	1.0	12	0:12
TRANSLATE TO ASSY FIXTURE WITH NODE RECEPTACLE	1.0	20	0:20
* TRANSLATE TO ASSEMBLY FIXTURE WITH STRUT	1.0	343	5:43
* TRANSLATE TO OPPOSITE END OF STRUT	0.5	208	1:44
Non-Telerobotic Tasks:			
CHECK-OUT RMS	10.0	1	0:10
CHECK-OUT SAM	10.0	1	0:10
DEPLOY ASSEMBLY FIXTURE BASE	15.0	1	0:15
OBTAIN SAM FROM STOWAGE USING RMS	10.0	1	0:10
ROTATE ASSEMBLY FIXTURE 90°	0.5	212	1:46

Σ_B = [illegible] hours

* Task is candidate for near term autonomous telerobotic operations

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