

R-1436

**PHASE 1 STUDY TO DEFINE AN APPROACH FOR DEVELOPING
A COMPUTER-BASED SYSTEM CAPABLE OF
AUTOMATIC, UNATTENDED ASSEMBLY/DISASSEMBLY
OF SPACECRAFT**

by

J.L. Nevins, T.L. De Fazio, D.S. Seltzer and D.E. Whitney

FINAL REPORT

Covering the period 1 June to 31 December 1980

Prepared for
NASA Goddard Space Flight Center
Greenbelt, Maryland
Contract No. NAS 5-26187



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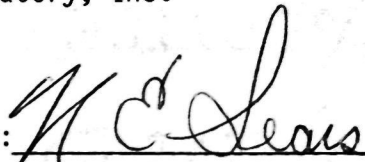
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Approved by:



N. E. Sears

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Seltzer, D. S., "Interfacing to the Cincinnati-Milacron T ³ Industrial Robot," CSDL Internal Memo No. MAT 1020-I, September 23, 1981

1.0 INTRODUCTION

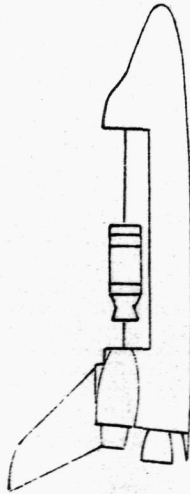
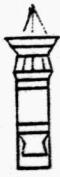
The advent of the Shuttle era marks the beginning of an opportunity to seriously consider maintenance, repair, replenishment or even refurbishment of satellites currently in space as well as presenting new design options for a whole new generation of repairable spacecraft.

To explore these opportunities in some systematic manner is easier if the above general tasks are segmented into trajectory motions such as rendezvous, docking, coupling, etc. Once the actual docking or coupling has taken place then the problem can be further categorized into specific work functions. These work functions can then be further broken down into assembly-disassembly tasks, diagnostic tasks, verification tasks, etc.

Trajectory motions may or may not be present depending on whether the work system is part of a work platform or work site or is totally separate. If the work system is separate and part of a larger maneuvering vehicle then trajectory motions can be classified into at least three basic motions, as follows:

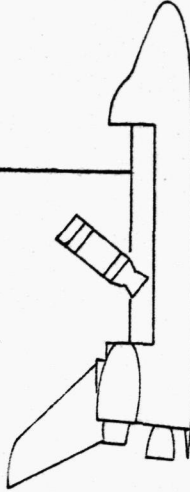
- An approach phase
- Near region/object phase
- Active work phase (attached to work site - or possibly not attached)

The approach phase generally involves orbital dynamics (Figure 1, Step 1) and has been actively studied by a number of groups. To illustrate, Figure 1 shows some of the many possible scenarios currently being studied. The near region phase (Figure 1, Steps 2, 3 & 4) similarly has been examined by a variety of groups. The active work phase, when the work system is actively attached to the work site, has been studied but only to the level of gross positioning of objects, or what we tend to classify as material handling tasks.



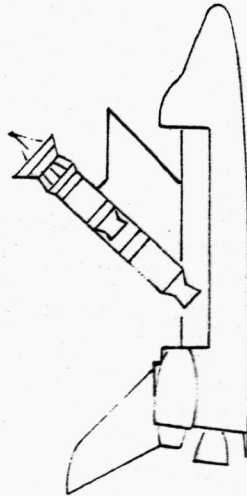
STEP 1 - RENDEZVOUS

- PAYLOAD BAY DOORS OPEN
- VISUAL INSPECTION OF IUS
- ESTABLISH RF LINK WITH IUS



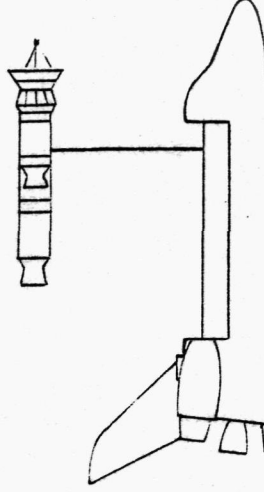
STEP 2 - ASSEMBLY PREPARATION

- ATTACH MANIPULATOR ARM TO IUS
- ROTATE DUAL SRM (TILT MECHANISM REQ'D)
- CONDITION IUS AND DUAL SRM FOR DOCKING



STEP 3 - DOCKING/ ASSEMBLY

- MANIPULATE IUS TO DOCK WITH DUAL SRM
- VERIFY IUS/DUAL SRM ELECTRICAL INTERFACE
- CONDITION IUS FOR DEPLOYMENT



STEP 4 - DEPLOYMENT

- RELEASE RETENTION/DEPLOYMENT LATCHES
- MANIPULATE IUS TO RELEASE POSITION
- VISUAL INSPECTION OF IUS
- RELEASE IUS

Figure 1.
(Proceedings, RMS Users Conference, Toronto, Canada, 30 May - 1 June 1979)

The specific functions required of a work system to perform maintenance and repair are quite complex. This study was devoted to consideration of this latter class of problems. Systematic study of this class of problems requires consideration of the following:

- Kinds of tasks required to perform these new functions.
- Delineations of the task requirements.
- Identification of relevant technology.
- Survey of present techniques or technology including man.
- Interaction of spacecraft design and technology options. This includes consideration of the strategic issues of repair vs. retrieval-replacement or destruction by removal and the necessary design tradeoffs for accomplishing each of the strategic options.
- Consideration of concept system design.
- Experiment or test plan for testing concept systems.

Out of this kind of study come both proposals for implementation as well as recommendations for new initiatives for development or research of potential interest in this area. However, it should also be noted that the funding support for this study effort was not adequate to explore all these issues in the necessary detail. So this report will attempt to highlight the critical areas and provide a framework for a more thorough study.

2.0 TYPES OF TASKS

2.1 General Problems

Present spacecraft designs fall into two categories, namely:

- (a) Spacecraft designed to be assembled, tested and repaired on the ground (only if necessary - not really designed for repair). These spacecraft are then launched, flown until either they fail, consumables are exhausted, or both, and then ignored. They then become one of the 2000-odd objects in space that may eventually pose a physical collision threat for future spacecraft.^{1,2}
- (b) Spacecraft designed to be fully or partially repaired in space. To date there is only one of them, the NASA GSFC Multimission Modular Spacecraft (MMS-1(SSM)). This unit, Figure 2, has been

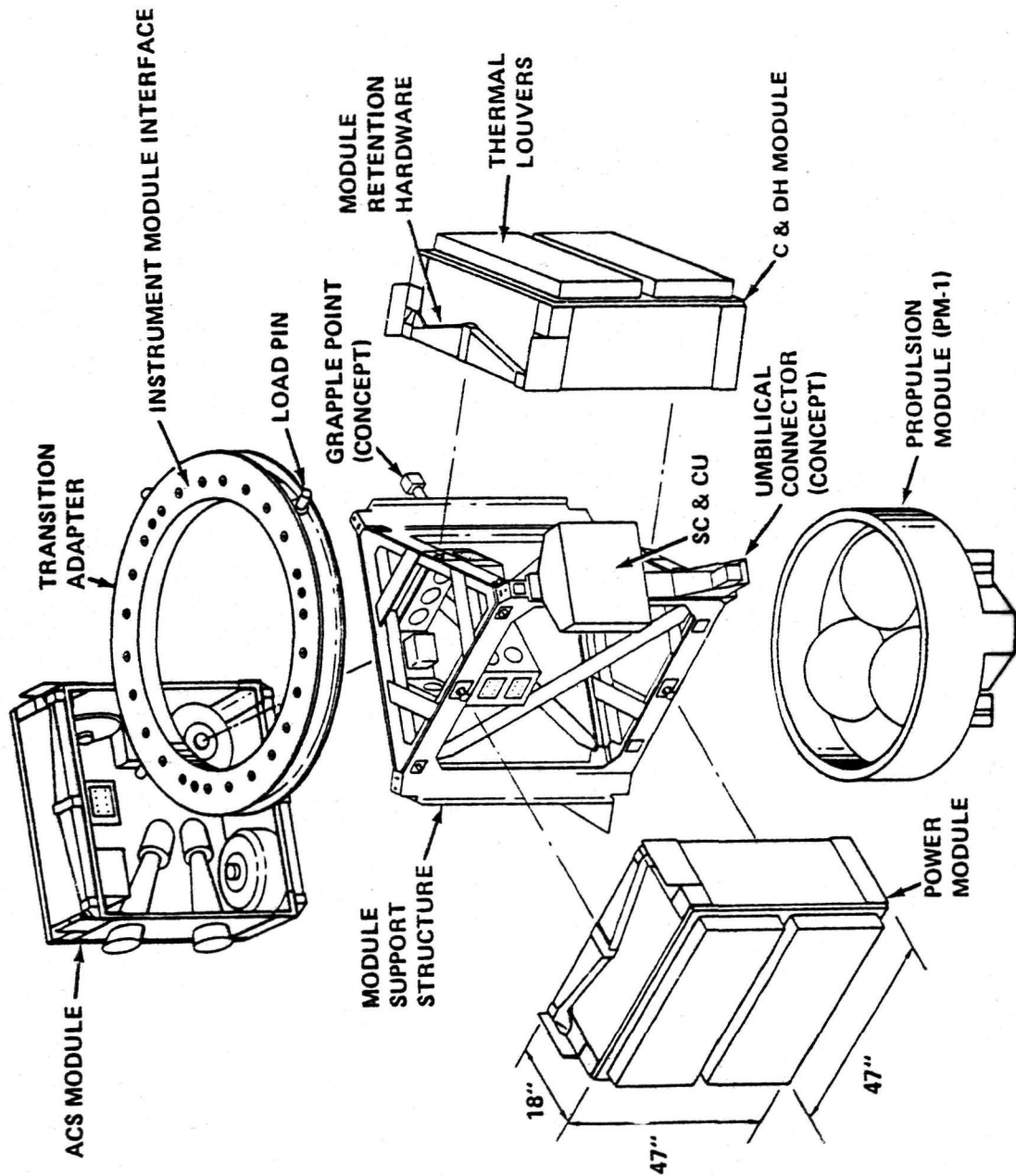


Figure 2. MMS mechanical system components (thermal blankets removed).
 (NASA GSFC, MMS Mechanical System Specification, S-700-13,
 Rev. A, May 1977.)

designed to allow easy tailoring of spacecraft for a variety of missions from a family of standard functional modules. Further, the basic modules have been designed with a common special interface that allows easy replacement in space by either an astronaut or the Shuttle Remote Manipulator System (SRMS). Either condition requires the use of a Special-Purpose End Effector (SPEE) in order to release or attach the basic modules.³ It should be noted that only the spacecraft functional modules have been designed to be easily replaced (Figure 2). These are the Attitude Control System (ACS) Module, the Command and Data Handling (C&DH) Module, and the Power Module. The other units, experimental package, propulsion unit, solar arrays, and antennae, do not have the same special interfaces as the functional modules. Their interfaces are the same as the rest of the spacecraft currently in orbit.

2.2 Classification of Tasks

Tasks for assembly/disassembly can be categorized into five main groups:

- Assembly/disassembly tasks
- Replacement tasks
- Diagnostic tasks
- Verification tasks
- Refurbishment tasks

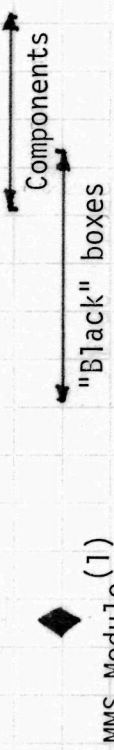
Note: This last group is something for the future and would be implemented when a capability in space exists that could support refurbishment.

Each task has a variety of requirements. To illustrate, Figure 3 shows only the positional requirements for a range of tasks. Tasks shown include:

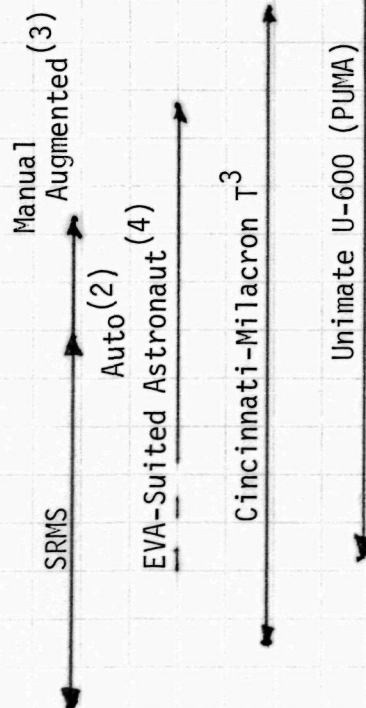
- (a) Replacing MMS modules
- (b) Replacement of "black boxes" (i.e., submodules within the larger MMS modules)
- (c) Replacement of individual electronic components on a printed circuit board.

FUNCTIONS

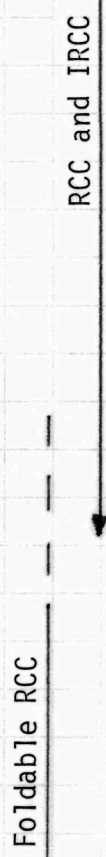
Replacement and Assembly



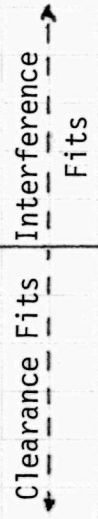
Manipulator Technology



Passive Technology



- (1) MMS Module - initial error ± 1.25 in., $\pm 5^\circ$, plus 0.25 in compliance.
- (2) SRMS Auto Mode ± 2 in. and $\pm 5^\circ$.
- (3) SRMS Manual Augmented Mode ± 0.5 in. and $\pm 1^\circ$
- (4) EVA - see Reference 13.



Feet 100

10

1.0

0.1

0.01

10^{-3}

10^{-4}

Inches

10

1

0.1

0.01

10^{-3}

10^{-4}

Figure 3. Positional requirements for various tasks including illustrative technology options.

As shown, these tasks impose a positional requirement on work systems that covers more than three orders of magnitude (i.e., from slightly over one inch to about 0.001 inch). Further, Figure 3 shows the general positional capability of technique/technology for meeting these requirements. Techniques shown include:

- (a) The SRMS
- (b) An EVA* suited astronaut
- (c) Some typical industrial manipulators.

In general it can be stated that replacement tasks can be constrained so that they involve principally positioning and/or orienting tasks. However, again only the MMS spacecraft module replacement has been so "organized." That is, ease of accessibility, minimum requirements on orientation, use of position guideways, and positional tolerances of greater than one inch, are all important items providing the minimum requirements on a work system to accomplish the replacement task. Again this is the only spacecraft designed this way, and this is not true of all the modules on the MMS.

Thus, for replacement tasks the mission system designer has two options.

- (a) He designs his equipment to meet the MMS replacement module interface requirements. Note: Table 1 lists the principal requirements.
- or,
- (b) He designs a system capable of addressing assembly/disassembly to at least the "black box" level. He could also design to the component level, but for now let us consider that refurbishment.

The first option is extremely limited in two directions:

- (a) It addresses only the MMS and future spacecraft, and
- (b) It imposes weight and design penalties to meet these interface requirements.

On the positive side, the SRMS and an EVA suited astronaut can accomplish this level of tasks.

The second option would allow access to most spacecraft presently flying and could address all future spacecraft as well. One initial problem is that the spacecraft have not been designed for remote maintenance; there-

*EVA - Extravehicular Activity

Table 1. Requirements for modules, black boxes, and components.

	MODULES	BLACK BOXES	COMPONENTS
NUMBER/S-C	3 - 6	(20-50) (3-6) 60 to 300	500,000
WEIGHT (1 g assumed)	450#	4# to 20#	.02# typical
SIZE	4'x4'x1.5'	1'x.5'x.2'	Fractional inch to one inch
FASTENERS	Pins & Bolts	Small Bolts, connectors	? ? ? screws, adhesives, solder, DIP
LOCATE TO:	1 1/4" say 5°	Guess .01" Guess 1°	Guess .005" - .05" Guess 1° .007" - .015"

fore accessibility to the desired module may be extremely difficult if not impossible. An additional problem is that space-qualified hardware does not exist for accomplishing these tasks.

2.3 Assembly/Disassembly Tasks

Basic assembly tasks for a variety of consumer goods assembled by industry have been identified and correlated. The types of products, the associated assembly tasks and the statistics of occurrence are shown on Figures 4, 5 and 6. The statistics for the consumer products listed on Figure 5 indicate that the most common tasks are simple insertion and screw insertion. Further, studies of larger products like automobiles have illustrated similar statistics.

A good deal of effort⁴ has gone into the analysis of basic assembly tasks and some interesting technology has ensued which will be gone into later in Section 3.1.2.

Analysis of simple insertion tasks has required extensive geometric and force-friction modeling of how parts behave during the mating process (Figure 7). Initial analysis was devited to rigid parts but during the last couple of years the analytical techniques have been extended to compliant or springy parts like electrical connectors. Reference [4] is a summary report on the early efforts and Reference [5] describes the work to date on compliant part mating.

Unfortunately, to date similar studies for spacecraft assembly/disassembly have not been performed. An analogy between this problem and similar problems indicates that requirements on technology cannot be determined until the process requirements have been determined. Otherwise, one is caught in the dilemma of having developed a technology or solution and then is faced with finding the problem that matches the solution.

The picture is not totally bleak because most of the basic part mating studies done so far for industry are applicable to this class of problems. What has not been done is the determination of the types of assembly/disassembly tasks that are unique to spacecraft: i.e., what are the unique spacecraft tasks not listed on Figure 5 and what is the statistics of their occurrence, and how do they differ from industry as shown in Figure 6. The problem, of course,

Product	No. of Pieces	Max. Linear Dimension
ELECTRIC TIMER COVER SUBASSEMBLY*	7	4.5"
ELECTRIC TIMER CASE AND FINAL ASSEMBLY*	18	4.5"
REFRIGERATOR COMPRESSOR FAMILY	26	10"
BICYCLE COASTER BRAKE	15	6"
TRANSFORMER ELECTRIC BUSHING FAMILY	6 to 8	10"
END CAP SUBASSEMBLIES FOR SMALL INDUCTION MOTORS	29	7"
INDUCTION MOTOR MAIN BODY SUB-ASSEMBLY AND FINAL ASSEMBLY	21	15"
ELECTRIC JIGSAW*	58	12"
TOASTER OVEN	41	15"
AUTOMOBILE ALTERNATOR FAMILY**	17	8"

*CURRENTLY ASSEMBLED AUTOMATICALLY.

**CURRENTLY ASSEMBLED BY A MIXTURE OF MANUAL AND AUTOMATIC WORKSTATIONS.

Figure 4. List of products studied.



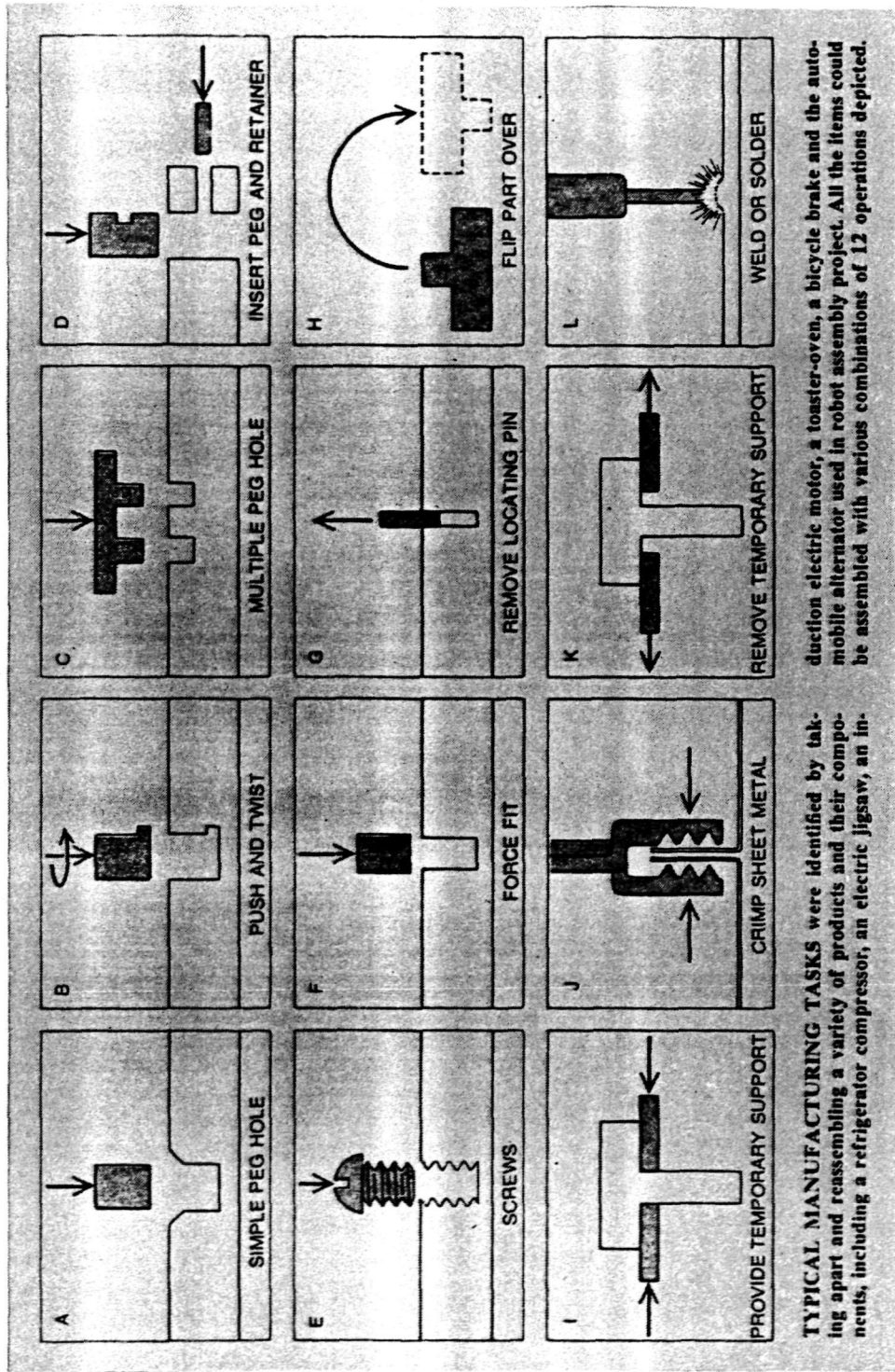


Figure 5. Types of assembly tasks.



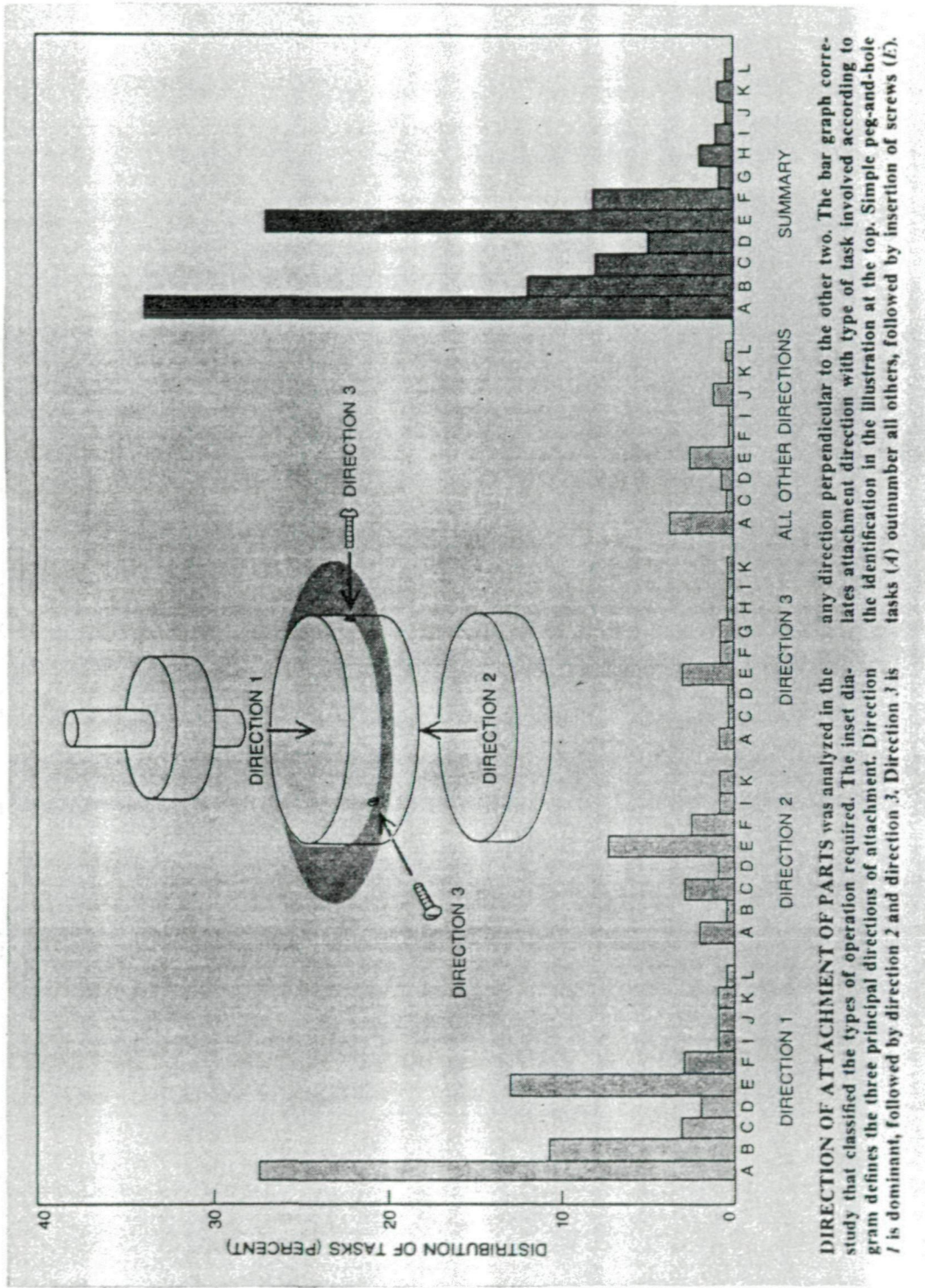
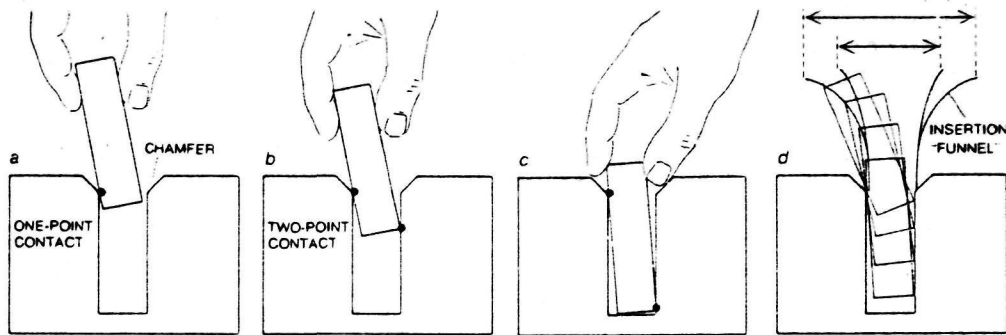


Figure 6. Product statistics.



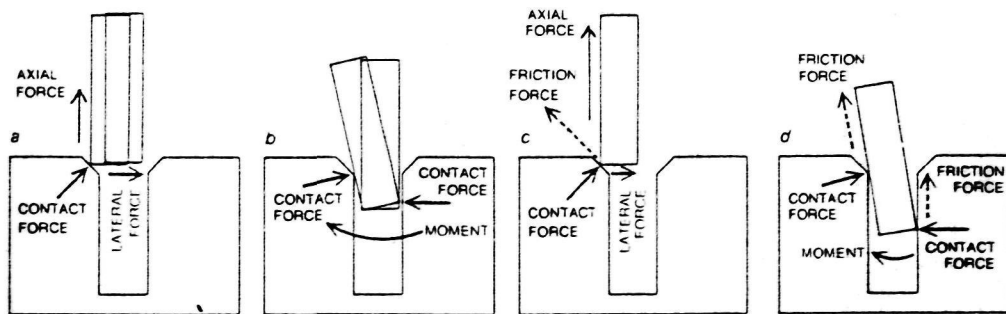
goes beyond any individual task. It is the integration of a variety of tasks to accomplish something interesting - an accomplishment worth the development cost of the system, worth the cost of redesigning the spacecraft.

Examples of more complicated groups of tasks that can occur are modifications to spacecraft harnesses or the modification or repairing of plumbing for either coolant lines, attitude control systems, or propulsion. To accomplish these demanding tasks groups will require the integration of spacecraft design and available technology for addressing these issues. To accomplish these will necessitate that the spacecraft be carefully designed so that it can in fact be repaired remotely. We call this approach "structuring" of the task. For example, welding of piping could be accomplished by rigid jigs and tooling or else another way of joining would be chosen which is more easily implemented in space.



INSERTION OF A PEG IN A HOLE, a typical assembly task, is basically a problem in positioning. Holes are usually chamfered (beveled around the edge) to aid insertion. As the peg slides down the chamfer and enters the hole (a) it touches one side of the interior first (one-point contact). If the angular misalignment is large (b), the peg will soon touch the opposite side of the hole as well (two-point contact), with danger of jamming. In manual assembly vision can help

to find the chamfer, but after the peg enters the hole one must rely on the ability to sense the resisting forces in order to maneuver the peg to the bottom (c). The geometry of the peg and the hole keeps the peg within the insertion "funnel" (d), the path that is traced by the top of the peg at successively deeper stages of the two-point contact. The smaller the clearance between the peg and the hole, the narrower the insertion funnel and the more difficult the insertion task.



CONTACT FORCES BETWEEN PARTS can be used to guide corrective motions of the "wrist" of an assembly robot's arm. In the absence of friction (a) the contact force at the chamfer is sensed as two equal reactions, one vertical and the other lateral. The lateral force can serve as a cue to the desired corrective motion (colored arrow). Later (b) contact forces create a moment around the tip, which pro-

vides a cue to the desired corrective motion (colored arrow). When there is friction (c), the upward reaction at the chamfer is exaggerated, reducing the useful lateral reaction. Friction also reduces the useful information about moment (d). The ratio of the friction force (broken arrows) to the contact force, in other words the coefficient of friction, is about 0.2 for steel parts and 1.0 for aluminum ones.

Figure 7. Analysis of the basically kinematic process of mating rigid parts.

What is quite obvious is that the spacecraft designer and the mission designer are now faced with a large array of options that interact strongly with spacecraft design, spacecraft operations, and space economics. One has to consider not only possible technology but methodologies, or design tools and techniques, for considering these many options in a systematic way. To do this requires large data bases and new types of Computer Aided Design (CAD) systems. To illustrate, similar industrial problems are now being addressed by a combination of economic modeling techniques and a CAD program based on mixed linear-integer formulations. With these tools, data bases containing technology processes for assembly or operational and cost constraints can be analyzed and solutions synthesized.⁶ Suitably modified, this class of tools can be applied directly to this class of problems.

3.0 TECHNOLOGY OPTIONS

Consideration of requirements must be coupled with consideration of available technology because it simply is not rational to expect that one can generate requirements without limit in the face of technology resources of finite capabilities. Thus, there must be interaction and tradeoffs between spacecraft design and available technology in order to find a viable economic solution.

The remainder of this section will be devoted to describing some of the newer options, their capabilities, and their limitations.

3.1 Available Technology

3.1.1 Sensors for Non-Surveyed Worksites

In the introduction it was pointed out that there are at least three phases to this type of problem. Further, that this report would be restricted to consideration of the third phase - the active work phase - where there is a strong physical relationship between the work site and the work system. One class of sensors which are of importance in the second phase - the near region phase - may also be important in the third phase if one is faced with unplanned maintenance on a work site not previously surveyed. These sensors are proximity sensors to help avoid obstacles⁷ and pointing or two-axis ranging systems⁸ (Figure 8) for mapping locations on an unknown or non-surveyed work site. Proximity sensor systems have been tested in the laboratory⁷ and SRMS tests in space are planned. A two-axis ranging system

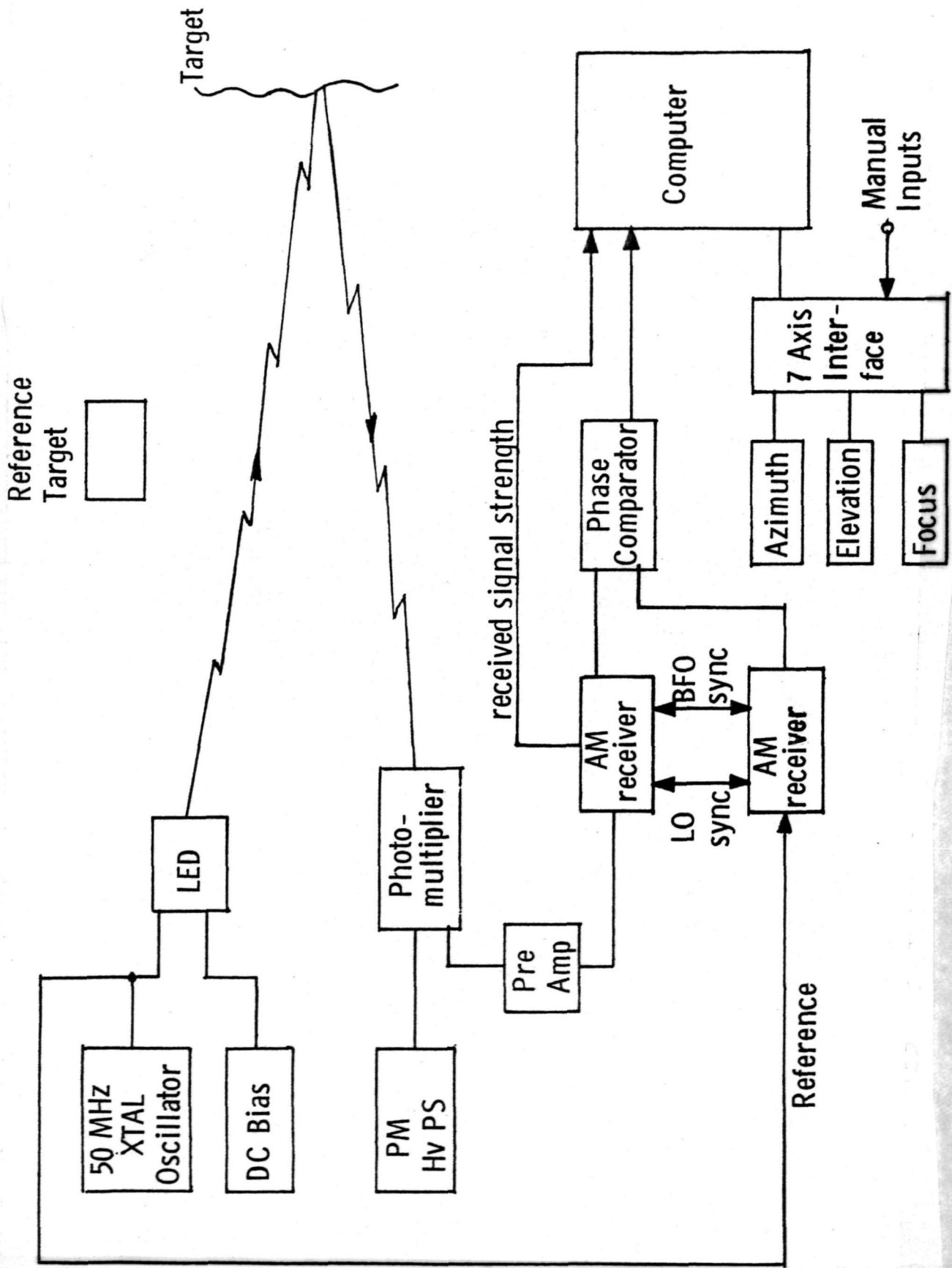


Figure 8A. Block diagram of pointing (ranging) system.

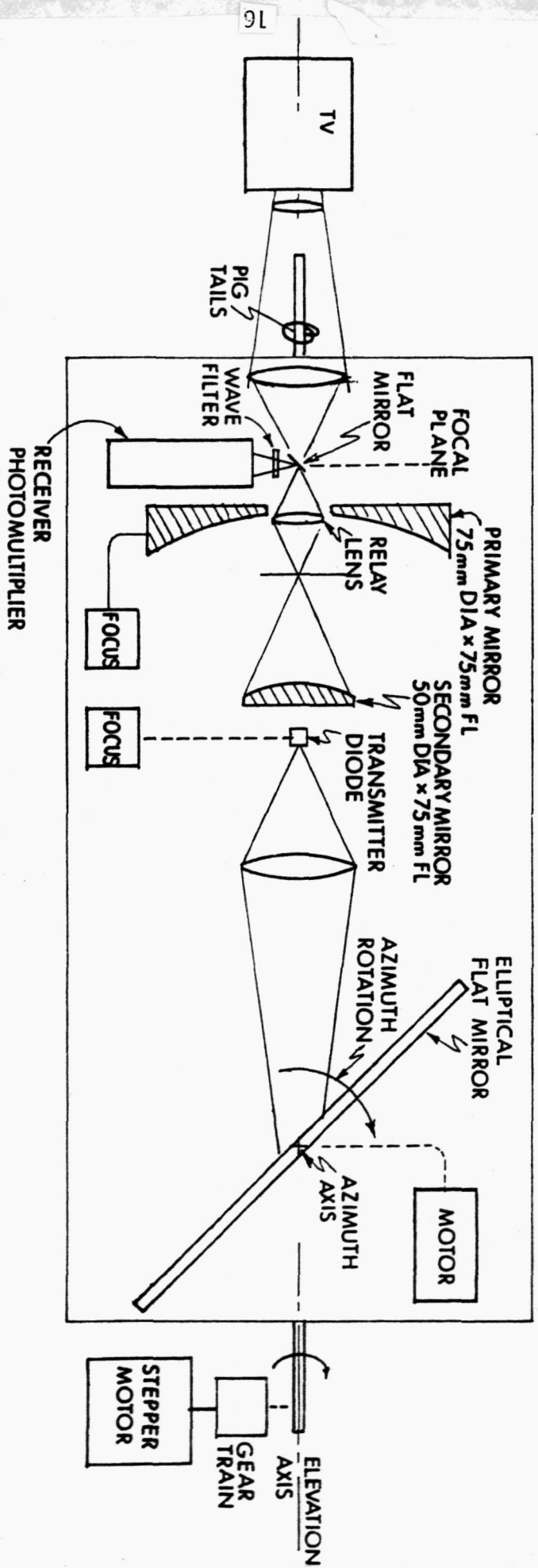


Figure 8B. Laboratory pointing system.

based on a modulated light emitting diode (LED) or a gas laser has been demonstrated in the laboratory that is capable of measuring range or distance to 1 millimeter in a work volume of 1-3 meters cubed. Further, SRI International using the same technique has looked into converting this from a single axis measurement to a scanning system capable of generating a range image of the worksite.⁹

3.1.2 Assembly Technology

There are two main classes of technology available for application to space assembly/disassembly. The two principal classes are active systems and passive systems.

3.1.2.1 Active Systems - Under active systems there are two principal techniques. One technique is vision systems and the other technique involves multi-axis force-feedback servos. Vision systems come in a variety of forms from full stereo systems in the visible spectrum to simple linear arrays or projected lines of light to give depth of objects and range, to single axis ranging systems or imaging ranging systems using various emission spectrums. Force-feedback systems can range from single axis systems to six-axis systems^{10,11} operating either small, low mass, limited motion but relatively high bandwidth platforms attached to some articulating mechanism or to controlling the entire articulating, large mass system. Six-axis force sensor technology has been developed that gives dynamic ranges (largest force sense/minimum force sense) of 2000/1, with threshold sensitivities of the order of 4 grams (0.14 ounce).⁴

Two problems with using vision systems for assembly are:

- (a) You can't look into a hole that you are trying to put something into; and
- (b) That measuring the misalignment of a work system to a work site to less than a degree is difficult but very important if one wants to avoid wedging or jamming of the pieces.

Vision or range imaging systems are very important for surveying previously unsurveyed worksites. The question is how many sites will be unsurveyed versus how many will be previously surveyed and practiced on many times before an actual space operation/task is attempted. Past experience indicates that the latter is the way actual space operations of this type will be carried out.

3.1.2.2 Passive Systems - There are two principal types of passive systems, namely:

- (a) Undocumented or unengineered compliant systems, and
- (b) Engineered compliant systems.

Undocumented compliance exists in any mechanical system. It is due to tolerances in the manufacture of the system, bearing slop, bending of beams or elements, etc. Some assembly systems in industry have depended on undocumented compliance, but as Figure 9 illustrates the probability of successful assembly can be quite low.

Engineered compliances developed as a result of our research perform with a probability of success of one throughout their performance range. These devices, called Remote Center Compliances (RCC) (Figure 10) act as though the applied force is centered at the tip of the peg (Figure 11) instead of the top of the peg. It is the latter condition that causes the peg to ride off one wall (what we call one-point contact) and wedge or jam against the other wall (called two-point contact). Further, RCCs can be equally successfully applied to interference fits. Industrial experience indicates that with interference fits, since the RCC is steering to minimize forces, reduction in tool breakage of as much as a factor of 10 can be expected.

Normal industrial application requires RCCs capable of lateral error correction of the order of ± 0.25 cm (± 0.1 inch), $\pm 1^\circ$ in vertical rotation, and $\pm 15^\circ$ about the vertical axis. Newer designs, with different geometries, allow lateral corrections of ± 25 cm (± 10 inches) and $\pm 30^\circ$ in vertical rotation. It has been suggested that these newer designs may be of interest as new types of docking mechanism.

The basic physical parameters of RCC mechanisms are its so-called focal point (S) (distance from the base to the end of its tool point) and its lateral (k_x) and rotational stiffness (k_θ). Current industrial units are of the fixed forms and fixed compliance variety. Active compliant systems can be constructed that would allow all terms to be variable if so desired.^{10,11} This would allow the system to compensate for various means, various tool lengths, and could allow for various size of errors. Some work is being done

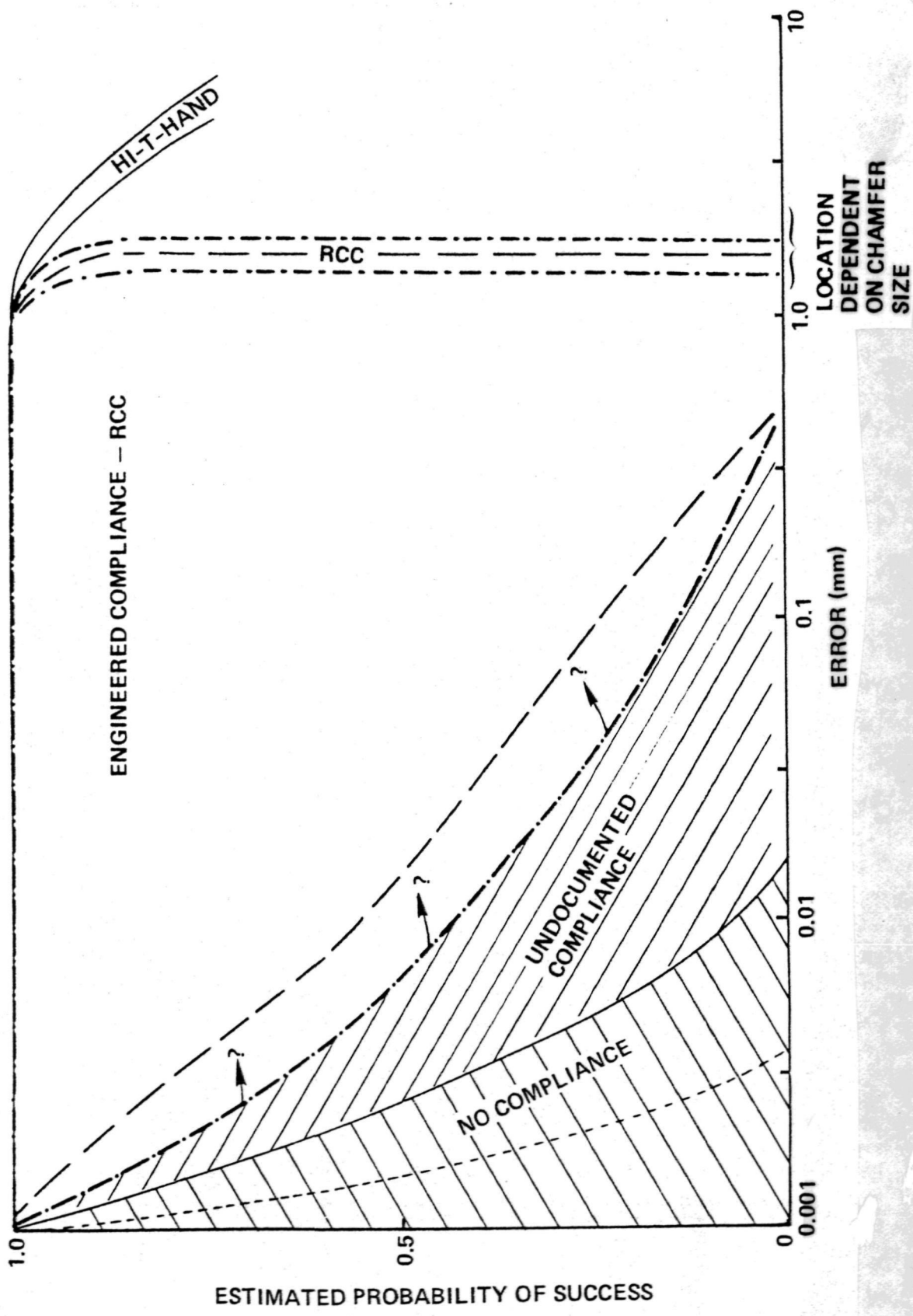


Figure 9. Error absorbers - probability of successful assembly by technique versus initial position error.

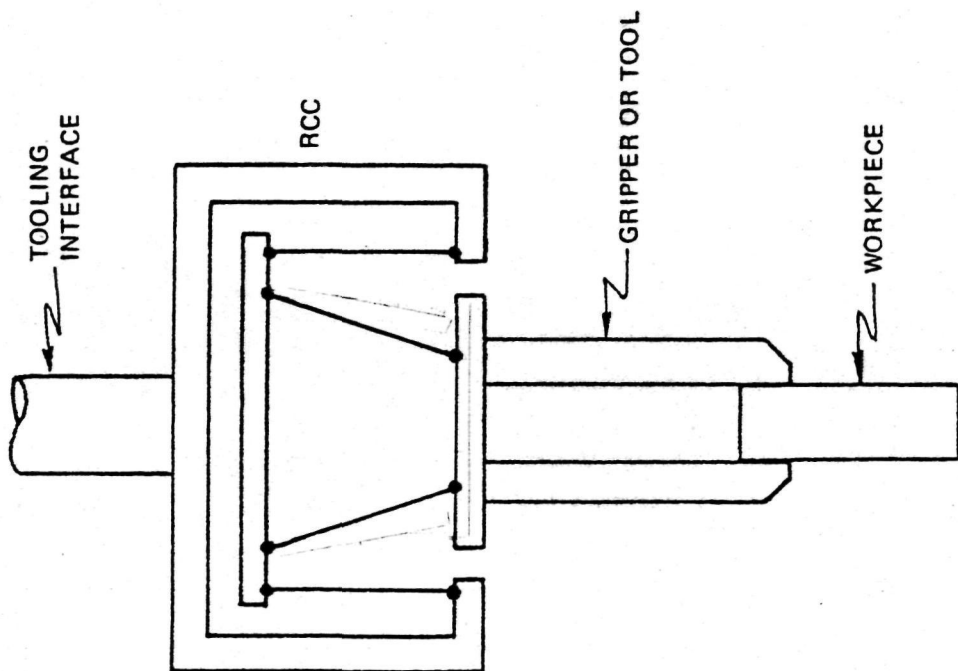
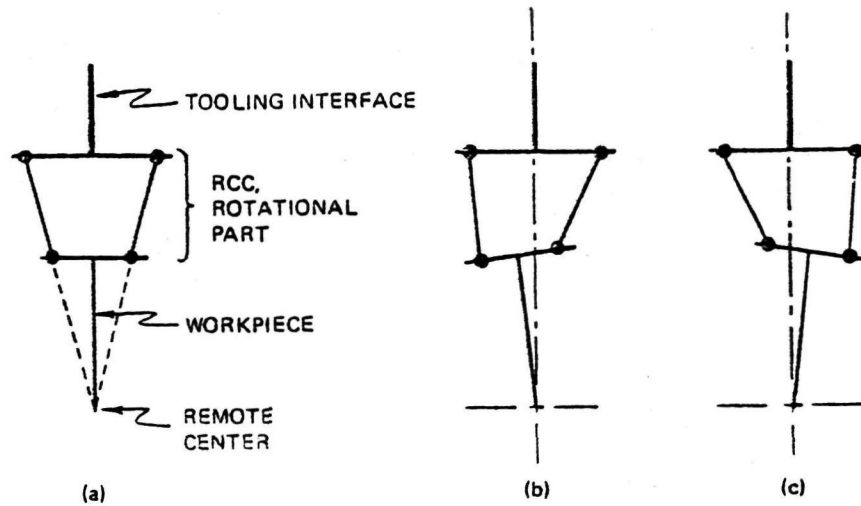
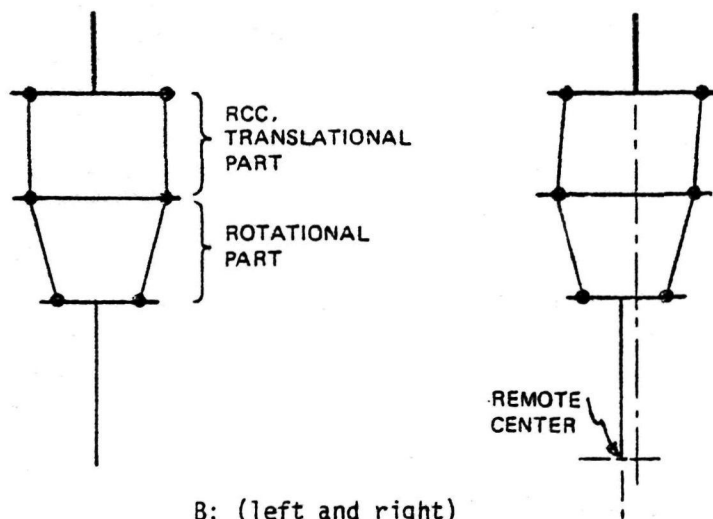


Figure 10. Remote Center Compliance - RCC.



- A:
- a) Two dimensional representation of rotational part of RCC;
 - b) Rotational part of RCC allowing workpiece to rotate counter clockwise
 - c) Workpiece rotating clockwise



B: (left and right)

Left--Planar representation of RCC showing rotational and translational parts

Right--Translational part of RCC allowing workpiece to translate to the left without rotating

Figure 11. The RCC.

to give these attributes to mechanical systems but this is early in the development. Of particular interest would be the capability to change focus, thus allowing more freedom in tool length design.

An additional feature of RCCs is that they exhibit relatively large motion (displacement) as a function of applied forces. Thus, with appropriate sensors, the displacement state of an RCC can be monitored. Figure 12 illustrates an RCC with linear diode arrays to monitor four axes of displacement, namely the lateral x and y displacement and the rotational displacement about x and y. A unit is currently in design to give five axes of information.

This information can be used in a variety of ways. For example, it can be used to indicate the applied force or the displacement state as a result of the applied force; it can be used in a learning loop for automatic teaching of a robot; it can be used to monitor an assembly process, as an inspection device; or it can be coupled to estimators to monitor the long term variations on part A and part B and how they interact with one another.

3.1.2.3 Other Assembly Technology - The above sections describe a limited set of technologies for assembly. However, there are many more tasks that need to be analyzed that may be helped with the above technologies or will need other technologies to be developed before the tasks can be handled correctly. In the meantime, spacecraft designers can either opt to restrict their designs to within the capability of the above systems or trust to luck that they will not construct a design that inhibits any attempt at remote maintenance.

3.1.3 Diagnostic and Verification Tasks

In Section 2.2 it was pointed out that there are five main groups of tasks, namely:

- (a) Replacement tasks
- (b) Assembly tasks
- (c) Diagnostic tasks
- (d) Verification tasks
- (3) Refurbishment tasks

Refurbishment we will not discuss here and replacement and assembly tasks have already been discussed.

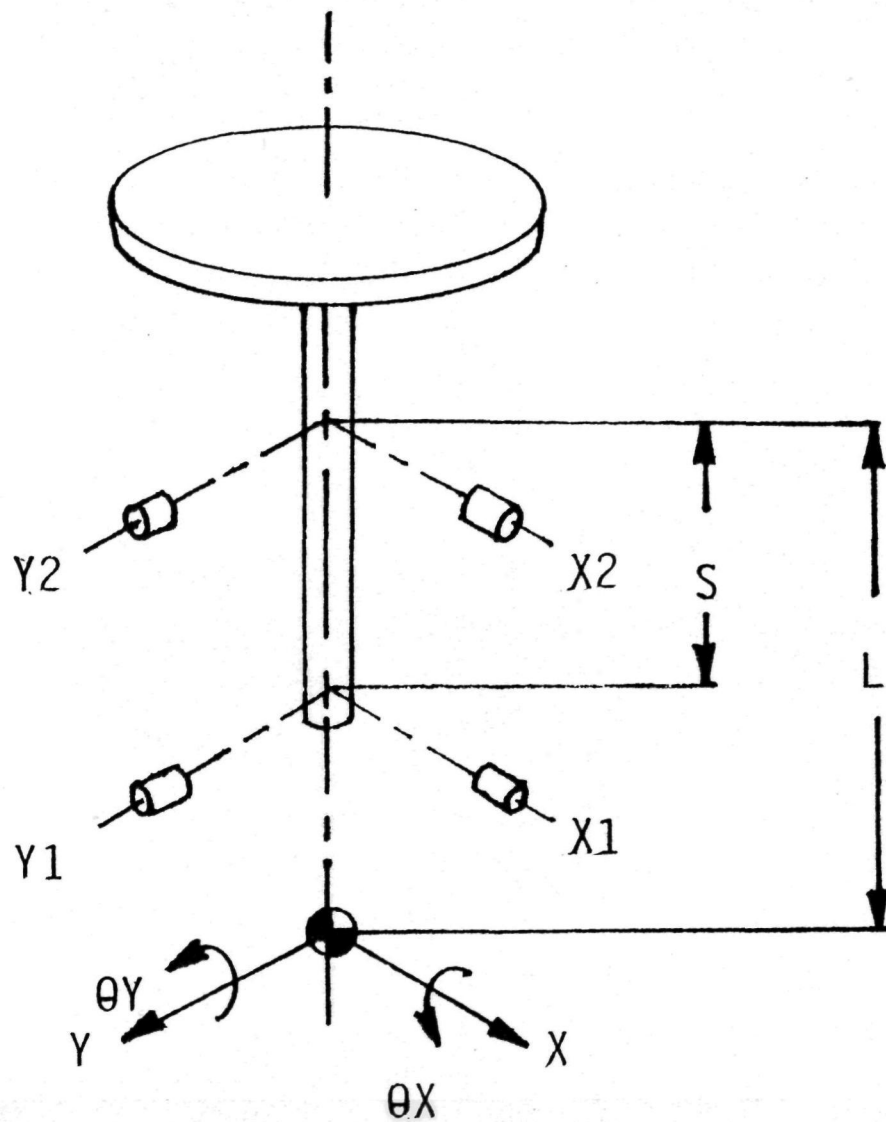


Figure 12. Schematic of the Instrumented RCC (IRCC).

3.1.3.1 Diagnostics - Diagnostics can be simply treated by defining that all major modules will have sufficient sensors and processing to be able to monitor the health and well-being of all its submodules. Further, that it will be able to communicate its findings to the work systems through communication links or connectors. Thus, the assumption can be made that the work system has all the data, plus the proper replacement module, in order to start a repair cycle. It further assumes that the major module can check the installed health of a replaced module to determine that the job was satisfactorily performed. This is also part of the verification phase.

More extensive diagnostic systems would get into the issues of sensor redundancy techniques, highly reliable bus communication and fault tolerant computer systems.¹²

3.1.3.2 Verification - Verification is perhaps the most difficult task, because it is the function that guarantees that whatever was done to the spacecraft was clearly understood and documented. The ideal is that the spacecraft is restored, or brought to, the design specification.

Verification requires that mechanical, electrical, and thermal interfaces be verified both before as well as after installation. In addition, the diagnostic system interfaces once reestablished should provide verification of functional capability.

3.2 Illustrative Example

To indicate the use of the above-described technologies, tables have been constructed listing possible solutions to four classes of problems. The problems are MMS modules, black boxes, components, and solar panels and antennas. Requirements for solar panels and antennas are based on estimates only.

Table 1 gives the number, size, weight, fastener type, and tolerance requirements for MMS modules, black boxes, and components.

Table 2 indicates technology options for assembly, verification, diagnostics and replacement functions for the four problem areas.

For illustration only, the performance capabilities of two commercial industrial manipulators (robots) are listed. The first one is a small electric unit, the Unimate Model 500 or 600 (PUMA), which has a similar reach

to humans. The second one is the Cincinnati-Milacron Model T³, a strong hydraulic unit, with a reach approximately three times that of humans. Table 3 lists the basic characteristics of these units plus an EVA suited astronaut and the SRMS.

4.0 CONCLUSIONS AND RECOMMENDATIONS

4.1 Conclusions

Section 2.0 and Figure 3 indicate that one way of viewing the assembly-disassembly-repair issues for spacecraft is to categorize the positional requirements for replacing MMS modules, black boxes within the modules, or components within the black boxes. As the figure indicates, there are almost three orders of magnitude separating the positional requirements of these tasks. Further, the figure shows the manipulator technologies - including an EVA suited astronaut - for accomplishing these tasks.

For MMS module replacement, where the positional requirements are about 1 inch, there are two options, namely: the Shuttle Remote Manipulator System or an Eva suited astronaut. But for black box or component replacement there are no space qualified systems, only the possibility of applying technology developed (or being developed) for industrial applications with similar positional requirements. It should be noted, however, that the control software for present day industrial robots do not have suitable interfaces for vision or multi-axis force sensors and these would have to be developed. To illustrate, a memo on interfacing sensors to an industrial robot is included in the appendix.

What is needed is the development of systems capable of performing at least the replacement of systems down to the black box level. What is concluded is that a concentrated study and laboratory test program must be undertaken to identify the specific tasks needed to accomplish assembly, disassembly, and repair or maintenance, and to develop verified means for accomplishing these functions. Further, the strategic issues of what spacecraft this new work system should be designed for needs to be resolved. If it is to be applied to the present population of spacecraft in orbit then studies need to be made of what actually can be accomplished in the light of restricted or impossible access, fasteners designed never to be unfastened, welded plumbing, etc.

4.2 Recommendations

The output from this study should provide the initial set of requirements for additional programs necessary to implement a space-borne work system capable, within specified performance, of achieving assembly, disassembly, and repair or maintenance in space.

Programs are needed in two principal areas, namely detailed studies coupled closely with a laboratory test program. The following studies are needed:

- (a) Detailed study to identify task requirements and statistics. Part of this study should be a tradeoff between technology options and spacecraft design, plus the strategic decision of what scale the system should be targeted for. I.e., modules of what size, weight, and mechanical tolerances should the system attempt first. What should be second, what time scale for development, etc.
- (b) System studies to determine which configuration of work system is best for what kind of task and what supporting systems are needed. Some of this work is being addressed by current studies but no tradeoffs are being made of work system configurations and task.
- (c) From the above studies, a detailed set of requirements on technology needed, research needed, and equipment to be developed and space qualified could then be drawn.

The laboratory test program has two main facets, namely:

- (a) The establishment of a laboratory to test concepts, tooling design, and sensor performance to provide both a research tool for exploring research ideas as well as a test and verification facility for developed hardware. Again at least two scales of laboratory mock-ups should be provided for; that is, black box level and MMS module or similar size packages.
- (b) The establishment of a facility for the development of "smart" end-effectors that integrate multi-axis force sensors, imaging systems of various kinds, proximity sensors, and active controllable variable compliances.

Table 2. Technology options for tasks.

	MODULE	BLACK BOX	COMPONENTS	SOLAR CELLS	or ANTENNAS
Number and weight	3 - 6 @ 450#	60 - 300 @ 4# - 20#	500,000 @ .02# typ.		1 @ 10# - 50#
Size	4' x 4' x 1.5'	1' x .5' x .2'	.05' typ.		
Fasteners	Pins & bolts	Small bolts, connectors	Screws, adhesives, dip, solder		
Locating tolerances	1-1/4"	.01" -	.005" - .02"		
TASKS					
ASSEMBLY	<ul style="list-style-type: none"> ● RMS + passive aids to fit ● RMS + designed compliance ● RMS-stanchion + RCC-tool* ● EVA 	<ul style="list-style-type: none"> ● CM T³ + RCC or RCC-tool ● PUMA + RCC or RCC-tool ● RMS-placed T³ or PUMA + RCC or RCC-tool ● EVA + specialized tools 	<ul style="list-style-type: none"> ● At or beyond state of art ● 1 or more PUMA + engineered compliance + adv. sensing ● Not a serious concern 		<ul style="list-style-type: none"> ● At or beyond state of art ● PUMA + eng'rd compliance + advanced sensing
VERIFICATION	<ul style="list-style-type: none"> ● Binary sensors on structure ● Count turns + check torque ● Response to mechanical disturbance 	<ul style="list-style-type: none"> ● Binary sensors on module ● Count turns + check torque ● Response to electrical excitation 	<ul style="list-style-type: none"> ● Responses to mechanical disturbance ● Response to electrical excitation 		<ul style="list-style-type: none"> ● Focus evaluation ● Response to EM + electrical excitation ● Binary sensors ● Mechanical response
DIAGNOSTICS	Moving parts to diagnostic terminals - requirements similar to assembly or replacement.	HARD WIRED DIAGNOSTICS			<ul style="list-style-type: none"> ● Focus evaluation ● Response to EM + electrical excitation
REPLACEMENT		SIMILAR TO ASSEMBLY	<ul style="list-style-type: none"> ● Not a serious concern 		<ul style="list-style-type: none"> ● PUMA + engineered compliance ● PUMA + eng'rd compliance + advanced sensing

*Limited option for fasteners only.

Table 3. Basic characteristics of available options.

	SRMS CLASS	T ³ (VARIANT)	PUMA (VARIANT)	HUMAN EVA
REACH	50'	8'	3'	~3'
TRAVERSE TIME	~ 25 sec.	~1 sec.	~0.5 sec.	10 sec.
SETTLING TIME	5 sec. 1 cycle (laden)	~1 sec.	~0.5 sec.	~.5 sec.
FORCE CAPABILITY	15# min.	150#	10#	10#
ACCURACY	Mode dep't 2" - 1-1/4"	.05"	.02"	.2"

REFERENCES

1. Kessler, D. J. and B. G. Cour-Palais, "Collision Frequency of Artificial Satellites: The Creation of the Debris Belt," J. Geophysical Research, Vol. 83, No. A6, pp. 2637-46, June 1978.
2. Nevins, J. L., S. J. Wang, D. E. Whitney, "Satellite Retrieval Study," CSDL Report No. R-1186, October 1978.
3. Phenix, J. E., "Spacecraft On-Orbit Servicing Using the Shuttle Remote Manipulator System with a Special-Purpose End Effector," NASA GSFC Report No. X-408-79-25, October 1979.
4. "Exploratory Research in Industrial Assembly Part Mating - Seventh Report," covering the period 1 Sept. 1978 to 28 Feb. 1980, CSDL Report No. R-1276, March 1980.
5. "Part Mating Theory for Compliant Parts - First Report," covering the period 1 Sept. 1979 to 31 Aug. 1980, CSDL Report No. R-1407, September 1980.
6. "Design and Control of Adaptable Programmable Assembly Systems - First Report," covering the period 1 July 1978 to 30 June 1979, CSDL Report No. R-1284, August 1979.
7. Bejczy, A. K., "Sensors, Controls, and Man-Machine Interface for Advanced Teleoperation," Science, Vol. 208, No. 4450, pp. 1327-1335, 20 June 1980.
8. "Annual Progress Report No. 2 for the Development of Multi-Moded Remote Manipulator Systems," for period ending January 1973, CSDL Report No. C-3901, February 1973.
9. Rosen, C., et al, "Machine Intelligence Applied to Industrial Automation," Research Report Series, SRI International, Menlo Park, CA.
10. Nevins, J. L., T. B. Sheridan, and D. E. Whitney, "Flexible Automation, a First Concept," a paper presented at IEEE NEREM, Nov. 1-3, 1972, and published as CSDL Report No. E-2707, August 1972.

11. "Servo Controlled Mobility Device," U.S. Patent No. 4,156,835, issued 29 May 1979, filed 29 May 1974, by D. E. Whitney and J. L. Nevins.
12. Deckert, J. C., and M. N. Desai (CSDL) and A. S. Willsky (MIT), "Reliable Dual-Redundant Sensor Failure Detection and Identification for the NASA F-8 DFBW Aircraft," NASA Contractor Report No. 2944, February 1978.
13. "Extravehicular Activity Design Criteria, Revision A," NASA MSC, Crew Systems Division, 20 September 1968.

APPENDIX



INTRALAB MEMORANDUM

TO: Int. MAT Dist.

MEMO NO: MAT 1020-I

FROM: D. Seltzer *D.S.*

DATE: September 23, 1980

SUBJECT: Interfacing to the Cincinnati Milacron T³ Industrial Robot

COPIES TO:

The Cincinnati Milacron T³ industrial robot was designed to operate as a stand-alone device. Although the robot controller incorporates a minicomputer, the CIP/3200, the software is essentially inaccessible to the user. "Programming" the arm consists of supplying operation sequence information, and motion parameters such as position, velocity, and tool dimensions. Position information is generally provided by the Teach by Showing method, in which the arm is physically placed at the desired location, and a record button is pressed to read the actual joint encoder values. Several keyboard commands allow the modification of previously taught data.

External interfacing is through separate sets of input and output lines. The output lines are relay contact closures which can be opened or closed to operate associated equipment. The input lines, also bilevel, are used by the WAIT and PERFORM command functions. WAIT causes the T³ to halt until a specified Boolean combination of input levels is achieved, permitting synchronization of robot operations with those of other devices. The PERFORM function controls branching to different command sequences based upon the states of the input lines. Typically, this is used to interface with simply binary sensing devices.

This basic system is entirely adequate for the majority of current industrial robotic applications, such as machine loading/unloading, welding, and spray-painting. It is not well-suited for more advanced applications involving interaction with sophisticated sensory devices and external computers.

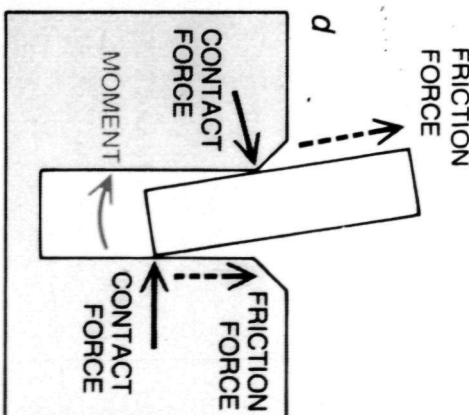
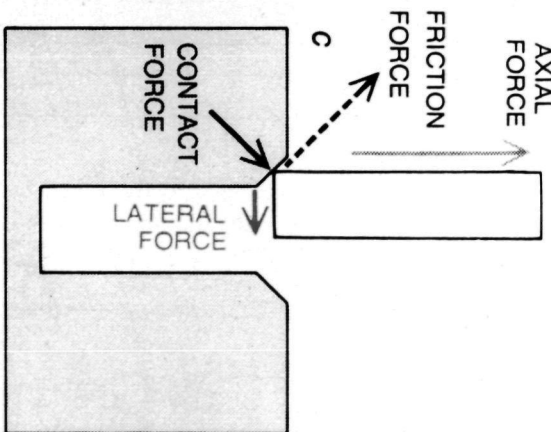
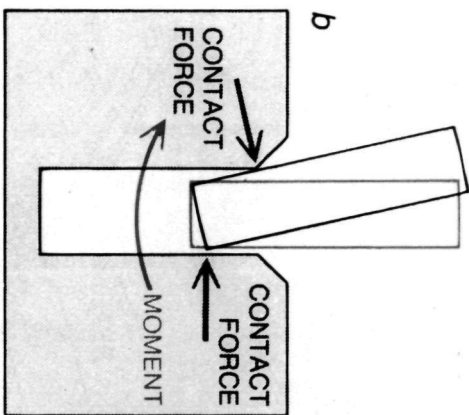
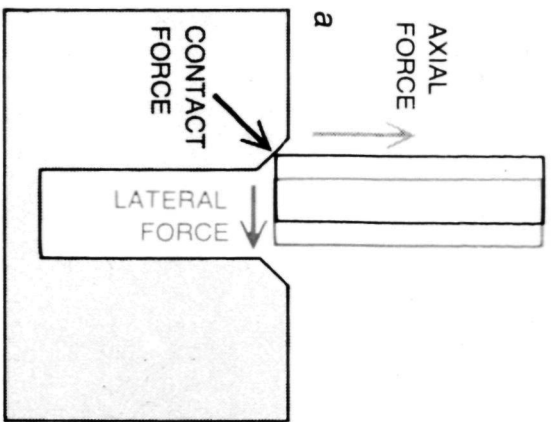
There have been a few instances, however, in which a T³ robot has been successfully interfaced with both computers and high level sensors. One of the more notable ones has been the General Motors Research Lab CONSIGHT project. CONSIGHT is a robot system for the identification and acquisition of parts from a conveyor belt, using a vision sensor. Besides the T³ robot, the original system included a line camera and a PDP 11/34 minicomputer. The mini is the controller for both the vision and robot subsystems. Raw vision data from the camera is acquired by the controller and processed to yield part identification, position, and orientation.

The T³ is programmed as though it were performing a simple material-handling task. The part-pickup point is not fixed, however. There is a different point for each cycle, depending upon where the part is placed on the conveyor belt and what its orientation is. This information is computed by the mini and is then transmitted to the T³ internal controller.

The software needed to implement this interface was developed by Cincinnati Milacron at the request of General Motors. C.M. now offers this interface as a software option for all of their T³ robots. Called the EXTERNAL function, it supports a serial interface between the T³ controller and an external device. The actual hardware link is a standard RS-232C interface operating at up to 9600 baud. The communications protocol is a subset of Digital Equipment Corporation's DDCMP. The T³ controller is the master device, controlling all communication.

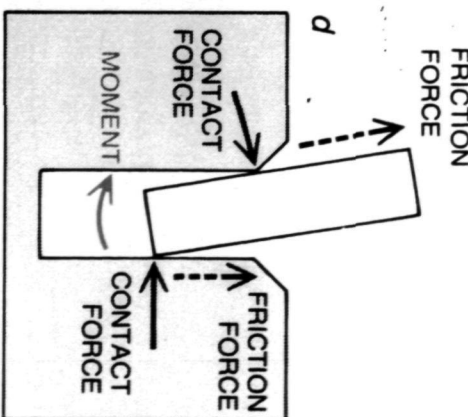
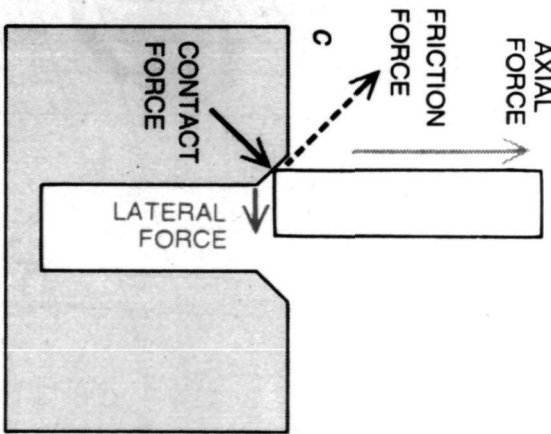
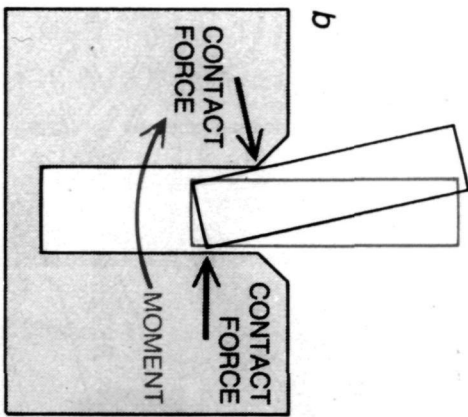
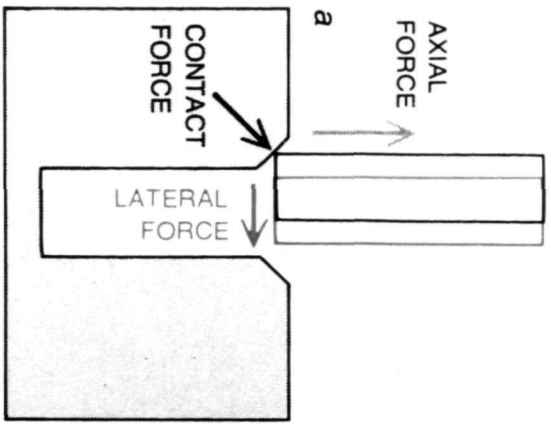
The type of information transmitted over the link is severely restricted. Only blocks of information, in the form of a complete robot program branch sequence may be sent. During Teach mode, only the robot can transmit over the link, sending the program sequence and data just taught. During Auto, or playback mode, the direction of transmission is reversed. When an EXTERNAL function is encountered, the external computer is asked to send the entire sequence. Either the originally taught sequence can be sent unaltered, or the external device can make modifications based upon other inputs. An additional restriction is that the length of the sequence may not be changed.

For CONSIGHT, the part pickup sequence is programmed as an EXTERNAL. For each cycle, the robot asks the system controller for a new pickup sequence based upon the vision system input. The interface is only called upon to transmit one block of data every few seconds. For real-time control applications with continual sensor updates, the EXTERNAL function interface could prove to be too slow.



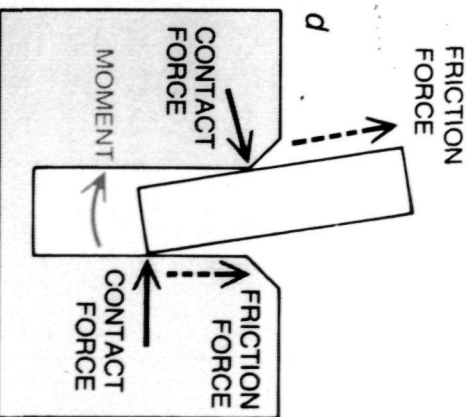
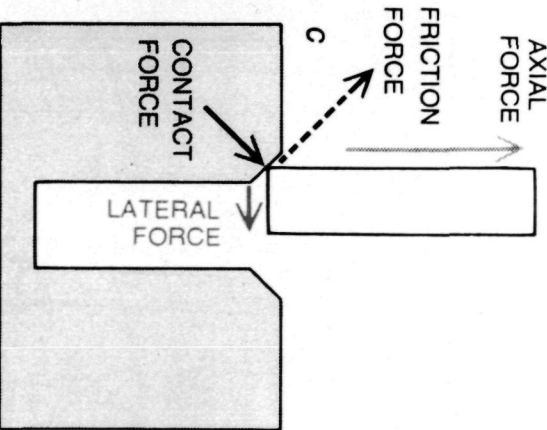
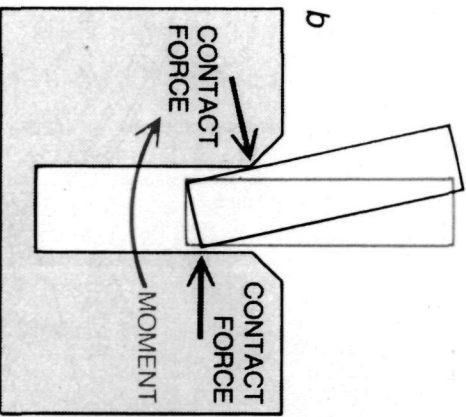
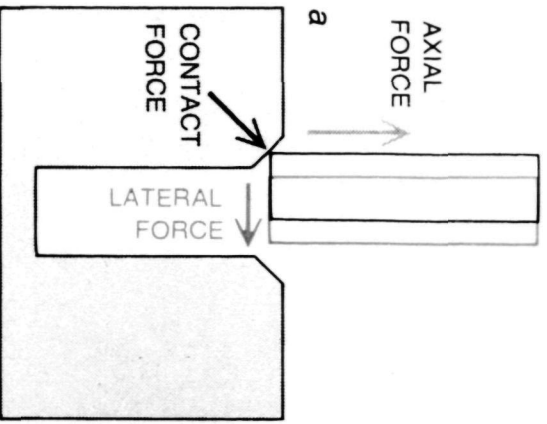
CONTACT FORCES BETWEEN PARTS can be used to guide corrective motions of the "wrist" of an assembly robot's arm. In the absence of friction (*a*) the contact force at the chamfer is sensed as two equal reactions, one vertical and the other lateral. The lateral force can serve as a cue to the desired corrective motion (*colored arrow*). Later (*b*) contact forces create a moment around the tip, which pro-

vides a cue to the desired corrective motion (*colored arrow*). When there is friction (*c*), the upward reaction at the chamfer is exaggerated, reducing the useful lateral reaction. Friction also reduces the useful information about moment (*d*). The ratio of the friction force (*broken arrows*) to the contact force, in other words the coefficient of friction, is about 0.2 for steel parts and 1.0 for aluminum ones.



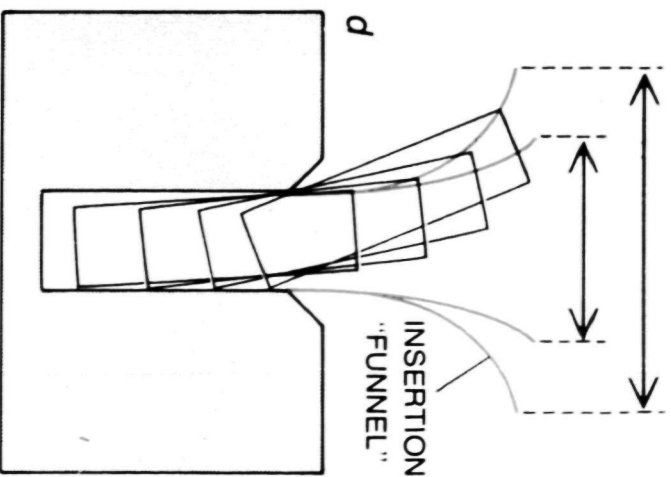
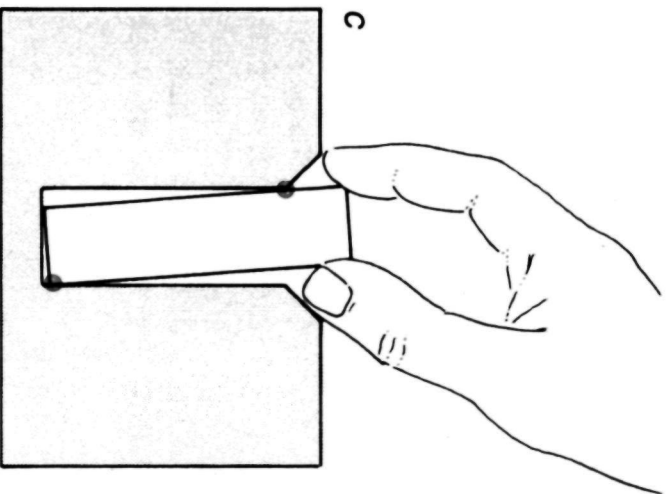
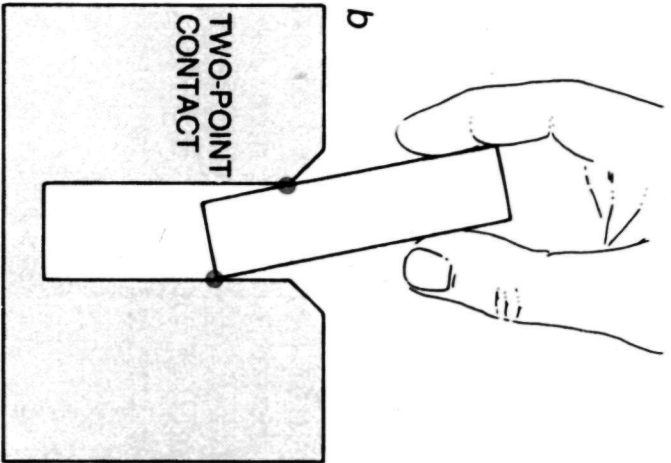
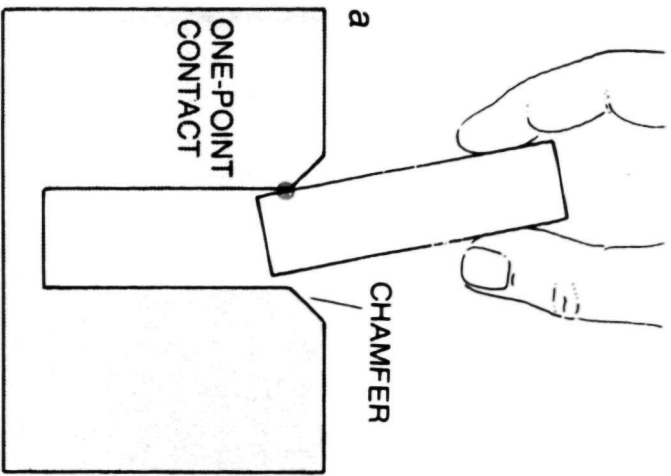
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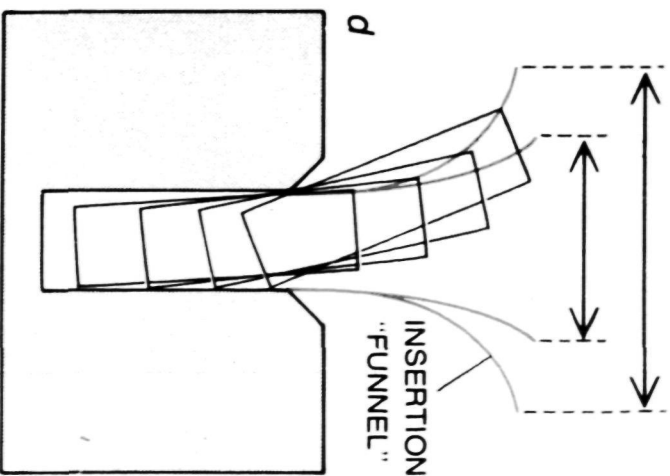
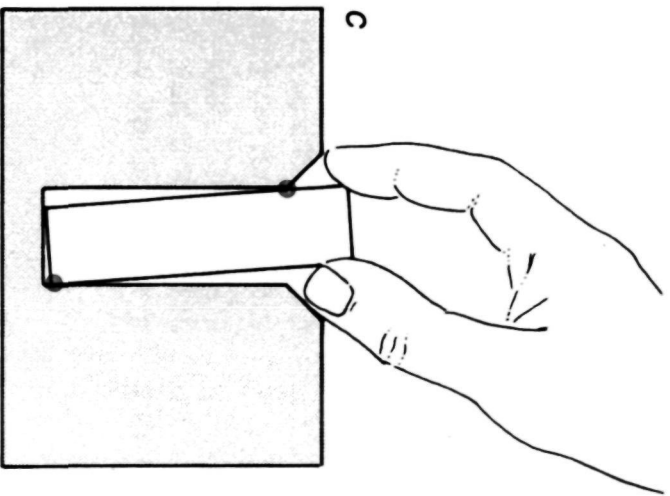
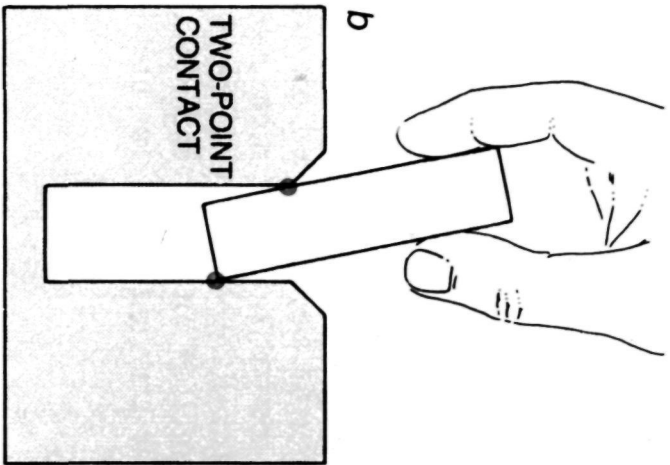
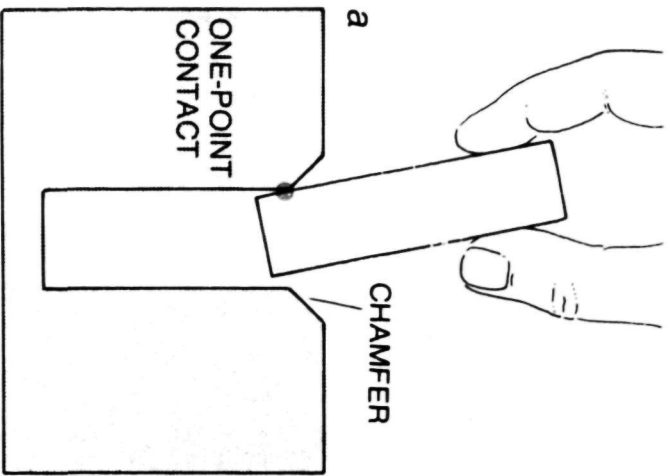
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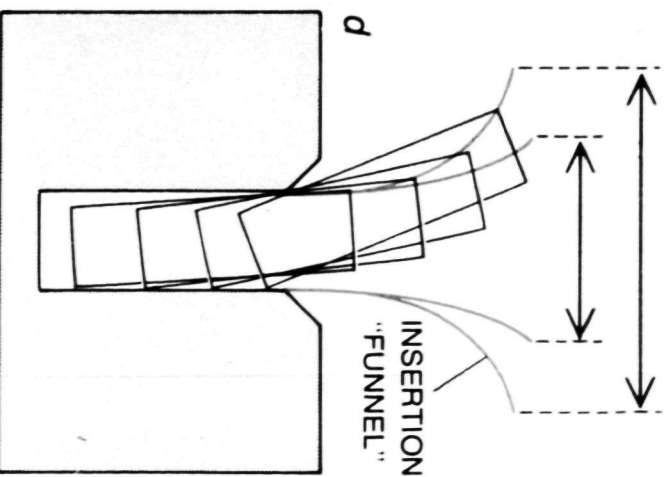
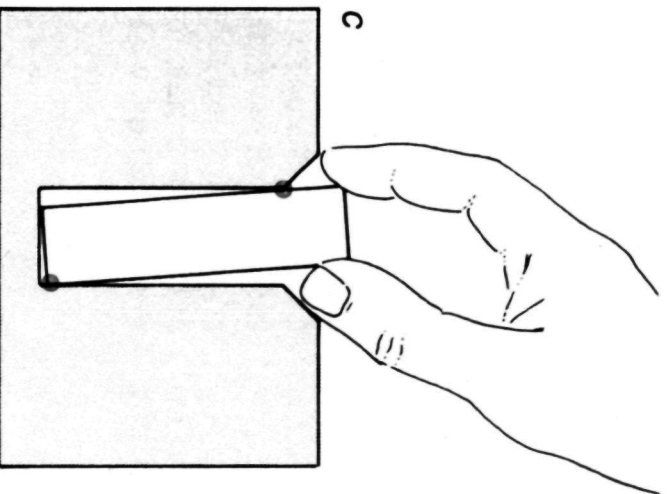
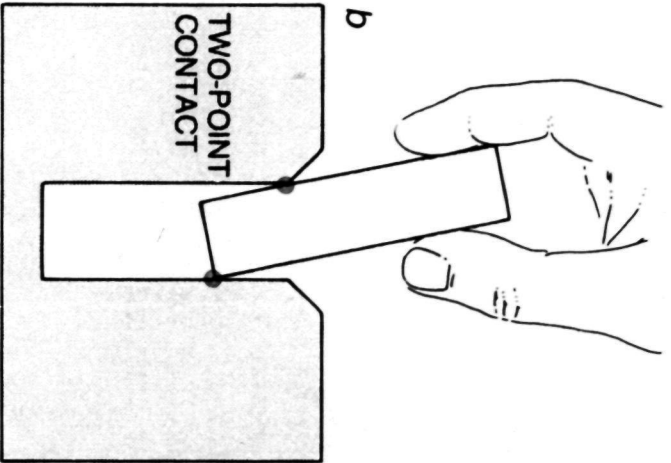
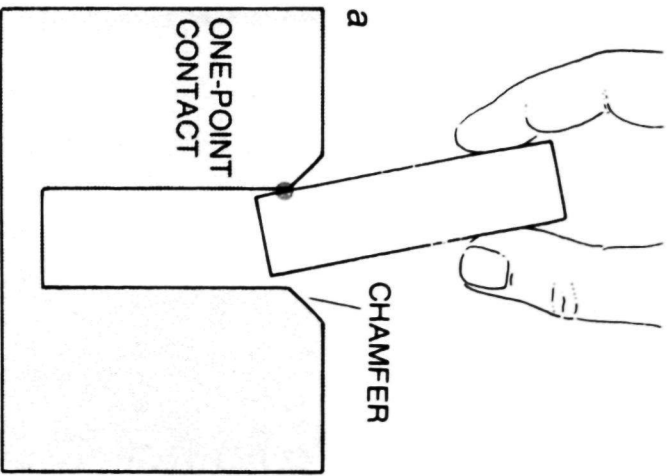
INSERTION OF A PEG IN A HOLE, a typical assembly task, is basically a problem in positioning. Holes are usually chamfered (beveled around the edge) to aid insertion. As the peg slides down the chamfer and enters the hole (a) it touches one side of the interior first (one-point contact). If the angular misalignment is large (b), the peg will soon touch the opposite side of the hole as well (two-point contact), with danger of jamming. In manual assembly vision can help

to find the chamfer, but after the peg enters the hole one must rely on the ability to sense the resisting forces in order to maneuver the peg to the bottom (c). The geometry of the peg and the hole keeps the peg within the insertion "funnel" (d), the path that is traced by the top of the peg at successively deeper stages of the two-point contact. The smaller the clearance between the peg and the hole, the narrower the insertion funnel and the more difficult the insertion task.



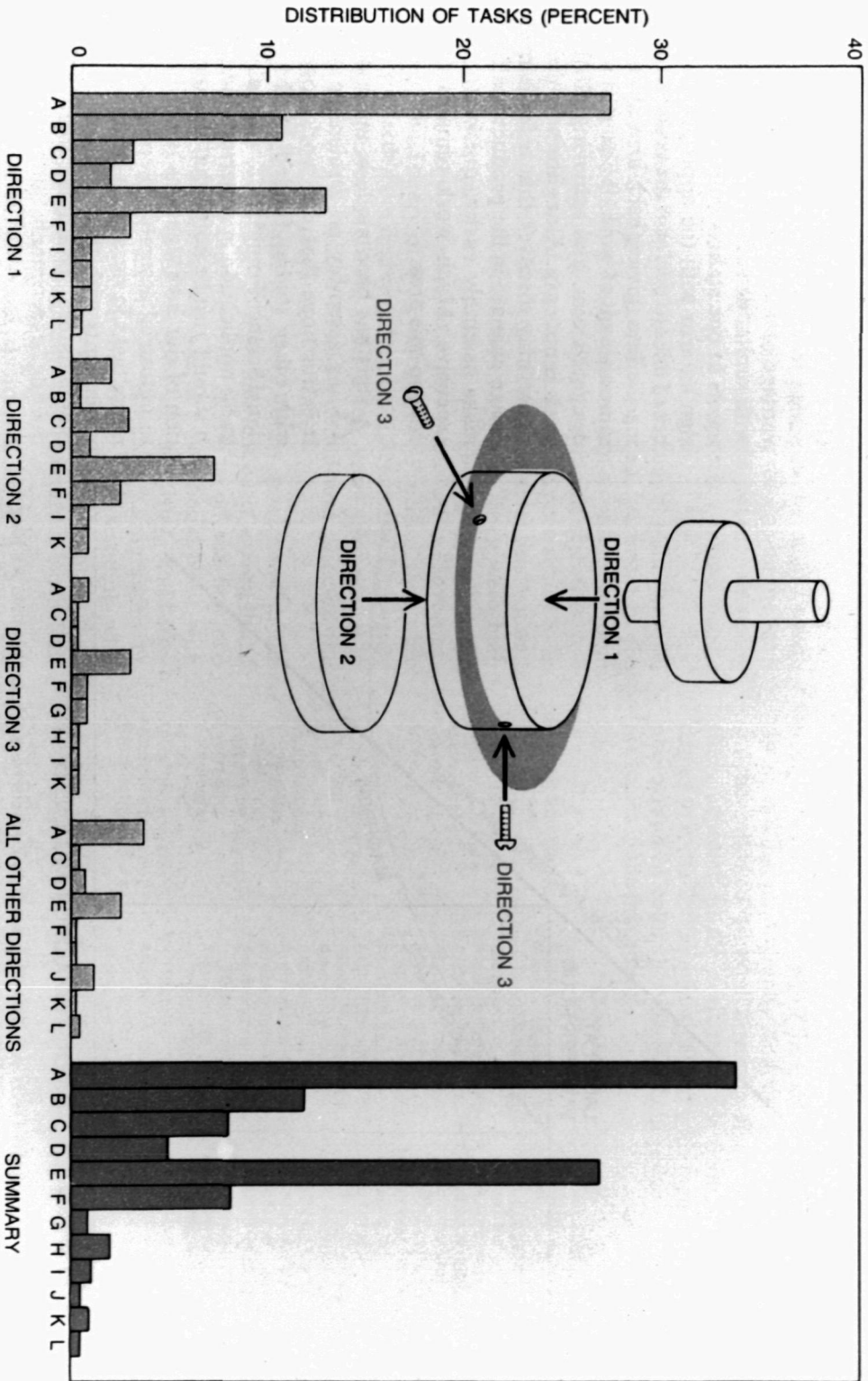
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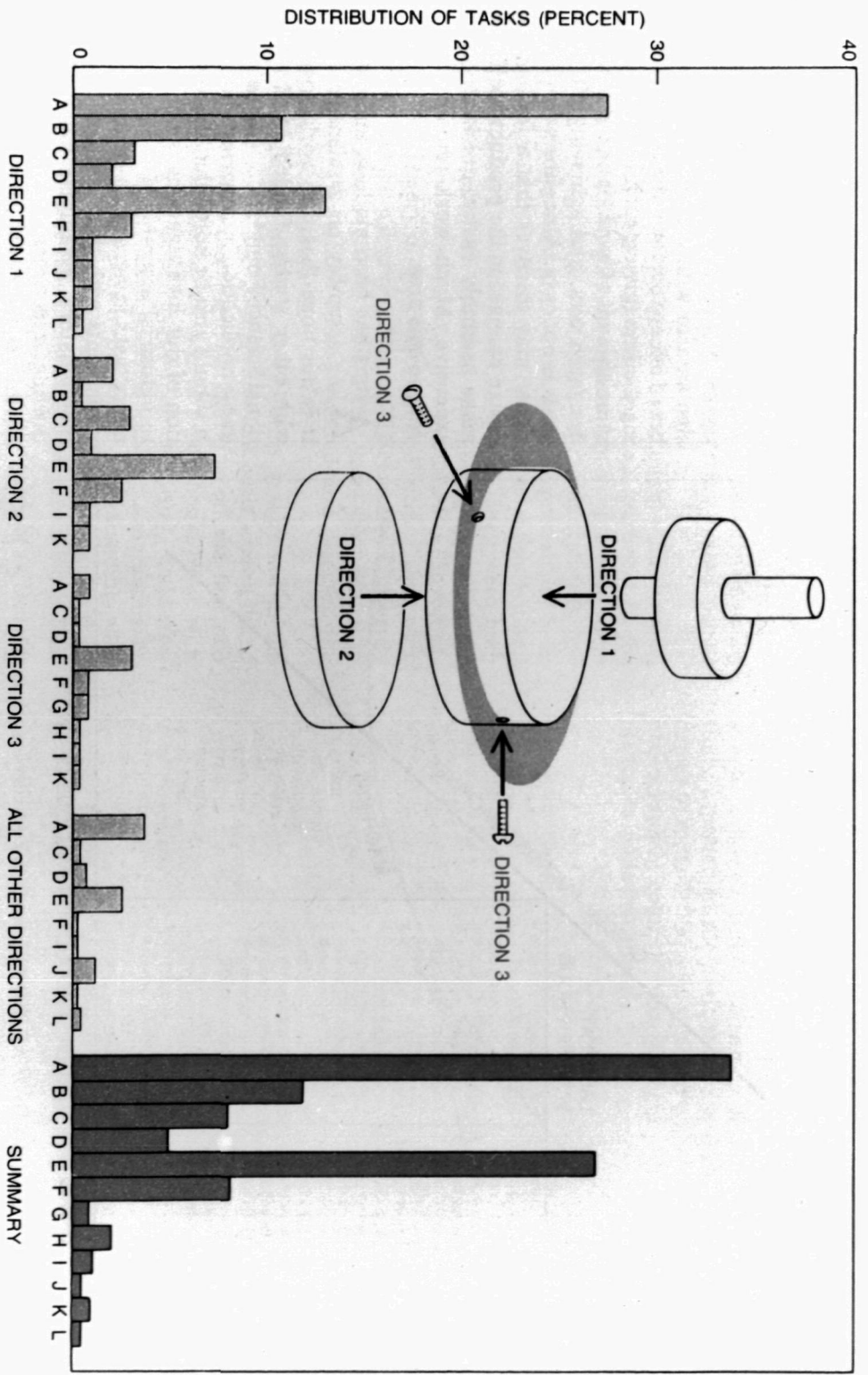
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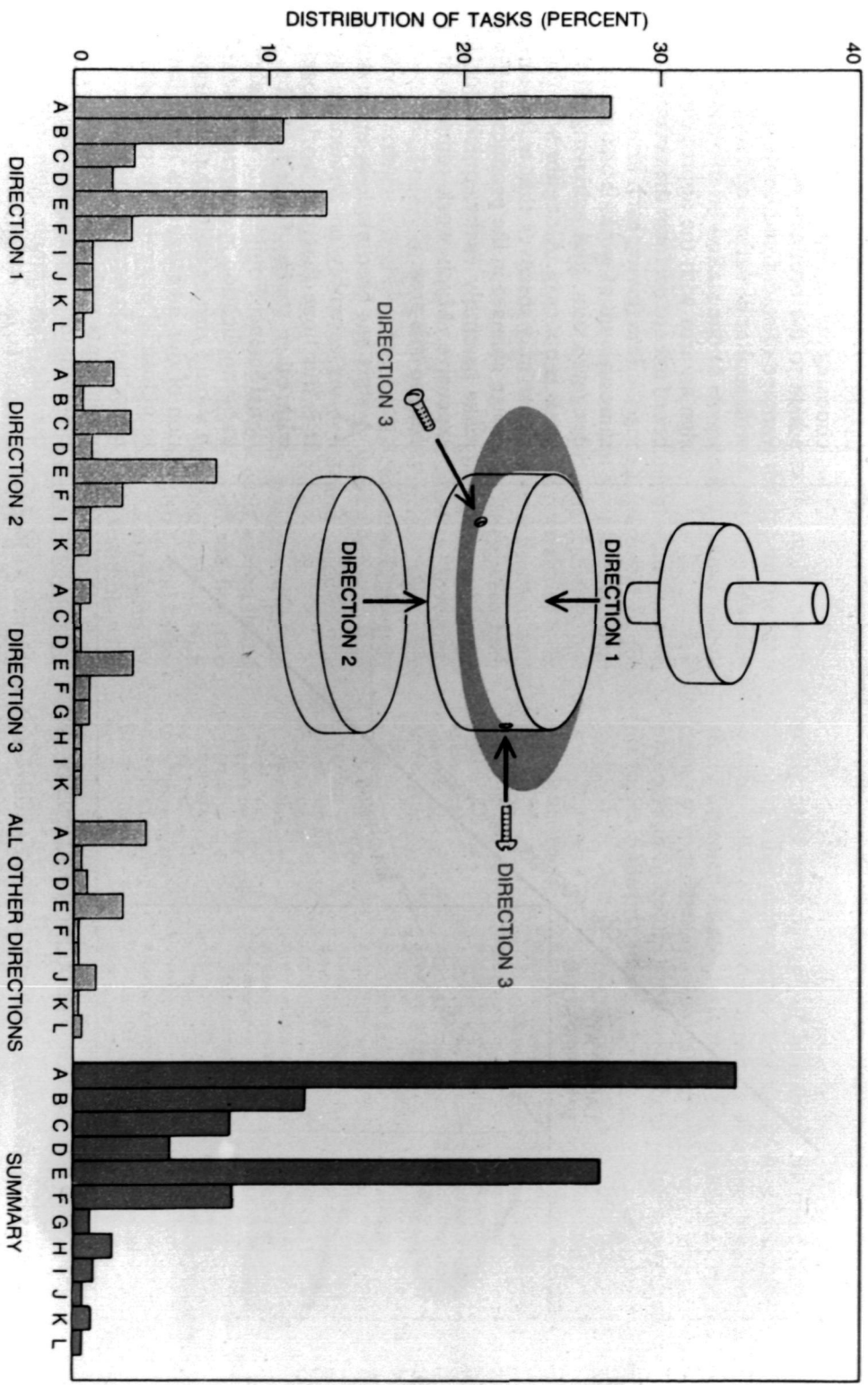


DIRECTION OF ATTACHMENT OF PARTS was analyzed in the study that classified the types of operation required. The inset diagram defines the three principal directions of attachment. Direction 1 is dominant, followed by direction 2 and direction 3.

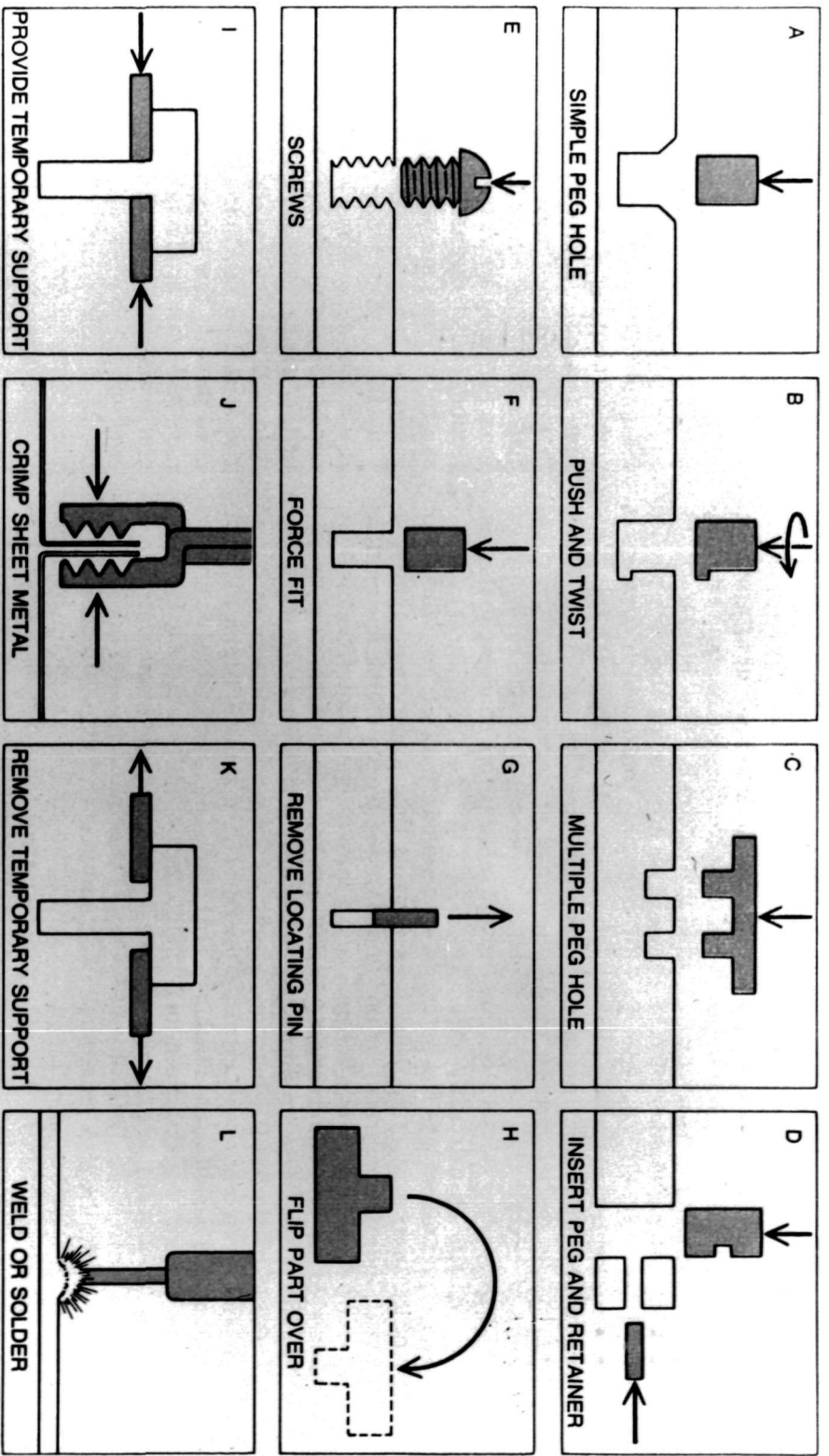
any direction perpendicular to the other two. The bar graph correlates attachment direction with type of task involved according to the identification in the illustration at the top. Simple peg-and-hole tasks (A) outnumber all others, followed by insertion of screws (E).



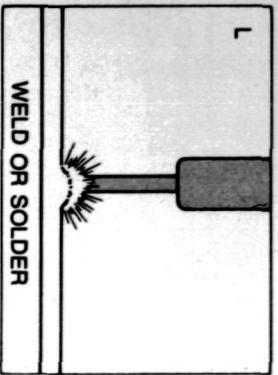
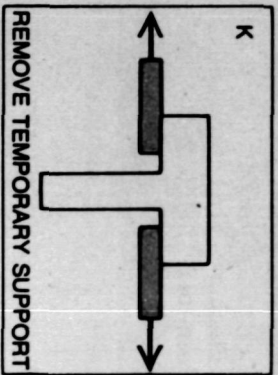
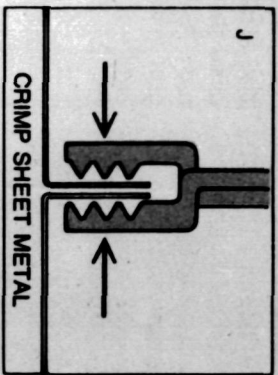
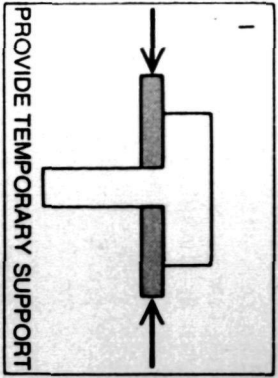
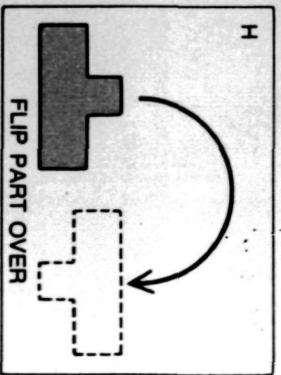
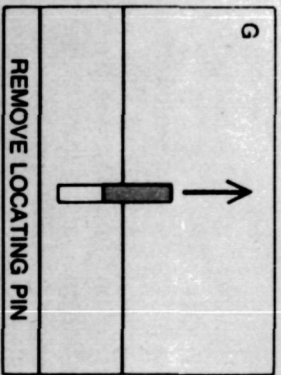
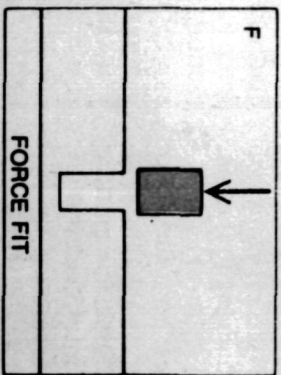
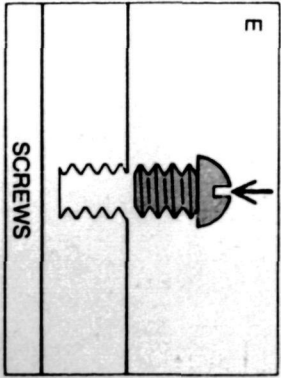
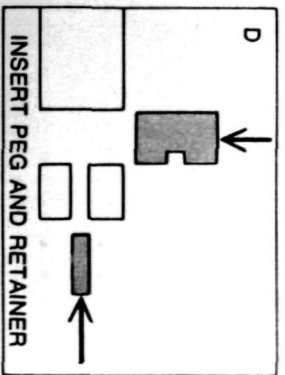
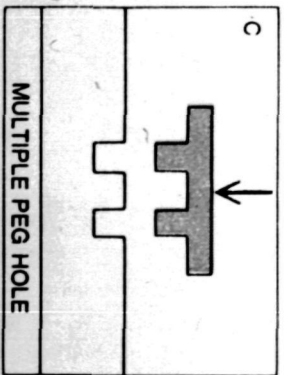
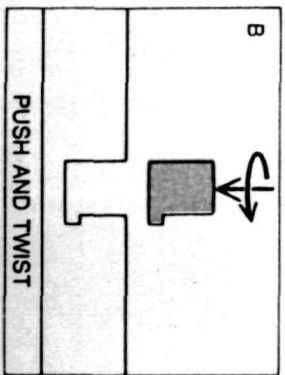
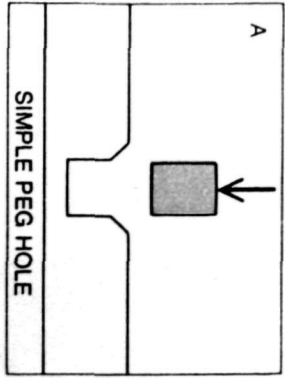
DIRECTION OF ATTACHMENT OF PARTS was analyzed in the study that classified the types of operation required. The bar graph defines the three principal directions of attachment. Direction 1 is dominant, followed by direction 2 and direction 3. Direction 3 is any direction perpendicular to the other two. The bar graph correlates attachment direction with type of task involved according to the identification in the illustration at the top. Simple peg-and-hole tasks (A) outnumber all others, followed by insertion of screws (E).



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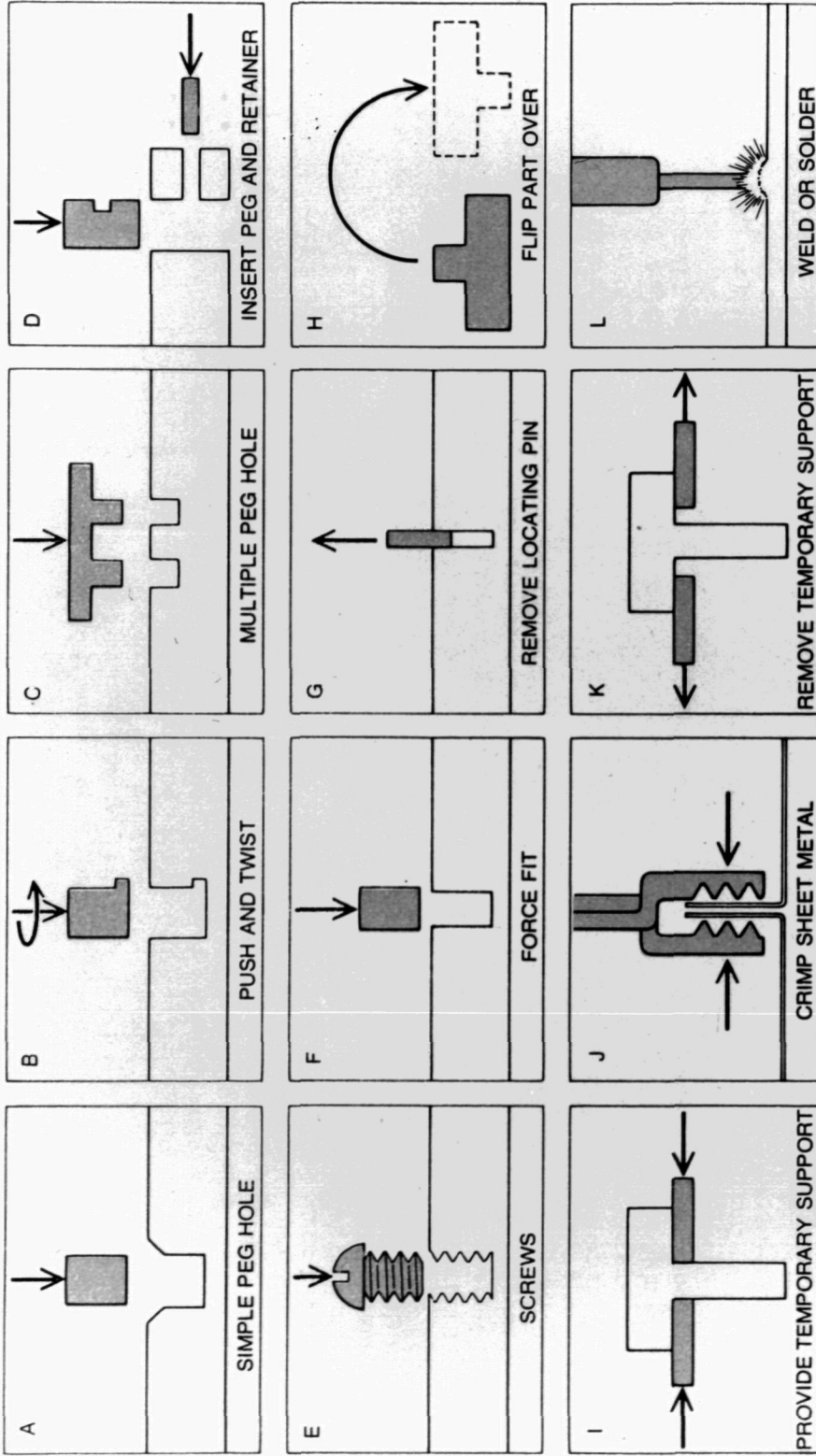


TYPICAL MANUFACTURING TASKS were identified by taking apart and reassembling a variety of products and their components, including a refrigerator compressor, an electric jigsaw, an induction electric motor, a toaster-oven, a bicycle brake and the automobile alternator used in robot assembly project. All the items could be assembled with various combinations of 12 operations depicted.



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