Space-Based Multifunctional End Effector Systems

Functional Requirements and Proposed Designs

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ABSTRACT

The end effector is an essential element of teleoperator and telerobot systems to be employed in space in the next decade. This report defines functional requirements for end effector systems to perform operations that are currently only feasible through Extra-Vehicular Activity (EVA). Specific tasks and functions that the end effectors must be capable of performing are delineated. Required capabilities for forces and torques, clearances, compliance, and sensing are described, using current EVA requirements as guidelines where feasible. The implications of these functional requirements on the elements of potential end effector systems are discussed. The systems issues that must be considered in the design of space-based manipulator systems are identified; including impacts on subsystems tightly coupled to the end effector, i.e., control station, information processing, manipulator arm, tool and equipment stowage. Possible end effector designs are divided into three categories: single degree-of-freedom end effectors, multiple degree-of-freedom end effectors, and anthropomorphic hands. Specific design alternatives are suggested and analyzed within the individual categories. Two evaluations are performed: the first considers how well the individual end effectors could substitute for EVA; the second compares how manipulator systems composed of the top performers from the first evaluation would improve the space shuttle Remote Manipulator System (RMS) capabilities. The analysis concludes that the anthropomorphic hand is best-suited for EVA tasks. A left- and right-handed anthropomorphic manipulator arm configuration is suggested as appropriate to be affixed to the RMS, but could also be used as part of the Smart Front End for the Orbital Maneuvering Vehicle (OMV). The technical feasibility of the anthropomorphic hand and its control are demonstrated. An evolutionary development approach is proposed and approximate scheduling provided for implementing the suggested manipulator systems in time for space station operations in the early 1990s.

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SECTION 1

INTRODUCTION

Planned operations in space in the next decade include assembly, construction, and satellite servicing and repair. All of these operations are expected to be accomplished, at least in part, by use of teleoperators and telerobots.

The end effector physically grasps and manipulates objects at the worksite. Its capabilities determine how skillfully objects can be grappled, handled, or manipulated. It is thus a very critical component of the teleoperator system. For space applications, the end effector system must be general purpose and multifunctional to accommodate the variety of tasks that must be performed.

The objectives of this document are to specify the functional requirements for a telerobot or teleoperator end effector system and to suggest alternative solutions fulfilling these requirements. The intent is to define the requirements to the level of detail necessary to guide implementation.

Section 2 provides the context of the analysis, including the types of missions in which multifunctional end effectors may be applied. Several terms commonly used in the field have somewhat different meanings in various situations; the usage of many terms found in this document is explicitly defined in this chapter.

Section 3 describes the systems issues that must guide the design of space-based end effectors. These include concepts of system robustness, human operator requirements, and sensor and control concerns. Performance is considered separately in Section 4.

Section 4 specifies tasks and individual functions multifunctional end effectors should be able to perform, as well as requirements for forces, clearances, compliance, and sensing. These needs, wherever appropriate, are defined from existing guidelines for planning astronaut EVAs (extra-vehicular activities).

In Section 5 we examine implications of the systems and task specifications presented in Sections 3 and 4. These include the options for mechanical and sensor elements. We consider components of the control station and the applicability of automation, since control (human or machine) of the end effector will be influenced by the physical design of the effector, and vice versa. The chapter also discusses design implications for other elements with which the end effector must coordinate, such as the tools it may use, and the arm to which it is attached.

Section 6 defines three concepts of alternative end effector approaches. We have derived four basic designs from these three concepts. Each design description is accompanied by a list of features associated with the design, with both positive and detrimental attributes. Where feasible, we have presented likely variations on the basic designs. Since we are synthesizing and selecting these designs for later evaluation, there is an implicit preliminary evaluation occurring in this chapter.

Section 7 is a comparative evaluation of specific characteristics of the various designs. Because of the great range of functionality required of space-based end effectors, and the strong likelihood that the only manipulator arm initially available will be the space shuttle RMS (remote manipulator system), we have performed two evaluations. The first evaluation considers a set of end effectors intended to substitute for EVA. The second evaluation looks at end effectors that could be adapted to the RMS. Both evaluations are based on a simplified, multi-attribute value model.

In Section 8 we provide expanded descriptions of the selected alternatives. We propose a plan for developing the suggested designs. Included is a rough schedule beginning with preliminary design and ending with space shuttle flight-testing.

Finally, in Section 9, we summarize the analysis.

SECTION 2

BACKGROUND

2.1   ANALYSIS APPROACH

There is little data available on performing manipulative tasks in the space environment. The only experience to date is that of astronauts who have performed extra vehicular activities (EVA). Space-suited astronauts have successfully retrieved, repaired, and redeployed satellites in space. Since the eventual intent of space teleoperators is to substitute for EVA, we have used the capabilities of an astronaut's gloved hand as the model for end effector task capabilities. We have used tasks performed by space-suited astronauts as sample tasks that should be feasible for teleoperators.

The task capabilities will be combined with other requirements in such areas as reliability and useability to represent the desired functionality for the end effector system.

The desired functionality for the end effector system will be tempered by the feasible functionality within the time frame of Space Station IOC (Initial Operational Capability). The final result will be a set of recommendations for end effector system design.

2.2   CONTEXT OF REQUIREMENTS

The functional requirements of the end effector system must be considered in a particular context:

- The end effector system must operate under the environmental conditions of space.

- The system should be functional by space station IOC, approximately 1994. This includes space-rating of system elements.

- The end effector system must be feasible using reasonable monetary and manpower resources.

2.3   MISSION DESCRIPTIONS

The end effector system will be an element of manipulator systems used to perform such missions as [1-4]:

- Inspection, servicing, and repair of:
  - Space station
  - Satellites in low earth orbit
  - Satellites in geosynchronous orbit
  - Space station co-orbiting platforms

- Satellite capture and re-deployment

- Assembly and construction of space structures

- Supervision of experiments

- Contingency handling

- Simple manufacturing

The variety and increasing frequency of these missions means that they will, as a rule, be performed without benefit of extensive simulation or rehearsal. The flexibility and adaptability required of the man/machine systems that will carry out these missions is unprecedented.

2.4 TERMS AND DEFINITIONS

2.4.1 Manipulator System and Component Definitions

Teleoperator System

A teleoperator system allows a human operator to directly control the manipulation or positioning of objects at a remote site. The only existing operational teleoperator system for use in space is the shuttle Remote Manipulator System (RMS), used to deploy and recover satellites. A teleoperator is distinguished from other types of manipulator systems in that the human operator continuously controls all actions of the teleoperator. In contrast, a robotic system would operate autonomously, without human supervision.

Telerobot System

A telerobot combines elements of teleoperators and robots. In a telerobotic system, a human operator controls some, or most, activities, but at least some operations are controlled autonomously, as in a robotic system. As the sophistication of robotics technology increases, telerobot systems are expected to evolve greater and greater autonomy.

Manipulator System

A manipulator system comprises all elements of the telerobot or teleoperator, including the hand, sensors, electronics, interfaces, the arm, base support, communication links, and the control station with its displays, functions and controls, and hand and arm master controllers.

Manipulator Arm

The manipulator arm consists of the 6 or 7 degrees of freedom (DOF) behind and including the wrist joint. Often the use of the term "manipulator arm" will also include the end effector that is attached to the arm. The design of the arm is beyond the scope of this paper, except in cases in which end effector requirements cannot be isolated from manipulator arm design issues.

End Effector System

A multifunctional end effector system is composed of two elements:

1)   The end effector (or end effectors in an exchangeable system)
2)   The tools that can be effectively utilized by the end effector

Each element must be designed with the other in mind. Various end effector design approaches assume significantly different functionalities and complexities in the tools to be used.

End Effector (EE)

The end effector is the mechanism, below the wrist of the arm, that has one or more degrees of freedom. The end effector physically grasps and manipulates objects in the work environment.

Depending on design choices, the end effector may or may not be exchangeable during the performance of a mission.

The end effector is composed of several subsystems supporting manipulation, sensing, and control.

Tools

The end effector may use tools to aid in carrying out tasks. The tools may be general purpose (e.g., screwdrivers or torque wrenches) or specialized (e.g., fluid coupling mate/demate tool).

Tools are distinct from the end effector itself, though they may have some sensing capability. A tool with significant information processing capacity or autonomy would necessarily be re-classified as an end effector.

Control Station

The control station is composed of all devices needed to control the manipulator system. This includes the control panel with its embedded controls and displays (visual or otherwise), the primary computer and its software, as well as the controller.

Controller

The controller is the manual human input device ("master") that controls the manipulator arm and hand ("slave"). The controller can take many forms, ranging from joysticks to arm-encasing frameworks.

2.4.2 End Effector Characteristics

Multifunctionality

In the context of this analysis, multifunctionality is defined as the ability of the end effector system to perform a wide range of tasks.

Smartness

Smartness is gained through sensors. If an end effector hand can recognize its environment through sensors integral to the end effector, then it is considered smart. The level of smartness is independent of the end effector's performance capabilities or its degrees of freedom.

Manipulative Capability

Manipulative capability is the skill to manipulate objects with the end effector. Typical examples are (a) squeezing a trigger on a power tool while holding the handle with the rest of the hand, and (b) turning an object in the hand. The basic requirement for manipulation capability is a two-DOF knuckle joint so that the fingers can clamp in several different directions, or move sidewise relative to individual finger surfaces. This also allows for fine alignment to the workpiece surface without the need to adjust through the relatively crude wrist motion. The hand usually requires at least three fingers.

A second approach to achieving manipulative capability is redundancy in clamping. An example of this would be two sets of three jointed fingers (with single-DOF knuckle joints) working cooperatively. One set of fingers can manipulate an object in one plane, with the other set taking over if the first set needs to regrasp the object in another orientation; alternately, the second set of fingers, aligned in a different plane than the first, could manipulate the object in the second plane.

Dexterity

Dexterity is the the combination of manipulative capability and smartness to skillfully manipulate objects with the hand.

Active Mechanical Compliance

This is the human muscle equivalent capability to tighten or loosen a muscle which acts as the joint stiffness control. In the "soft" mode, a compliant limb will yield to outside forces; in the "stiff" mode, the limb will resist yielding. As a practical consequence, a hand commanded to close over an object will conform to the object's shape. The hand can then be stiffened, and clamping force applied, enabling a much better grip on the object. Compliance also protects the manipulator arm and the object if the arm should accidentally strike the object, since the soft mode allows arm parts to yield, cushioning the impact.

Compliance may be purely mechanical, or be implemented through software control. The level of compliance may be varied autonomously, or under human operator control.

2.4.3 End Effector Types

The catagories of end effector types are summarized in Figure 2-1. The more important categories within the context of this analysis are defined below.

Smart Hand

An end effector with several types of sensors built in, such as a combination of force, proximity, and position sensors. A smart hand does not necessarily possess manipulative capabilities. Unless otherwise specified, a smart hand or smart gripper is assumed to have one degree of freedom.

Multi-DOF End Effector

Multi-DOF end effectors possess more than one DOF, but unless otherwise stated, do not have manipulative capabilites. In general, the various degrees of freedom are acting in a single plane.

Dexterous Hand

A hand with at least three manipulative fingers and incorporating sufficient sensors to possess dexterity.

Anthropomorphic Hand

A hand with a thumb, two to four fingers, palm and wrist in a human shaped configuration, capable of dexterous manipulations. Additional features include fingernails, soft surfaces on inner hand surfaces, compliance, and the thumb's capability to move out of opposition with the fingers to form an open-faced clamping device.

2.5   RANGE OF END EFFECTOR DESIGNS

The options considered initially in this analysis range from the simplest two-claw gripper to human-like hands. Different designs may handle standard tools or a variety of customized tools. End effectors may or may not be exchangeable. As the analysis proceeds, these options will be further and further honed to a set of viable distinguishable alternatives, and finally to a single recommended development approach.
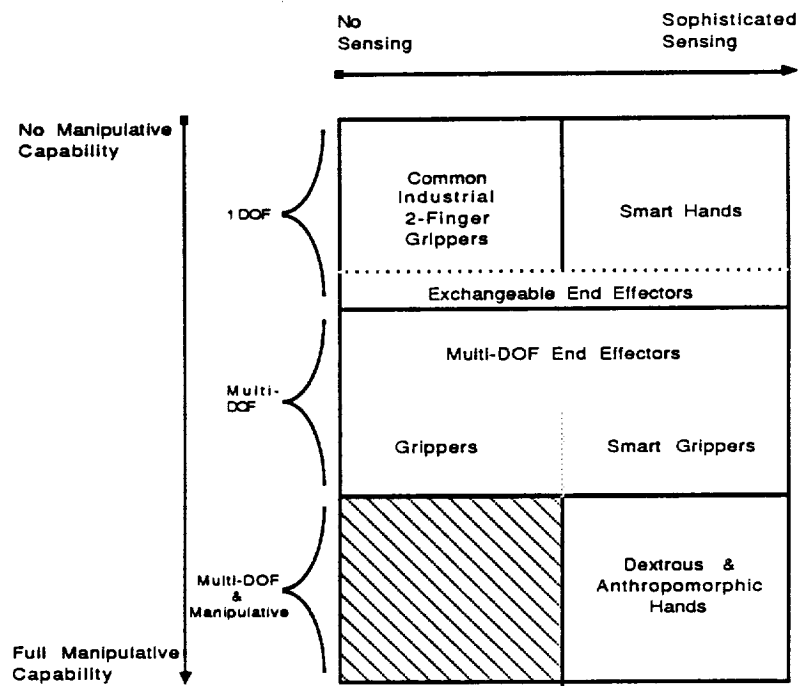
Figure 2-1.   End Effector Categories

SECTION 3

SYSTEM SPECIFICATIONS

3.1   SCOPE OF SYSTEM NEEDS

The end effector system must be considered in the context of the teleoperator system of which it is a part. Where there is interaction between the end effector system and other teleoperator elements, the end effector specifications must cross system boundaries. The objective of the teleoperator and end effector system is to perform a variety of tasks that would otherwise be possible only through EVA. The design approach selected must have the potential to evolve into a practical "workhorse" for space applications. The end effector system will initially be directed by a human operator whose own requirements must be understood. Autonomous systems will gradually take over portions of the human control task.

The principal requirement for the end effector system is that it be able to accomplish the mission scenarios specified, and perform as many of the current and future EVA-feasible tasks as possible. The capability to perform tasks is separately considered in Section 4, "Task Specifications."

Other systems issues are addressed below.

3.2   SYSTEM ROBUSTNESS ISSUES

The end effector system must not only be capable of high performance, but must be reliable, consistently maintaining that performance, with few breakdowns requiring space repairs. If the end effector system can perform all tasks, yet fails after every other mission and requires EVA for repair, it may have little usefulness; EVA would likely prove a more effective use of resources.

Issues and design goals related to the end effector system's robustness, reliability, and complexity are discussed below.

Exchange Operations. Most conceivable end effector systems will change end effectors, tools, or both, numerous times during a mission. The design of the interface between the fixed base and the exchangeable EEs or tools will depend on the power, sensing, and data requirements of the exchangeable elements, and on the manipulator arm design. The complexity of the interface and alignment requirements for mating of connections will generally increase the time required for an exchange. The number of exchanges in a given mission will be a function of the generality of the exchangeable elements. All of these factors will significantly affect mission completion time.

Self-Repair and Replacement. Ideally, an end effector system should be repairable without EVA. In a multi-arm teleoperator system, one arm may be able to perform work on another. To be feasible, "repair" will likely take the form of changeout of modular elements of the end effector system. If the expected time between system failures is low, this "self-replacement" capability will be especially critical. We can conceive of placing

exchange interfaces in series, so that if the lower interface failed, the interface and jammed end effector could be exchanged as one unit.

Modularity of Design. In addition to facilitating replacement of failed components, modular design should be enforced to enable incorporation of new capabilities as technology becomes available. Given sufficient modularity, the teleoperator system could be re-configured for different tasks (e.g., limb length could be optimized for work sites of varying volume).

Sensitivity to Environment. The end effector system must be able to operate under conditions of significant thermal gradients. Byproducts of servicing, construction, and repair tasks will include free floating debris: scraps of wire, tape, metal shavings, and other items. This debris could potentially damage or jam an end effector system. The end effector system must be relatively insensitive to these environmental hazards. This insensitivity will be especially difficult to achieve if the end effector system includes a complex exchange interface.

Impact of Failures on Work Site. The system should be designed to cause no or minimal damage to the work site in the event of system failure.

Manual Overrides/Safety Issues. If the space shuttle Remote Manipulator System (RMS) fails, the following can be done through EVA: (a) release of RMS shoulder brace, (b) tiedown of RMS, and (c) alignment of RMS joints to allow restraints to latch. These manual capabilities are necessary to ensure that the payload bay doors can be closed and RMS secured for safe de-orbit. Similar safety features will surely be required for other space-based teleoperator systems, and should at least be considered for the end-effector itself. The end effector system may also be designed to be easily jettisoned if necessary.

Space-Rating of System. A single end effector system could potentially have a large number of operating configurations (e.g., two dozen exchangeable end effectors). To space-rate the system, each configuration may require separate testing. This could add significant unanticipated time and cost to the system design and development effort.

3.3 HUMAN OPERATOR ISSUES

As space-based teleoperator systems evolve, automation will aid more and more functions. Initially, however, we can assume limited automation with a human operator doing most of the work of controlling the teleoperator and end effector system. The human operator is crucial and must be considered explicitly at all stages of design and development. Important issues include:

Choice of End Effector Controller. The controller must be tailored to the characteristics of the end effector. This is especially true if the end effector incorporates multiple degrees of freedom. The controller must be abke to interpret a sufficient number of distinguishable commands to support the requirements of the end effector.

Consistent Operator Interface. The operator interface must allow the operator complete control over the full range of end effector system multifunctionality. Designing a human-factored operator interface, let alone one controlling a variety of functions, is not a trivial task. A potentially ineffective approach to employing multiple exchanged end effectors might be distinct operator interfaces for each effector. If there are inconsistencies among the control methods for different functions, the result will be an increase in the frequency of operator errors.

Mission Complexity/Operator Fatigue. Control of the teleoperation system will, at least initially, involve significant task loading of the human operator, until AI techniques provide meaningful user aid. The end effector system will likely contribute as much loading as the rest of the teleoperator, since the task elements requiring the greatest dexterity will be performed with the end effector. If the operator fatigues quickly, the teleoperator system will be ineffective. The same is true if the average teleoperated mission requires too much elapsed time or too many individually commanded operations compared to EVA.

3.4 CONTROL AND SENSOR ISSUES

Sensory Feedback to Operator. The human operator needs sufficient information from the remote work site to successfully direct the teleoperator system. Some sensory data will be generated within the end effector system (e.g., tactile and force sensing, local visual information); other data will be generated outside the end effector system (e.g., global visual information). Data from both sources will be critical to control of the end effector. The end effector system design must include the necessary sensory capability and avoid interfering with the operation of other teleoperator sensor systems.

Use of AI Techniques. AI tools should be implemented wherever feasible to aid the human operator. These include intelligent information displays, suggested trajectories or command sequences, and autonomous functions. Since we expect the teleoperator system to develop greater and greater autonomy, the initial design should be consistent with this growth. This may affect how sensors are placed and how the data they produce are processed.

SECTION 4

TASK SPECIFICATIONS

In order to be useful in guiding the design of the end effector system, mission scenarios have been broken down into as much detail as possible. The missions are decomposed first into major task categories, then into sets of tasks, and finally into basic individual functions that must be performed. These functions and the related capabilities of an astronaut during EVA are analyzed to develop functional requirements for forces and torques, clearance, compliance, and sensing.

4.1   TASK DESCRIPTIONS

4.1.1   Task Categories:

(1)	Assembly/Construction
(2)	Servicing/Repair
(3)	Supervision/Inspection
(4)	Contingency Handling

4.1.2   Task List

The tasks below are derived from analysis of possible missions [1-4], as well as missions performed to date by astronauts during EVA. (Appendix A lists tasks performed to date by astronauts, as well as the tools and equipment available to EVA astronauts.) Tasks to be performed in space applications include:

- Inspect
- Checkout
- Retrieve/stow equipment and tools
- Use hand tools and power tools
- Handle payloads
- Remove/replace ORUs
- Grasp/grapple irregular objects
- Fasten/release restraints, tethers, latches, access panels, etc.
- Control rendezvous and docking
- Retrieve debris
- Mate/demate umbilicals
- Wrap and tape thermal blankets
- Flip switches, turn knobs
- Remove/install threaded or rotary connectors
- Align fragile components
- Clean, resurface (e.g., mirrors, lenses)
- Solder

4.1.3 Sample Tasks

Sample tasks representative of end effector requirements include:

- Deploy/retrieve vertical telescoping antenna
- Remove/replace ORU held in place by captive screws
- Replace/reconfigure thermal blanket
- Position, align and tighten rotary electrical connectors
- Inspect irregular surface
- Clean mirror
- Operate tether hooks and stow/unstow various tools

4.2   REPRESENTATIVE END EFFECTOR FUNCTIONS

The end effector system must be able to:

- Inspect
- Orient in space
- Align
- Grasp/release
- Rigidize
- Manipulate objects
- Mate/demate
- Insert/remove
- Lock/unlock
- Screw/unscrew
- Bolt/unbolt
- Rivet
- Cut
- Tape
- Patch
- Grind and polish
- Coil/uncoil
- Solder

4.3   REQUIRED FUNCTIONAL CAPABILITIES

4.3.1 Force/Torque Requirements

Loads Nominally Applied by Astronaut

The approximate ranges of forces and torques an astronaut may be expected to apply during EVA are shown in Table 4-1[5,6]. Maximum loads applied, broken down by type of activity, are indicated in Tables 4-2 and 4-3. Note that an astronaut may apply an instantaneous or breakaway force of up to 36 lb [5].

	Maximum	Minimum
Force	20-30 lb (situation, duration dependent)	≈ 0.6 lb
Torque	11 ft-lb	≈ 0.1 ft-lb

Sources: [4, 5]

Controlled, Directed Loads Applied During EVA

Table 4-1

Load Description, Restrained Crewmember Actuations	Load Limit
• Gloved hand, steady-state force application	* 25 lb
• Gloved hand, instantaneous or breakaway force	36 lb
• Gloved hand torque, wing tab connector	** 50 in-lb
• Gloved hand, single cycle hand squeeze	30 lb
• Gloved finger, toggle switch actuation	** 0.63 to 6.25 lb
• Booted foot, toe-button detent (one foot restrained)	** 4.0 to 20.0 lb

Notes:
* The useful work involves a 10-Btu work output for a 5-min duration, interspersed with a rest period between applications.
** Force range includes a minimum value to ensure a resistance level for tactile feedback.

Maximum Work Force Applications, EV Crewmembers
(Data reproduced from reference [5])

Table 4-2

Connector Diameter (inches)	Torque (in-lb)
1.0	4.0
1.5	5.6
2.0	8.6
2.5	12.4
3.0	16.0 (finger curl)
4.0	24.8 (finger curl)
5.0	33.6 (finger curl)

Connector Actuation Resistance, Fingertip, EV Gloved Hand
(Data reproduced from reference [5])

Table 4-3

Loads Confined to Tool/Workpiece System

Higher forces and torques have been applied to a workpiece in situations in which the loads were not transmitted to the astronaut. For example, a torque of up to 100 ft-lbs was applied by the Module Servicing Tool (MST) to tighten and loosen jackscrews holding subsystem modules to the Solar Maximum Mission satellite.

Such loads are not part of the requirements for the end effector. Note, however, that the end effector may position or operate tools that do apply these loads.

4.3.2 Clearance Limits

Minimum clearances around workpieces will depend on the assumed means of access to the workpiece in an EVA situation. Access may be by an astronaut's gloved hand or by a tool used by the astronaut. All manipulation functions to be performed on a workpiece by an astronaut are assumed to be one-handed; therefore, clearance greater than that needed for a single glove cannot be assumed.

Minimum distances between connectors, and minimum clearances for access by an astronaut's gloved hand to those connectors are shown in Figures 4-1, 4-2, and 4-3 [5]. Clearance around handholds is shown in Figure 4-4 [5]. If an end effector is to take advantage of existing handholds, its active volume must be comparable to that for a gloved hand.

Figure 4-5 [5] indicates minimum clearances between tools used by an astronaut and structures in the workspace. In a comparable teleoperation situation, the end effector is likely to either grasp a similar tool or actually consist of a modified version of the tool.

4-4
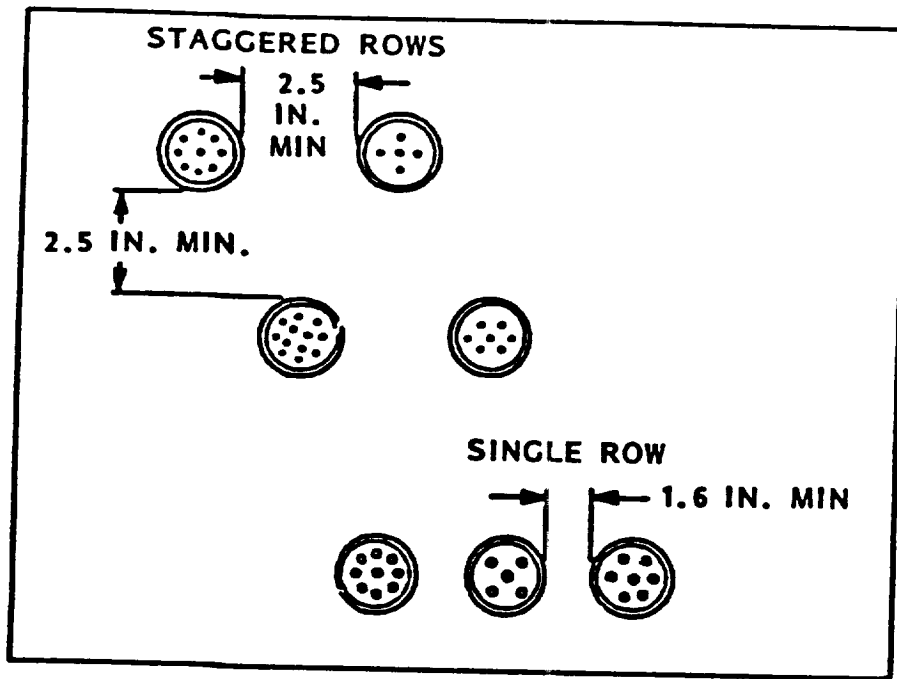
Minimum Clearances Between Single Rows and Staggered Rows of Connectors
(Reproduced from reference [5])

Figure 4-1
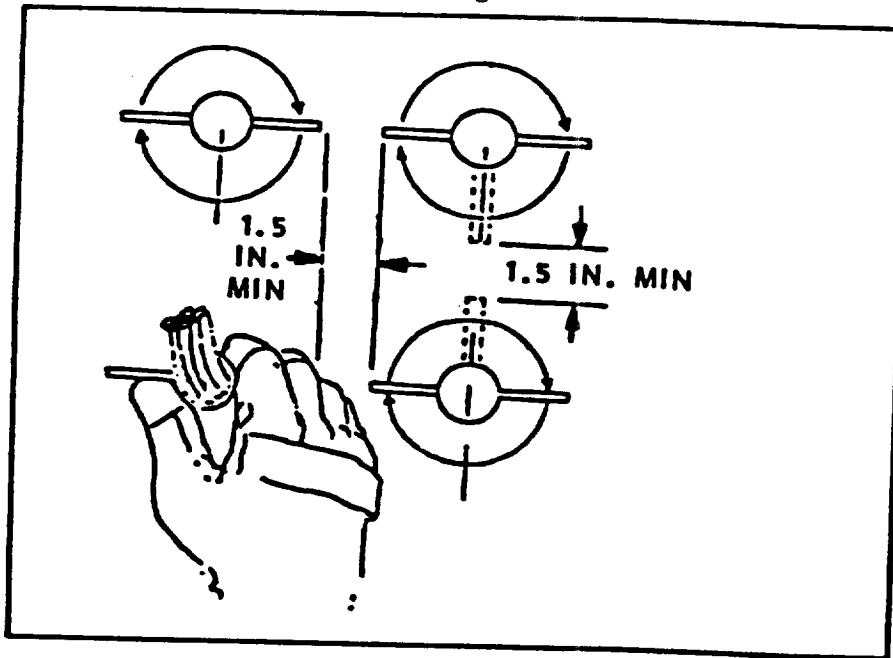
Minimum Clearance Required Between Connector Tabs
for EV Gloved-Hand Access
(Reproduced from reference [5])

Figure 4-2

4-5

VIEW A

VIEW B
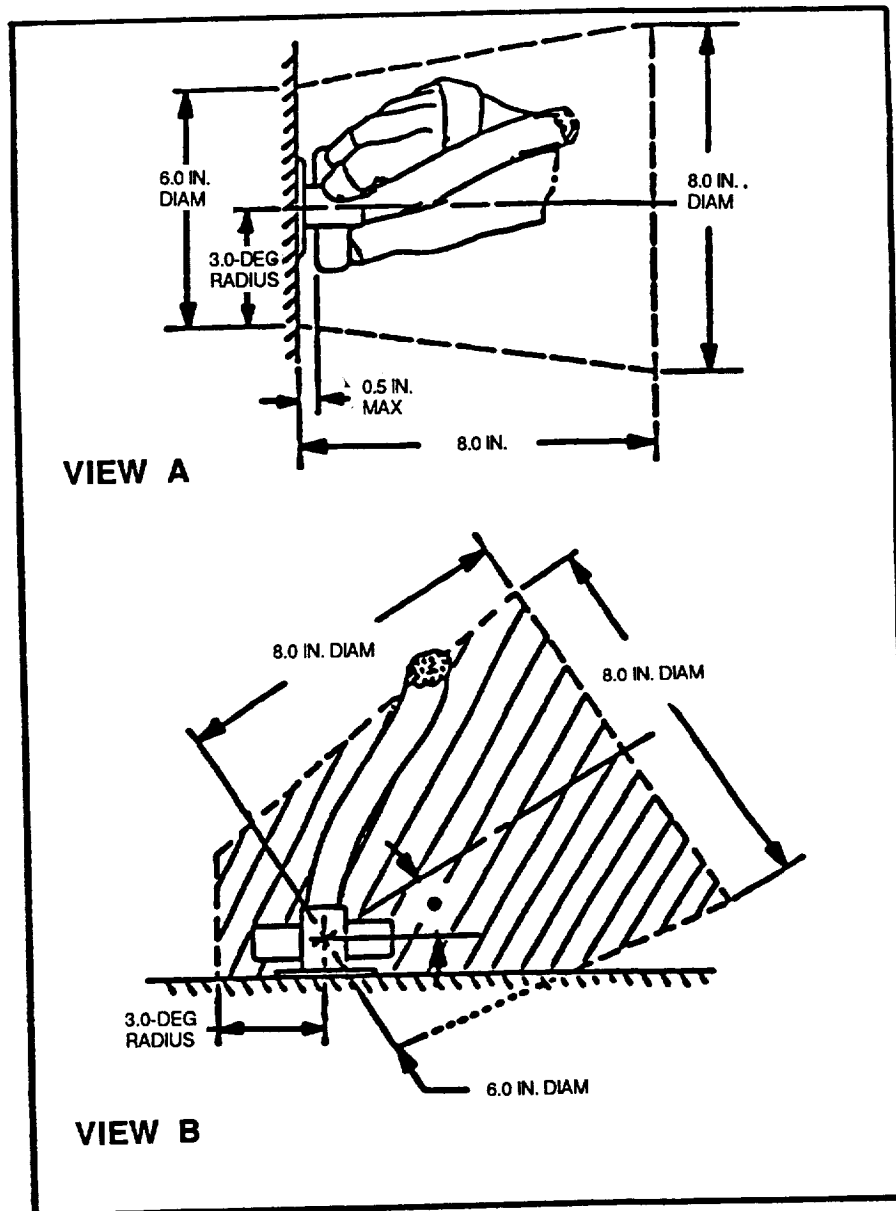
EV Gloved-Hand Clearance Envelope for Wing Tab Connector or Equipment
Tether Operation
(Reproduced from reference [5])

Figure 4-3
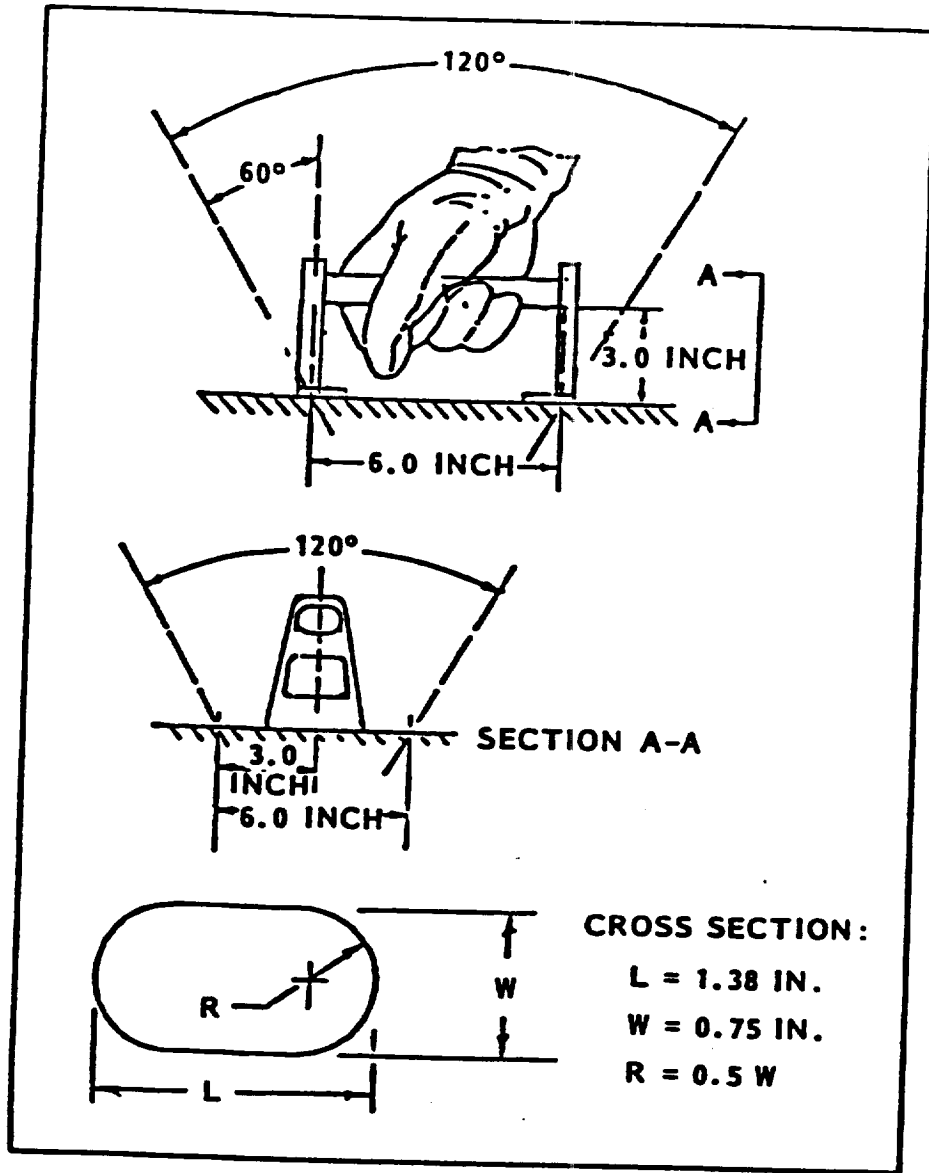
**EV Gloved-Hand Clearance Envelope for ORU Handle
and Handrail Terminations
(Reproduced from reference [5])**

Figure 4-4
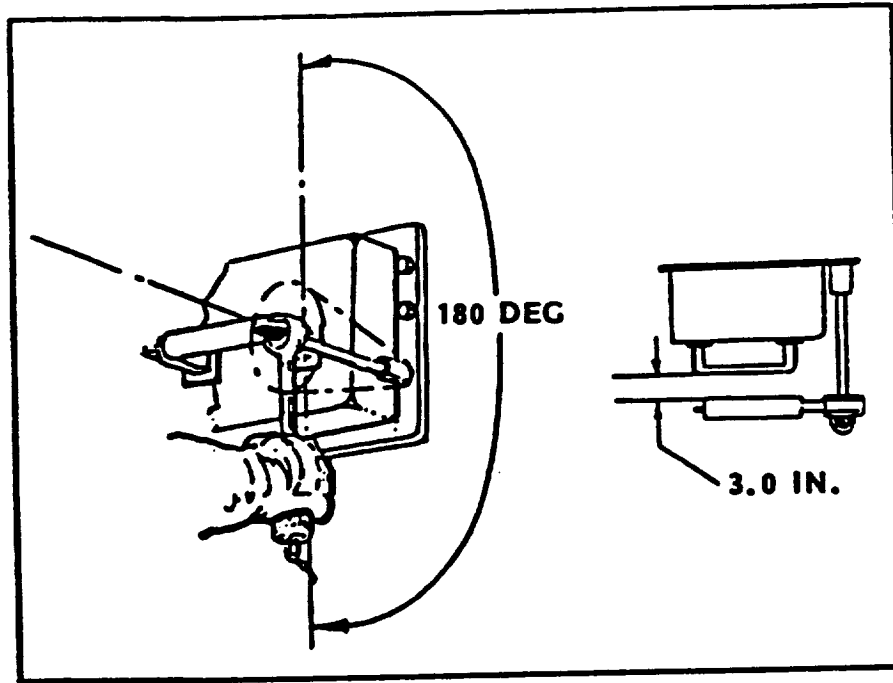
**Minimum Sweep Clearances Between
Interface Tools and Hardware/Structures
(Reproduced from reference [5])**

Figure 4-5

4.3.3 Compliance Requirements

Some degree of compliance is required of the end effector system. With compliance, several types of tasks become far more practical, while the chances of inadvertent damage to the workplace are reduced.

Common tasks involving alignment and tightening of threaded fasteners are generally infeasible without compliance. EVA guidelines and practice to date suggest that captive fasteners will be used whenever possible; however, even captive fasteners must be aligned at the interface between the parts to be joined.

In general, hand tools must be carefully aligned. To operate a wrench or similar tool, the end effector must either have compliance or the ability to move through extremely precise circular paths relative to the workpiece orientation, which may be of arbitrary orientation to the manipulator. This applies also if the end effector must open a hinged access panel while grasping it. Real-time control of complex motions or two-handed operations may be infeasible without compliance. Dual arm robots will also need compliance to manipulate rigid objects with both hands.

Some tasks may require the end effector to shift position while continuing to apply force to hold the workpiece in an aligned orientation (e.g., connection of cylindrical Canon-type connectors that require two distinct alignment operations). With appropriate compliance these tasks may be feasible.

4-8

In addition, compliance is desirable to reduce the effects of inadvertent contact of the end effector with objects in the workspace. Guidelines have been developed that define the magnitude of accidental loading that may be imposed during EVA (see Table 4-4 [5]). The guidelines are limited to only a few elements of the work area, but do provide some indication of the forces that might be applied by the end effector without causing significant damage.

The need for compliance combined with the need to perform precise manipulative functions suggests the further requirement that the end effector system possess variable, active compliance. The human operator could potentially directly control the degree of compliance.

Load Description	Load Limit (lb)
• Hand/arm forces on translation handholds, handrails, equipment tethers, and foot restraint attach points	* 100
• Safety tethers, personnel	300
• Exposed electrical harnesses -- gloved hand contact	20
• Hand loading on wing tab connector/connector shells, inadvertent hand torque application of force to wing tabs	** 50
• Multilayered insulation (MLI):	
- Push and impact (normal to covered surfaces)	100
- Tension	20

Notes:
* Surfaces and structures within the normal EV crewmember access planes shall be constrained by this limit load.
** Assumes a shell diameter greater than 1 inch plus two 1-inch wing tabs.

Maximum Loads Inadvertently Imposed by Crewmember
(Data reproduced from reference [5])

Table 4-4

4.3.4 Sensing Requirements

To successfully accomplish its range of tasks, the end effector system must have access to the following information, especially if it is operating autonomously or otherwise under machine control:

(1) Orientation of end effector elements relative to each other
(2) Orientation and positon of end effector relative to other objects in workspace
(3) Forces and torques acting on the end effector
(4) Confirmation of grasp
(5) Location of forces on end effector
(6) Configuration of objects in the workspace

This information will be provided by a combination of sensor types. Note that these types may be implemented as local or global sensors (e.g., one force/torque sensor may recognize grasp, while another resolves the overall force vector acting on the end effector). Possible sensor types include:

- Position/Velocity
- Vision
- Force/torque
- Proximity
- Tactile (surface mapping)
- Temperature

Most visual sensing may fall outside the boundaries of the end effector system, in the form of a vision system for the entire teleoperator. However, the quality of feedback to the primary visual sensing system may be limited for a number of reasons, including the geometry of the manipulator arm or end effector system. If so, some visual sensing may need to be incorporated into the end effector itself. Illumination capability in the end effector is likely to be necessary for the same reasons.

Forces and torques applied by the end effector must be measurable with some precision across the ranges specified in Table 4-1. Force feedback to an astronaut through the pressurized glove is limited, but is still available at the range minima.

The physical size of the sensing subsystem must not compromise the clearance constraints described above.

SECTION 5

IMPLICATIONS FOR END EFFECTOR DESIGN

The system and task specifications just defined in Sections 3 and 4 have implications for the implementation of the end effector system design. In this section, we consider the elements within the major end effector subsystems, and the range of design options available for those elements. We also examine certain design considerations that transcend individual subsystems, including those that should influence the design of other manipulator system elements.

5.1   MECHANICAL SUBSYSTEM

The major parts of the mechanical hand include: power actuators, power transmission, clamping system, frame, and several auxiliary elements [7, 8].

Power Actuation

Common actuators used in robotic systems are:

- Hydraulic
- Pneumatic
- Stepper motors
- DC motors

The options are limited to stepper motors or DC motors for space applications. DC motors are generally preferred; DC motors offer higher precision and their output power versus weight ratio is much higher than for stepper motors.

Power Transmission

Among the available power transmissions are the different gear types, spindles and leadscrews, mechanical linkages, cable drives, and pneumatic or hydraulic lines.

Clamping System

The clamping system specifies the configuration of the gripper or "hand." Major hand types are:

(1)   One degree-of-freedom hands, having two fingers

(2)   Special purpose hands, e.g., suctions cups, magnetic devices

(3)   Multiple degree-of-freedom robotic hands, e.g., 3- or 4-finger claws with the fingers in a circular arrangement

(4)   Dexterous hands, usually with three fingers with three degrees of freedom each

(5)   Prostheses, designed as functional substitutes for the missing hand of an amputee

(6)   Anthropomorphic hands, configured similarly to a human hand, designed for teleoperator or robotics applications

Some of these alternatives are clearly unsuitable for space applications: special purpose hands are simply too limited in capability; prosthetic hands are generally not designed to be controlled remotely, and possess insufficient power. The nine or more degrees of freedom of computer controlled dexterous hands make real-time control and coordination computations difficult, and these hands are not generally adaptable to teleoperator control. (Note that an anthropomorphic hand, though possessing many degrees of freedom, avoids the computational complexity of dexterous hands, since a human hand input device is utilized in a master/slave configuration.) Only the general purpose hands (1, 3, and 6) will be considered further in this analysis.

Auxiliary Elements

Among the more common items which should be considered in advanced mechanical hand construction are:

- Modular design
- Overload release mechanisms
- Mechanical compliance (active or passive)
- Mechanical self-centering
- Mechanical damping
- Concave geometrical clamping cavity shapes that can "hug" objects rather than rely solely on friction forces
- Exchangeable parts and/or hand exchange mechanism

In some cases it may be advantageous to incorporate exchange mechanisms enabling the use of plug-in end effectors designed so that the integrated mechanical and electronic subsystems are exchanged. However, since automatic coupling of mechanical, electrical, and hydraulic or pneumatic connections is rather complex and error prone, greater advantage might be derived from exchanging only parts of the end effector, such as"fingers" or "fingertips." Fingers and fingertips would be designed with limited or no connections except for mechanical coupling.

Additional mechanical elements that will be needed, but are not part of the end effector itself, are various tool adapters. Tool usage enlarges the application range of the mechanical hand.

5.2   SENSOR AND FEEDBACK SUBSYSTEM

The requirements for multifunctionality and smartness put high demands on the sensor subsystem. The end effector may also act as a source of data generally needed by the manipulator system.

Sensors in the subsystem will include a combination of:

Vision
Force/torque acting on the end effector
Grasp
Tactile
Temperature
Proximity
Position
Motion

A block diagram of the sensor subsystem is shown in Figure 5-1. When possible, support electronics will be remote from the sensor head to reduce end effector encumbrance. As necessary, raw sensor data will be converted to the appropriate form to be processed or transmitted (e.g., optical signal converted to electronic signal, analog signal converted to digital signal). The sensor data will be multiplexed for processing and transmission.

The sensors will generate data requiring significant processing to be converted into meaningful information. Some data may be processed locally, within the end effector system, while other data are transmitted directly to central processing facilities for the manipulator system. Locally processed data may provide direct feedback to the end effector controller for certain autonomous functions.

5.2.1   Vision Sensors

Visual images will be the primary sensory feedback to the operator of the teleoperator system. The variety of tasks to be performed by the end effector system require high fidelity vision sensing.

Useful locations for the mounting of visual sensors may be the manipulator wrist, arm, or in the hand. Cameras may be mounted on their own boom completely independent of the manipulator arm. Only sensors on the wrist or in the hand fall within the boundaries of the end effector system.

Considerations for the selection of visual sensors in the multifunctional end effector system are image quality, size, sensitivity to physical shock, and adaptability to multiple end effector configurations.

Sensor Types

The four camera technologies available for vision sensing are:

- Vidicon
- CCD (Charge Coupled Device)
- CID (Charge Injected Device)
- Fiber optics (not a camera, but does allow distant placement of any of the three camera types listed above)

For some short range visual sensing, it may be possible to use CCD or CID devices without attached lenses, significantly reducing the size of the sensor head.

To further aid the human operator, the visual image may be processed for contrast enhancement or to compress the dynamic range.
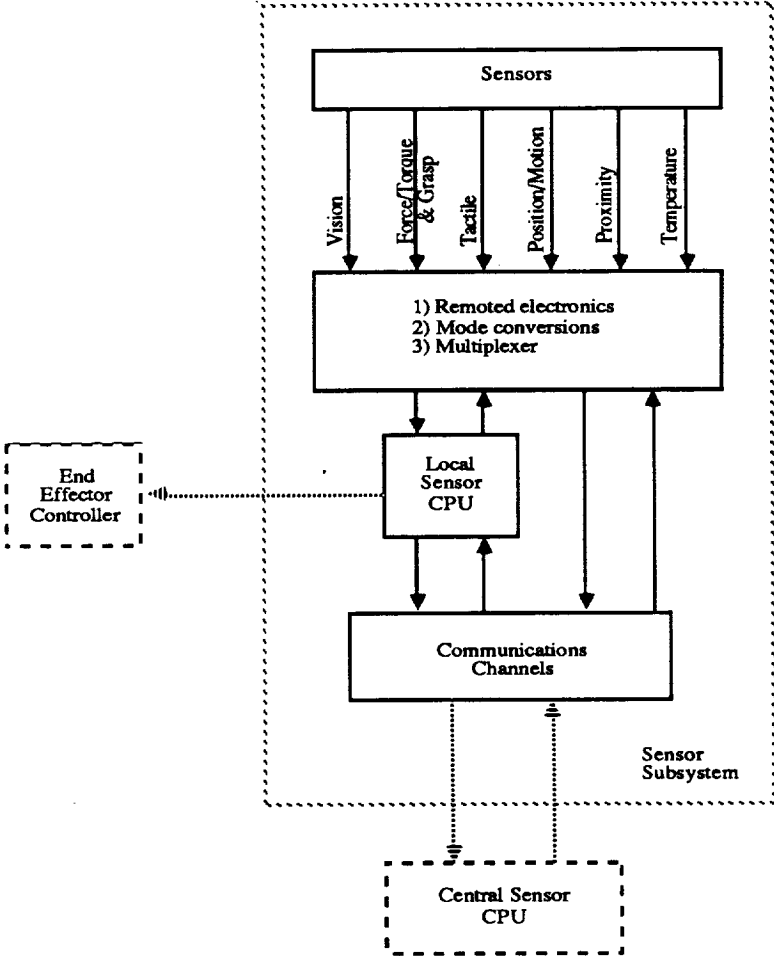
Sensor Subsystem

Figure 5-1

5.2.2 Force/Torque and Grasp Sensors

Information about loads being applied by or to the end effector is critical to the success of many tasks in which visual information is unavailable or is inherently insufficient (e.g., it can be impossible to visually distinguish an aligned captive screw from a misaligned one at the beginning of the tightening process).

Confirmation of the end effector grasp on an object reduces chances of slippage and loss of grasp, especially when the object is in turn used to apply loads to other objects in the work area.

Sensors can be located at the wrist to determine overall forces and torques acting on the end effector. Grasp sensors need to be mounted on the inner surfaces of the fingers or claws.

Size and operating range of load sensors are important in their selection.

Sensor Types

The two principal sensor mechanisms for measuring loads are:

> - Strain gages (measure strain)
>   - semiconductor
>   - thin film
>   - unbonded wire
>   - bonded metal foil
> - Piezoelectric sensors (measure forces)

Depending on the set-up and geometric arrangement, the structure can be configured so that the sensors measure forces, torques, or moments.

The data generated by these sensors can be sent directly to a central processing system or locally processed to minimize communications demand.

5.2.3 Tactile Sensors

Tactile sensors provide indications of the location and distribution of forces on the end effector. The data from these sensors can define the shape and orientation of objects held by the end effector; the sensors may also determine whether an object is slipping from the end effector's grasp (this may be accomplished via the successive evaluation of force distribution "snapshots"). The importance of this information depends on the capability of the end effector to take advantage of it; if the end effector has many degrees of freedom, tactile information may be required for their coordinated control. In general, the more dexterous the tasks to be performed by the end effector, the greater the need for tactile sensors.

Tactile sensors may be useful if located on all surfaces of the end effector that may make contact with objects in the work space; however, they are most needed on the surfaces designed for grasping, such as the inner surfaces of fingers.

To be practical for space applications, tactile sensors must be of small size while possessing sufficient resolution, resistance to damage, repeatability of measurement, and low hysteresis.

Sensor Types

Various technologies have been applied to developing tactile sensors [9,10]:

- Optical
- Photoelectric
- Semiconductor
- Piezoelectric
- Magnetoresistive
- Conductive elastomer

None of the existing sensors are sufficiently rugged for practical space applications. Most existing sensors are experimental. Resolutions vary, but have been reported up to 10,000 points/cm^2 [11]. Depending on the sensor, the data path may be wire or fiber optics.

The requirement that tactile sensors be placed on the surface contacting the object being manipulated makes isolating the sensor data path from exchange operations difficult.

While the number of data points for tactile sensing is generally much lower, tactile images of sufficient complexity can be processed using algorithms similar to those used for vision processing. Until these image processing facilities are available, the usefulness of tactile data will be limited by our ability to meaningfully interpret it. Furthermore, as with vision, tactile imaging may require fast and powerful data processing facilities.

5.2.4 Temperature Sensors

The variable thermal environment of space necessitates incorporating temperature sensors into the end effector. These sensors are part of the internal design of the end effector. Sensor information may be used locally to activate heating units to prevent freeze-up of moving parts in the effector.

Thermocouples and thermistors are mature technologies generally used to sense temperature.

5.2.5 Proximity Sensors

Proximity sensors provide range information for objects in the immediate vicinity of the end effector (e.g., within one foot). This is particularly useful for autonomus operations such as collision avoidance, self-centering of the gripper or other effector on an object, surface area inspection, and automatic grasping.

For self-centering and grasping, proximity sensors should be directed forward and inward from the forward and inner surfaces of the end effector equivalent to fingers. For collision avoidance,

sensors should be located at various points on the outer surfaces of the effector.

Sensors integrated into the end effector system must be relatively small, and must be able to accurately measure the proximity of a variety of types of objects. These sensors may be adversely affected by contamination of the end effector surfaces.

Sensor Types

Proximity sensor technologies include:

- Optical interrupter
- Reflective
- Microwave
- Ultrasonic
- Capacitive
- Eddy current

The ultrasonic, capacitive, and eddy current type sensors have limited applicability to space operations. The optical interrupter, reflective, and microwave sensors should be more useful.

5.2.6   Position/Motion Sensors

If the end effector system has multiple degrees of freedom, it will need sensors to report its precise position. From position information velocity can be derived or position integrals computed. This feedback is of even greater importance if the end effector is to be operated autonomously.

Sensor Types

Sensors commonly used in robotics applications for determining position include:

- Linear potentiometers
- Single- and multi-turn potentiometers
- Variable transformers
- Optical encoders
        - absolute
        - incremental
- Magnetic encoders
- Tachometers

5.3   CONTROL STATION

The control station is the means by which the human operator interacts with the manipulator system. The control station must display the information appropriate to the particular task the operator is currently performing, and allow the operator to efficiently control the appropriate

function selected from the many available to him.

One consequence of multifunctionality is that the appropriate functions and information are constantly changing. The number of options available through the operator interface may make operator error highly probable (e.g., the operator may select an option appropriate to the previous tool used by the end effector, rather than the current tool). If distinct operator interfaces are required for many functions, much of the benefit of the multifunctional system may be lost. The properly designed control station must be flexible without overloading the operator.

The primary components of the control station are discussed below [12].

5.3.1   Control Panel

The control station control panel will incorporate several displays and controls:

Displays

- Graphics. Displayed graphically will be status indications, data
  from the various elements of the sensor subsystem, option menus,
  and recommendations of expert systems or other user aids.

- TV. Television monitors will show various views of the work site,
  including stereoscopic images.

- Indicator lights.

Controls

- Buttons, switches
- Keyboard
- Touchscreens
- Joysticks

5.3.2   Master Manipulator/End Effector Controllers

The manipulator and end effector controllers together provide the human operator with his primary teleoperator control capability. The two controllers are not independent, since the operator will often use them simultaneously. The position of the human operator's own arm or hand is commonly the input to control the manipulator arm; this constrains the operator's options in using his hand to control the end effector.

Since human operators may need to control two manipulator arms for future tasks, the control of manipulator and end effector should be integrated into a single arm/hand controller if at all possible, leaving the operator's other arm free to control a second manipulator.

<u>Manipulator Controller</u>

The manipulator controller may be implemented by several means, such as:

- Joystick
- Six or more DOF hand controller (6 DOF position control plus push button)
- Exoskeleton
- Strap-on harness
- Voice
- Self-supporting frame
- Computer control of pre-programmed functions
- Autonomous control

Note that some of these techniques could easily interfere with any multiple degree-of-freedom end effector controller. Others may not be feasible in the short term.

The manipulator controller will use some combination of rate, position, force and operator aided control strategies, and may provide force, position, or other stimuli feedback to the human operator.

<u>End Effector Controller</u>

Candidate devices to control the operation of the end effector system are:

- Hand triggers
- Glove controller with finger resolution (position or force control)
- Control panel controls
- Voice
- Computer control of pre-programmed functions
- Autonomous control

The type of multifunctionality impacts the hand controller design. The capability and degrees of freedom of the end effectors must be reflected in the controller. If only exchangeable, single degree-of-freedom end effectors are used, the hand trigger should suffice. If the end effector is anthropomorphic with multiple fingers, the human operator must be able to control multiple degrees of freedom simultaneously (if the degrees of freedom are controlled sequentially, the advantage of multiple fingers is lost). The glove type controller provides the necessary level of control by taking advantage of the many degrees of freedom of the human hand and the similarity in configuration between the human hand and the appropriately constructed anthropomorphic hand.

Control panel controls, or other controls (see below) may supplement the end effector controllers, but are unlikely to supplant them. For example, a button on a panel might be used to reverse the default rotation of a powered screwdriver end effector, or even to trigger its operation, but the panel controls would not be used to position or orient the screwdriver in space. The control panel would likely be used for fine adjustment, zero setting, re-indexing, and auxiliary functions.

Force, position, and/or tactile feedback incorporated into the end effector controller would present the operator with information about the end effector system in an intuitively understood format. This would free the operator to concentrate his visual attention on the primary TV displays, rather than possibly distracting graphics displays of forces or torques.

5.3.3   Other Controls

The task loading induced by the manipulator/end effector controllers will not leave the operator with his hands free to control auxiliary functions. These functions may include positioning of TV cameras or other sensors, setting of active compliance, controlling the illumination of the work site, selecting information to be displayed, temporarily decoupling the manipulator/end effector controllers from the slave arm, freezing the slave arm while the operator removes his own from the master controller, and setting end effector modes (e.g., tighten, loosen). The operator will use a combination of the following to accomplish these functions:

- Voice
- Foot pedals/buttons
- Knee pads
- Head position
- Eye position
- Chair position

5.3.4   Other Displays

Additional displays may provide necessary information without compromising control functions:

- Helmet mounted TVs for stereoscopic display
- Heads-up displays
- Force feedback display
- Direct tactile displays (incorporated into the end effector controller)
- Auditory feedback

5.4 END EFFECTOR CONTROL AND PROCESSING

5.4.1 Feedback Control

Feedback control can be incorporated into the end effector system. Position, velocity, and position integral feedback would allow for correction of position, velocity, and systematic displacement errors.

5.4.2 Processing Considerations

Some information processing will go on within the end effector itself, while much processing of the data generated by sensors embedded in the end effector will occur at a central location. Local processing of sensor data may be used to reduce bandwidth requirements for the communications channels, or to provide information to the local end effector controller to support autonomous operations. The end effector controller will of course perform processing of its own to carry out the appropriate end effector functions.

Processing requirements for control of the end effector system should initially be low. An exception to this will occur if the end effector system has several DOF while the kinesthetic configuration of the master controller is significantly different from the configuration of the end effector. Complex tranformations would then be needed to match control signals to actions by the end effector, and provide appropriate feedback to the operator.

In either case, the processing requirements will grow by orders of magnitude as user aid becomes part of the system (see Section 5.5), and as the sophistication of sensor processing increases.

Control algorithms may change completely with different functions, end effectors, or tools. The control software should be implemented in a modular environment that supports future expansion and use of AI tools.

5.5 AUTOMATION TO SUPPORT MULTIPLE TASKS

Automation will play an increasing role in the tasks the multifunctional end effector system is designed to support. The end effector development effort must therefore consider the future requirements of automation at all stages. However, autonomous telerobots will certainly not be available to replace EVA operations until the late 90s. As a consequence, this document emphasizes needs of teleoperation as they influence end effector design.

Certain operations related to the multiple tasks the end effector system will perform are candidates for early automation. Several tasks could be performed autonomously, with the human operator intervening only if serious errors would otherwise occur. The following discussion identifies some of these tasks, and points out areas where automation is clearly desired.

End effector or tool exchange is a repetitive, time-consuming function. An automation scenario for exchange operations follows: After using a wrench at the work site, the human operator

moves the end effector to a neutral position from which inadvertent motions are unlikely to impact the work site. He then gives the voice command "Select screwdriver." An automated control subsystem commands the manipulator arm through a sequence of actions: move the end effector to the tool storage assembly, stow the wrench, move to the stowed screwdriver, unstow the screwdriver, and return the end effector, now grasping the screwdriver, to the previously established neutral position. Such automatic exchange operations may be feasible by pre-programming a limited number of motion sequences.

If the end effector system has some means of recognizing tools automatically, the tool exchange operation above could become more flexible. Automatic tool recognition would not necessarily restrict tool stowage to single, pre-defined locations in a tool rack.

With vision input to an autonomous system, the hand could be commanded to automatically track and lock onto an object. A simple "close hand" command would then close the aligned hand to clamp an object appropriately (assuming sufficient compliance in the end effector). A glove controller could be used as a motion teaching device for even quite sophisticated and complex motions, including such grasp modes as close hand, clamp, pinch, etc. These motions could then become pre-programmed functions activated through simplified voice commands.

Tasks such as polishing, inspecting, cutting, taping, or soldering may require the end effector to follow workpiece surface contours precisely. This surface following capability is necessary in both contact and non-contact modes (e.g., inspection). In the contact mode, the end effector may need to apply a constant force to the workpiece along one axis while the end effector performs another action (e.g., polishing). Automation of these surface following operations would significantly reduce operator loading in these situations.

Collision avoidance would prove an extremely useful automated capability. It would allow the human operator to concentrate on the task he is performing, without undue concern for the configuration of teleoperator and environment beyond the immediate work site. Without collision avoidance, the operator could conceivably devote half of his attention to being sure he was not about to damage equipment near the work area.

5.6   SYSTEM IMPLICATIONS

5.6.1   End Effector Exchange Operations

Use of exchangeable parts (in addition to tool usage) is one approach to enhancing the multifunctionality of an EE. We can distinguish three different types of exchange operations:

(a) Exchange of the whole EE, including power lines and signal interfaces and handling of thermal blankets.

(b) Exchangeable fingers only, including limited communication channels but no power line interfaces and no thermal blanket handling.

(c) Exchange of finger tips only beyond any sensing devices, requiring a mechanical exchange mechanism only.

The appropriateness of these exchange options varies significantly between non-dexterous and dexterous end effector types.

Non-Dexterous Hands

Any full end effector exchange would require the following complex links between the exchangeable end effector and the permanent base:

> - Data lines for commands to the end effector
> - Sensor data lines (vision, force, torque, etc.)
> - Electrical power or mechanical drives
> - Structural connections
> - Coupling, aligning, and centering mechanisms

For space operations, the interface would need to be thermally protected (e.g., by a reconfigurable thermal blanket).

The feasibility of exchange operations is influenced by the time per exchange, reliability of an individual exchange, the number of exchanges, the stowage requirements (size and location), and the possible need for an additional arm or active stowage facility to help in an exchange. Related factors influencing the choice of an exchange strategy include:

- The number of simple exchangeable EEs needed to execute typical EVA tasks.

- The costs of development, testing, and flight certification of a number of special purpose EEs.

- The requirement imposed by exchangeability to develop reliable automatic exchange mechanisms for mechanical, electrical, and electronic interfaces to couple them to the arm as well as to every individual storage cell.

- Exchange operations would require an automatic tether dock/undock mechanism at every EE interface. This potentially escalates the development costs, while introducing a new source of failure: the tether cable might get entangled in the exchange mechanisms or the working area.

- The distance the arm must travel to change EEs, and the accuracy needed to align the arm to enable coupling.

- The feasibility of handling thermal blankets.

- The likelihood of debris in the exchange mechanism preventing a successful coupling. Self repairs in space after a breakdown are unlikely.

- The development costs and space requirements of a special EE stowage system. A special stowage facility would likely increase storage space requirements since the EEs need to be presented with the exchange mechanism exposed to enable an exchange

operation.

- Since exchange operations should be done automatically, the proper docking, locking, and tethering mechanisms must be implemented on the arm as well as at every EE and every stowage location.

- Different EEs might require different control strategies which are likely to confuse the operator.

The above factors will make automatic gripper exchanges a rather unlikely task, if not totally infeasible. Use of non-physical links, such as modulated lasers for sensor and command data communication, may significantly improve the speed and reliability of exchanges. Exchangeable fingers or fingertips only would diminish the exchange complexity. However, the docking/undocking problem still remains if the exchange operation is supposed to take place automatically.

Manual exchanges are of course much simpler; in this case the desired fingers are manually attached to the hand prior to an EVA operation.

Dexterous Hands

Due to the capabilities of dexterous hands, no whole EE exchange operations are required. Fingertip exchange operations are feasible with these hands since their dexterity would allow a second hand to snap on and secure fingertips at the other hand without the need of automatic exchange mechanisms. The fingertip in this type of exchange is separated beyond any sensing organ so that only a mechanical interface exists. Possible fingertips are Velcro pads for handling objects with Velcro surfaces, and custom curved or straight shapes for better grips on selected objects.

Under some circumstances, a second dexterous hand might carry out the exchange of another hand that had failed.

5.6.2   Tool Manipulations

It is obvious that no single hand design can accommodate all requirements to successfully handle all objects. Even the most sophisticated end effector, the human hand, uses a variety of manual and power tools and still needs other aiding devices for even quite common tasks.

Employing tools marked the turning point in early man's life. It will have the same effect on robot hands where the use of tools will enhance robotic capabilities and application ranges. It is therefore important to realize that the successful use of tools by the mechanical hand is one of the most important design criteria.

Two different sets of requirements exist for the proposed EEs, again depending on the dexterity level of the EE:

Non-Dexterous Hands

The criteria for tool handling by non-dexterous hands are somewhat similar to the criteria for the exchanging of end effectors:

- Development of a specially designed tool stowage facility is needed where each tool must be presented in the proper orientation for grasping.

- Each tool must be equipped with a feasible clamping section to be grasped with a non-dexterous EE, requiring specially designed tools.

- Many tools may need a special adapter between hand and tool to hold the tool in a certain fashion.

- Development is necessary of automatic lock and unlock mechanisms to operate while each tool is being stowed/removed. A possibly distinct development would be an automatic tethering mechanism to work for all tools.

- Questions such as docking mechanism robustness, reliability, frequency of breakdowns, and servicing or repairs in space must also be addressed.

- Enough clearance between tools in the stowage bin is required so that the hand can reach in.

- Moving the whole arm from the work site to the EE stowage location is required for each exchange operation.

- Non-dexterous EEs are unlikely to possess the capability to squeeze a trigger to start the action or flip a reverse-direction lever. Radio control for activation of certain power tools may therefore be necessary.

- These EEs would have limited tool manipulative capabilities; the hand just holds and moves the tool. (Tools cannot be turned in hand; a pair of pliers could not be grasped while being opened or closed.)

- A second EE would provide limited aid in positioning of tools for proper grasping.

- Without compliancy in the hand-arm, it is impossible to rigidly hold a tool and follow an arbitrary arc on the work site as would be required around hinges and with wrench-type tools.

- Non-dexterous EEs have little capability to handle very small tools, work in small spaces, or execute accurate small motions.

Dexterous Hands

Characteristics of tool manipulations with dexterous hands:

- Off-the-shelf tools can be used with minor modifications.

- The currently used EVA tool stowage can be used without modifications since the tools can be grasped in any orientation (for instance from Velcro strap surfaces or in styrofoam holders) and manipulated until they are rigidly aligned in the hand.

- Appropriate clearance must be provided between stowed tools.

- A second dexterous hand can assist in grasping and holding of tools.

- The tether can be attached to a tool's security ring with a second hand. No automatic tether coupling mechanism needs to be developed.

- A dexterous hand/arm would have built-in compliance required for many tool manipulations.

- Powered tools can be plugged into a socket on the tool holding arm with a second hand.

- Triggers can be squeezed with one finger.

5.6.3 End Effector/Equipment/Tool Stowage and Retrieval

The end effector system must be able to retrieve and stow its exchangeable end effectors and tools. Current practice for EVA tools and equipment often relies on various techniques:

- form-fitting foam receptacles
- tether rings attached to objects
- Velcro straps

Combinations of these devices may be sufficient for most tools and equipment. However, using them without modification would require dexterity and, most likely, two-handed manipulation (note that tool preparation is an EVA function that permits the use of two hands by an astronaut). For example, once a tool has been pulled free of the foam via its tether ring, the tool is typically swinging free at the end of its chain. Its position must then be stabilized; next the tool is grasped in a tool-using configuration, or temporarily stowed in a portable workstation for later use.

Standard EVA tool stowage techniques will be insufficient for stowage of exchangeable end effectors: the end effector/base interface must be exposed and available while the exchangeable end effector is stowed. The requirements for the stowage facility include:

- Maintain end effector in precise orientation for interfacing
- Provide compliance or other means to avoid damaging end effector during repeated insertions and removals from stowage facility
- Protect end effectors from thermal or other radiation
- Survive thousands of exchange operation cycles
- Be reconfigurable for various end effectors
- Prevent inadvertent loss of end effectors due to float away

The difficulty of fulfilling these requirements depends largely on the complexity of the interface.

5.6.4   Negative Subsystem Interactions

The various subsystems must be integrated into an effective end effector system. Certain subsystems, particularly those containing the mechanical and sensor elements, could easily degrade each other's performance if not considered carefully during design.

The need for a wide range of sensor information can lead to bulky sensor packages modifying the effective configuration of the end effector, limiting clearances, and generally reducing the effectiveness of the mechanical subsystem.

Mechanically simple end effectors may be most reliable and offer greater surface area for sensor placement; but the result may be much sensor data with little capability to respond to it. Alternately, complex mechanical configurations may severely limit the type and quantity of available sensor data.

As sensor and control complexity increase, the requirements for the communications channel will also increase. Parallel rather than serial communications becomes necessary; radio frequency interference may degrade transmissions.

Increasing complexity in all subsystems may result in an undesired growth in overall system mass.

Some of these negative interactions may be unavoidable given the current state-of-the-art of the relevant technologies. No subsystem should be inherently dominant; tradeoffs among individual subsystems must be guided by the objective of improved overall system performance.

5.6.5   Protection from Environment

The harsh and variable conditions of space will require several types of shielding for the end effector:

- Thermal shielding (e.g., thermal blankets)
- Radiation shielding
- Resistance to abrasive surfaces

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5.7 END EFFECTOR IMPACT ON OVERALL ARM DESIGN

Capabilities of the end effector system may impact the design of the manipulator arm in such ways as choice of number of arms, size of arm, number of degrees-of-freedom, and inclusion of end effector actuators within the arm.

5.7.1 Number of Arms

Several issues related to end effector multifunctionality suggest the use of multiple arms in the manipulator system, as discussed below.

- Limited Exchangeability. Limitations in exchangeability may lead to use of two or more arms with significantly different end effectors. Operation over the full range of power or force requirements may be infeasible within a single arm/end effector configuration. Multiple non-identical arms might support the full range.

- Symmetric Manipulators. The variety of tasks to be performed may require use of symmetric (left and right handed) cooperative manipulators for "two-handed" tasks. This may be necessary even if end effector exchangeability is not an issue. One arm may hold an object in place while the other arm manipulates the object.

    Current EVA guidelines require tasks to performable with one hand, with the other hand used for restraint. The dexterity of multifunctional end effectors is unlikely to be identical to that of an astronaut's gloved hand; even if the teleoperator can perform the same function as a gloved hand, it will likely do the job in a different way. Cooperating manipulators may be needed to do the same function an astronaut can do with only one hand.

- Bulk Load Handling. Two arms will be needed for general purpose manipulations, in order to resolve occurring moments into a couple of forces, one on each arm. This will allow for scaling the arms to a much smaller size, enabling fine and accurate motions. If only one arm were used, it would have to be sized to securely withstand large moments.

- Self-Replacement. Replacement of a failed end effector system without EVA would require a second arm to perform work on the first.

- Teleoperator System Transportation and Grappling. Multifunctional end effectors on multiple manipulator arms may be able to "walk" the manipulator system to the work site. Once at the work site, multiple arms could rigidize the connection between the manipulating arm(s) and the work piece.

In the later sections of this document, we may sometimes assume the existence of a second identical (or symmetric) arm/hand to allow perfomance of functions an astronaut might perform

using both hands during an EVA.

5.7.2 Actuator Placement

Multifunctional end effectors may have multiple degrees of freedom requiring several actuators. To reduce the size and generally improve the performance of the end effector, it may be necessary to place these actuators above the wrist, on the arm itself. This is analogous to the human arm: the muscles controlling the human hand are located in the forearm.

Alternately, the end effector system can be redefined to extend beyond the "elbow" of the manipulator arm, keeping the actuators within the end effector boundaries.

5.7.3 Manipulator Arm Degrees of Freedom

The complexity of the hand must be matched by the arm, i.e., a dexterous hand requires a seven-DOF compliant arm.

Minimally six degrees of freedom are necessary to position the end effector appropriately at a work site. However, this assumes no obstructions between the manipulator and workpiece. To reach around objects, at least one additional degree of freedom would be necessary. Two or more manipulator arms used cooperatively on the same task (as described above) could easily become obstructions to each other, even if no other obstructions exist. If each arm has sufficient degrees of freedom, this potential problem can be prevented.

A seven-DOF arm must have its appropriate end manipulator controller. Among the previously introduced manipulator controllers, only the six or more DOF hand controller (where the seventh DOF would be controlled with software if the six-DOF controller is chosen), the exoskeleton controller in anthropormorphic shape, or computer control are feasible.

5.7.4 Arm Scaling

The size and mass of the manipulator arm must be commensurate with the size and functions of the multifunctional end effector system attached to it.

For example, the shuttle RMS is too large for easy positioning of an end effector performing a variety of precision tasks. Re-orienting the end effector to tighten a series of screws would require undue time, since the entire mass of the arm would have to be moved and then stabilized. Any end effector or tool exchanges would also be time consuming operations. Unless a tool stowage facility can be mounted at the work site, the RMS would have to go to an exchange rack located near its base for exchanges.

The front end mass which will be moved for fine positioning must be comparatively small to avoid vibrations. A direct consequence of this is that no 50-foot arm can be used for accurate handling. A low mass arm in front is needed for fine adjustments and to avoid dynamic problems. The big arm can be used as base support which moves the small arm and hand system(s) into the working area. The small mass arm is likely to be the "Smart Front End" to be developed for use on the OMV and Space Station. The Smart Front End is intended to

service satellites. Current concepts incorporate multiple arms and tool racks.

5.7.5   Interfacing with the Shuttle RMS

Certain limitations on the use of multifunctional end effectors with the shuttle RMS were addressed during the discussion of arm scaling requirements in Section 5.7.4 above. Additional issues are raised below.

In an appropriate arm, the joints must be flexible enough to properly align the EE to the workpiece with the wrist joints as close to the EE as possible. The RMS arm has its last wrist joint at least 6 feet away from the claws, which is inadequate for accurate alignments.

The 50-foot RMS shuttle arm has a snaring device EE that allows capturing slightly misaligned objects in space. The grasp is then gradually tightened and the object aligned. If a one-DOF smart hand without compliance were rigidly mounted on the RMS EE, not only would the soft grasping capability be lost, but one would have to move the 50-foot arm into accurate position for grasping. This is impossible due to arm drive accuracy, mechanical tolerances, and the arm's elastic flexibility oscillations when moved or stopped. As a result, a smart hand cannot be hard mounted to the RMS, nor aligned accurately; the hand would bang into the workpiece at each oscillation. The soft grappling capability of the RMS is desirable to keep induced moments and stresses to a minimum, but becomes unavailable when the RMS picks up the end effector.

SECTION 6

ALTERNATIVE END EFFECTOR DESIGNS AND PRELIMINARY EVALUATION

This chapter consists of three parts:

Section 6.1 outlines three advanced EE design categories evolving from 1) improving the current state-of-the-art "smart hand;" 2) increasing multifunctionality by adding additional features that will require a new basic EE design; 3) the creation of an anthropomorphic hand capable of object manipulation including a human hand adaptable hand controller. Previously introduced relevant theory is reviewed and expanded pertinent to the EE concept discussions, enabling a preliminary evaluation of mechanical concept feasibilities.

Section 6.2 discusses system integration issues for each of the three advanced EE design concepts. Each hand has to be matched with the proper system elements such as its arm, the controller, exchangeability features, and tool usage.

Section 6.3 proposes four specific EE solutions which are based upon the preliminary evaluation of parts 1 and 2. Their designs are described and will be evaluated in Section 7 to find the most capable EE for performing upcoming space tasks.

6.1   OVERVIEW OF DESIGN ALTERNATIVES

(1) Single-DOF Hand

- Basic Model. The state-of-the-art, general purpose EE design is the two-finger gripper with a linear closing motion [13]. Its primary advantages are the simplicity in design and the available technology. However, based on the definition of terms outlined in Section 2.4, it has very limited multifunctionality—with clamping capabilities only, no manipulative capabilities, no dexterity, and handling of only a narrow range of object sizes and shapes. Tool handling is very restricted, too, to a mere holding of tools. Proper tool presentation and orientation for grappling is necessary, requiring elaborate tool docking mechanisms and storage facilities. And without compliance control, accuracy in alignment is essential, requiring a stiff arm and high performance joint motion capabilities that still might not be good enough for space applications where objects have a tendency to float around and are presented at random orientations.

- Smart Hand. Advanced gripper developments add a variety of sensors in and around the hand (i.e., clamping force, proximity, and wrist force-torque sensors). These sensors aid in object recognition and grasping; the hand is thus referred to as a smart hand. These sensor capabilities must be traded off with increased hand size, requiring larger clearances between objects. Even with the addition of sensors, the single-DOF smart hand has no manipulative capability.

Section 6.1.1 discusses single-DOF hands where the state-of-the-art OMV smart hand with its intermeshing claws is the primary example. Improvements are suggested that could be implemented without altering its basic design.

- Exchangeable EE. In order to increase the system's capabilites it is often suggested that exchangeable special purpose hands of different sizes or functions be used. Even though a larger range of objects could thus be handled, there still is no dexterity for skillfull object manipulations, while costs become prohibitive: the design and creation of storage space for a number of exchangeable EEs together with reliable exchange interfaces and EE racks with docking/undocking and tethering mechanisms becomes mandatory. Exchange interfaces were discussed separately in Section 5.6.2. Due to the mechanical complextiy, exchange mechanisms are only considered for single-DOF hands.

(2) Multi-DOF Hands

Section 6.1.2 outlines the key issues to be resolved for the successful implementation of a multi-DOF EE. The analysis reveals a natural breakdown into two types of multi-DOF hands: (a) hands with a one-DOF knuckle joint, using a simpler design and existing technology at the expense of not having any manipulative capabilities, and (b) hands incorporating two-DOF knuckle joints, giving the hand manipulative capabilities but requiring a more complex design. One such hand shape, the human hand-like anthropomorphic hand, has control advantages that justify considering it separately (see (3) below).

(3) Anthropomorphic Hands

The theory developed in 6.1.2 for multi-DOF hands also applies for this hand type with one major improvement: the shape of the hand is proportional to the human hand. This configuration allows a sensed human hand to be used as a motion input device (master) to control the mechanical hand. Since computer control is not yet capable of controlling a multi-DOF hand efficiently, the human hand controller is the most feasible short term way to execute complex object manipulations, and it will be vital for contingency operations. Furthermore, the human hand can be used as a teaching device, teaching the control computer fundamental hand motions. This will be an important feature for automatically controlled executions in the future. Section 6.1.3 examines anthropomorphic hands.

6.1.1 The Single-DOF End Effector

The OMV smart hand serves as the base for this design (see Figure 6-1).
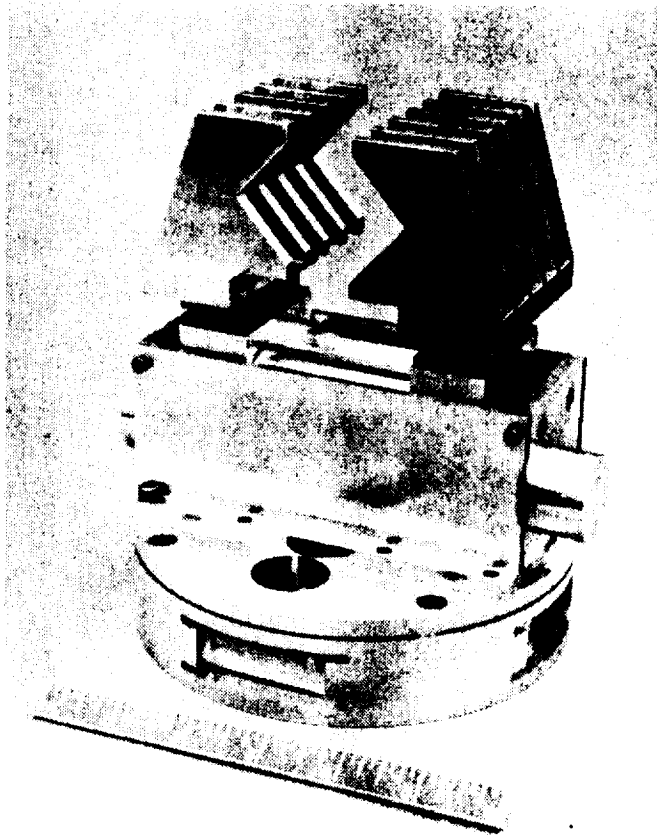
Figure 6-1. OMV Smart Hand

The advantages of the smart hand are as follows:

- Simple design

- Reliable

- Relatively high clamping force strength

- Smart through sensing

The smart hand has serious disadvantages:

- Clamping capability only, not very multifunctional

- No manipulative capabilities

- No compliance

- Cannot handle small objects. Small pieces might get stuck in-between the intermeshing claw sections and might deform the claw segments.

- Cannot work in a small workspace and needs big clearances around the object to be grasped.

- The bulk of the hand will obstruct the workspace for the global vision system, which is likely to be the most important sensing system during operation of the manipulator.

- Very limited tool holding capability and only in restricted directions.

- Several EEs might be needed to accomplish certain tasks, requiring exchangeable EEs, exchange mechanisms, complex tool rack mechanisms, and substantial EE stowage space.

- Handling delicate objects will be a problem since the hand can only clamp at the two opposite sides on an object with a relatively high clamping force because holding the object is done primarily by relying on frictional forces.

- The hand needs a wrist and an arm of proper size for flexibility in aligning. (This is discussed in Section 6.2.3.)

- If the hand has no compliance (as is the case in the current design), there is a potential problem that the gripper may lose the workpiece because the brake simply freezes the clamping motion at a certain point without supplying any additional clamping force when needed.

- With no compliance, objects can only be "hard" grasped. This is not permitted with the RMS for safety reasons.

In summary, this hand has very limited capabilites and application ranges and is certainly not suited for EVA tasks. It can be used, though, for two special space applications: (a) serving as a rigidizing device or satellite holder, holding the satellite stationary relative to the space robot while more sophisticated hands perform the EVA operations; (b) the hand could be employed as a "vise-workbench" on a special arm in front of a dexterous hand pair, temporarily holding removed equipment to be worked on during on-the-spot satellite repairs.

One of the OMV sample tasks cited is the retraction of a space antenna. This task has not yet been attempted. Keeping in mind that the geometrical shape of the claws will spatially constrain two linear and two angular positions with only the longitudinal axis of the antenna and its rotation around its own axis being unrestricted, it is very unlikely that the antenna can be retracted without breaking it. The reason for this is that it must be guided exactly along its longitudinal axis. This direction, however, is arbitrary with respect to the robot coordinate system. The use of the proximity sensors for orientation purposes is impossible since they show zero gap betweeen hand and object and are thus rendered useless for guidance once the object has been grasped. Relying on the force/torque sensor will fail also because pushing the antenna with some force will cause a moment at the wrist sensor that is in the same direction as a moment exerted on the antenna due to misalignments. Therefore, it is very unlikely that the

antenna can be successfully retracted. The conclusion from this example is that the hand needs other features besides sensing; in particular, it requires some degree of compliance.

Creating another single-DOF EE as a research tool for conceptual evaluations or as a production model would not be warranted at this time, since the recently built smart hands have not yet been evaluated. This evaluation will take place over the next one to two years. Only after these evaluations suggest fundamental improvements should a new basic design be attempted. Furthermore, it was already determined that a one-DOF hand is not EVA capable and, as will be shown later, cannot be used directly on the RMS arm for lack of compliance which would defeat the RMS EE's soft grasping capability. Therefore, no new single-DOF EE design is proposed here since it seems that one-DOF linear motion end effectors have reached their peak functional capabilities. Thus, this section only suggests improvements for the OMV hand that can be incorporated without changing its basic design.

Suggested improvements for OMV hand:

(1)   Exchangeable Fingers. These require some modifications to easily remove/replace the current set of intermeshing claws and with it the proximity sensors. Exchange operations require relatively little work if the claws are changed manually prior to an operation. Automatic finger exchange and stowage would require extensive research and design efforts.

(2)   Snap-on Finger Inserts. Inserts with flat surfaces for instance, could be retrofitted onto the current claws when a flat, uninterrupted clamping surface is needed. The inserts might obstruct the inward-facing proximity sensors. Manual mounting prior to use is trivial, but automatic exchanges would have same problems as in (1) above.

(3)   Fingertips. Protruding slender tips might allow work in restricted spaces that are not accessible with the normal claw. Attachment issues are the same as described above.

(4)   Develop an automatic finger exchange and stowage mechanism.

(5)   Add an exchange mechanism at the back of the EE.

(6)   Build in smaller sensors so that the fingers become less bulky.

(7)   Self-centering in longitudinal direction (Figure 6-2). The claw is suspended on linear ball bushings and springs and can slide up and down the rod. The spring will be compressed by clamping an object so that the claw rests on the roughened surface that prevents sliding.

(8)   Springloaded Clamping (Figure 6-3). The clamping force sensor is hinged and the mechanism spring loaded.

        Advantages: - Some self-centering capabilities in the clamping direction
                         - Limited passive compliance
                         - Better force control, less likely to lose the clamped workpiece
                         - More gradual clamping
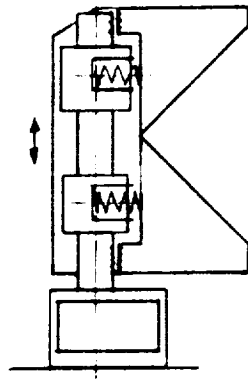
Self-Centering in Longitudinal Direction
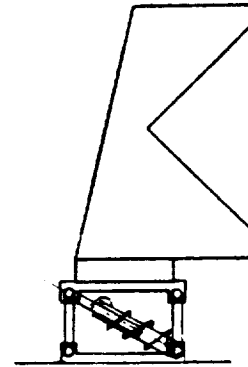
Figure 6-2

Springloaded Clamping

Figure 6-3

Disadvantages: - Requires different clamping force sensor
- Passive compliance causes problems under certain clamping
conditions

6.1.2   Multi-DOF End Effectors

Several multi-DOF hands have been attempted. They inherently have three basic characteristics that are hard to implement [14-20]:

(1) Complex mechanical design.

It takes a major design effort to build several DOF into a finger-shaped configuration and incorporate the driving mechanism to actuate all joints properly. Dexterous hand models have been built without a palm and the wrist so that the dexterous hand in essence is a set of dexterous fingers. The usual set up is three fingers with three DOF each where the knuckle joint has the two motion directions needed for manipulative capabilities. Thus, those hands have the fundamental features for dexterity.

A more promising approach is the construction of individual finger packages. Initial evaluations were extremely successful so that the proposed multi-DOF solutions are all based on the finger package approach. Only one basic finger actuation package needs to be built and tested which, in slightly modified form, can be implemented in each of the differently shaped multi-DOF hands. Tremendous savings will result with this modular design since the development costs for the package occur only once for its mechanical, sensing, and electronic components, which can then be reconfigured to many different hands of varying sizes and configurations.

(2) The capability to control the many-DOF to execute coordinated hand motions.

Computer control has evolved to the level where fingertip positions can be computed and the fingers aligned for a simultaneous three-point contact at the workpiece. What is needed, though, is that the fingers can "hug" an object with many points of contact. This capability is difficult to implement for directly driven joints without compliance, partially because of accuracy problems and machining tolerances, partially due to computer programming and computational complexities. Hand control differs according to the complexity of the hand. It will be discussed in Section 6.2.2 and in the individual sections of 6.3.

(3) The requirement for active compliance.

A definition for active mechanical compliance was stated in Section 2.4.2. When commanded to close in the soft mode, the hand will reach around any arbitrarily shaped objects, achieving multi-point contact for each finger, snugly hugging the object. In this tight wrap-around grip, the mechanism can then be stiffened and the clamping force applied thereafter. A much better grip on the object results which no longer relies on friction forces alone for clamping. The successful incorporation of an active compliance mechanism has tremendous advantages:

- The hand can conform to the shape of the object.

- It allows object-finger contacts over the length of the finger and not just at one point on the fingertip.

- Holding a load near the base of the finger rather than with the finger tip reduces the lever arm and thus the moment the joint has to withstand. A larger load capacity is the result.

- The arm, hand, or finger will yield to applied outside forces if in the soft mode.

- Compliance provides impact protection, since the hand is normally in a loose state if the hand is not clamping an object.

- Active mechanical compliance can be integrated with computer control to provide hybrid control.

- The hand can grasp an object without prior mathematical modeling of object shape and orientation.

- Compliance will aid time delayed operations, such as orbital teleoperations controlled from a ground station.

- New types of applications are gained through hybrid control. For instance:

  - Cooperative two arm operations are enabled.

  - Delicate work such as surface scanning at constant finger pressure (used in

operations such as cleaning mirror surfaces) becomes feasible.

- Loosening up on joint stiffness will provide the necessary give-and-take to align one part with its mating part in assembling operations, especially in the weightlessness of space where the bodies' weights do not matter.

The multi-DOF EEs that are proposed in Sections 6.3.2 and 6.3.3 are technically more advanced than the OMV hand. But even though the design is more complex, it relies on existing technology to assure immediate practical implementation. Consequently, a one-DOF knuckle joint is chosen that keeps the finger design relatively simple even though it eliminates manipulative capabilities. Major advantages of these hands are that they are more multifunctional than the single-DOF hand and have more strength than the anthropomorphic hand. A two-DOF knuckle joint is deliberately not chosen for these hands since its implementation increases the design complexity by an order of magnitude. (As previously stated, if a more advanced dexterous hand is what is needed, it will be an anthropomorphic hand because of the controller advantages.)

The new design features that are built into the proposed multi-DOF hands are:

(1) Modularity. Each finger will need the same features which include the finger, power drives, actuators, and compliance control. All fingers will thus be built as complete entities (packages), containing the above features. The packages will be built into the hands as a unit. Tremendous advantages result from the modular finger package design. Among the advantages are:

- Independent design, manufacturing, and testing.

- Removal capability of the entire finger package for service, maintenance, or repair.

- Available spare packages allow replacements of faulty units in space and repairs on the removed unit with minimal system down time.

- The finger package can be used for many different applications, including commercial robots. This wide applicability would eventually result in lower costs.

Exchange of finger packages should take place only when a package malfunctions. Therefore, the interface between the finger package and the base does not require the robustness that would be necessary for quick-change end effectors.

(2) Compliance. As described above, active mechanical compliance is a must for multi-DOF hands. Otherwise, limited accuracy would not allow multiple object contact points from each finger, nor delicate object handling or hybrid control.

(3) Finger design. Each finger will have two DOF. The major drawback is that both finger joints rotate into the same plane which means that the hand does not have manipulative capabilities. One proposed finger design will be a modified two-DOF intermeshing claw. Another is a rotating front claw so that different clamping surfaces can be used without the need for any exchanges.

(4) Control of hand. A hand with several DOF on each independent finger needs the proper controller for effective, efficient control. Triggers and joysticks have insufficient capability to simultaneously control the large number of DOF involved. A several-DOF hand controller requiring full hand motions through the wrist would be inconsistent with simultaneous slave arm wrist control. The glove-type hand controller is thus suggested. It will be described in Section 6.2.4. (A previous study [6] gave a mediocre rating to the glove-type controller, largely due to the lack of a defined technology base. The glove was not then considered in the context of the requirements of a multi-DOF end effector. In the time frame of this analysis, the glove-type controller is seen as clearly feasible.) Since computer control of multi-DOF hands is still problematic, the glove is likely to be the first available controller for multi-jointed fingers.

6.1.3   The Anthropomorphic Hand

This hand is in the shape of the human hand in somewhat enlarged size which makes it very comparable to the gloved astronaut hand. The driving idea behind this configuration is, of course, that our human brain can relate to this shape in a natural way as it controls our hands. A sensed human hand (with the glove controller) will serve as a motion input device until computer controls become available. It is the only suggested hand that has manipulative capabilities, a feature which is a must for EVA tasks as the EVA task analysis showed. It is dexterous because of its manipulative capabilities and through implementation of sensory systems that are located throughout the hand. The construction is a compact design that has sufficient multi-functionality and tool grasping capabilities so that no hand exchange mechanism is needed to exchange EEs, but it may have exchangeable fingertips that can be retrofitted by a second hand of the same type, enabling special tasks to be executed. The hand's actuators must be placed into the forearms. Its design thus already includes a three-DOF wrist as well as the elbow attachment because the elbow has to fit to the forearm. Thus, the anthropomorphic hand extends to the elbow.

Recent suggestions for space station robot EEs seem to lean toward the construction of exchangeable EEs because nobody expects a real breakthrough in dexterous hand design within the next 5 to 10 years. But the experts agree that if there was a dexterous hand available, it would be so much more capable for any kind of advanced robotics. More capable (dexterous) EEs are needed in the near future for EVA applications.

Considering the development costs of one anthropomorphic hand versus several simpler smart hands plus exchange mechanisms, complex tool racks and EE stowage facilities with their mechanisms and the need for proper object orientation to be able to latch on to the EEs and tools, it is plausible that one sophisticated compact design could be more economical in the long run. Dexterous fingers could pick up tools from existing simple tool stowage facilities of the kind which the astronauts use right now for their EVA operations. Off-the-shelf tools stowed with Velcro straps or styrofoam tool holders could be picked up and properly oriented with the hand where the tether can be attached with the other hand. Thus, one set of anthropomorphic hands could have more capabilities than a whole series of simple exchangeable EEs combined.

An anthropomorphic hand with fingers and palm has several levels of operation which in

essence combine several EEs into one to make this hand truly multifunctional: (i) It has fingernails which can be used for scratching and probing or dispensing adhesive tape to attach items such as heat blankets. Special fingertip inserts could also be used. (ii) Individual fingers serve for precision work and for manipulating small objects where the palm can lean against the object structure for support so that very accurate fine-adjust manipulations can be performed. (iii) Several fingers acting together on the same side increase load capability and, with their flexibility, objects can be hugged. Finger and thumb combined should also be able to handle Velcro straps and heat blankets. (iv) The palm is used for heavy loads where the load is applied near the wrist and may rest at the arm to reduce moments and to increase stability. In this mode, the fingers are used mainly to clamp the object rather than lift it. (v) The thumb can move out of opposition to the fingers. In essence, it can move out of the way so that the hand becomes an open-faced clamping device. This greatly enhances two-handed and bulk-load operations, from the reach of one hand to the reach of two arms. Large loads or partially obstructed objects can be grasped from one side only, without the need for special handles tailored to the grasp of the hand. This feature expands the clamping range from the customary 2-3 inches of a typical EE to 5 feet.

Other advantages are that the smaller size fingers can reach between objects which the current smart hand cannot. Grasping can be done in many different ways due to the hand's flexibility which includes grasping from the side so that object observation by the vision system is not obstructed.

Features such as the previously described compliance, modularity, and glove controller can be incorporated with this hand. (See Section 6.1.2.)

6.2   SYSTEM CONSIDERATIONS

A more advanced EE cannot be an independent development but must be considered as an integral part of the whole system. This section discusses the issues that need to be analyzed in order to create an attuned working system in which the EE is a fitting element.

6.2.1   Interface with Robot Arm

Arm requirements for interfacing the three different types of hands are as follows:

(1) The one-DOF smart hand.

This hand has no compliance and no wrist of its own and would thus not be a good match for the shuttle arm. Without soft grappling capabilities, it probably will never be permitted to be hard mounted onto the RMS. It will require an arm of approximately 3-6 feet in length. With no EVA capabilities, the hand's space use probably will be of the kind described in Section 6.1.1. A PUMA-type arm or, especially for the workbench-vise applications, the PFMA arm could be used. Arm accuracy will be essential for exchangeable EE operations with this type of arm/hand having no compliance.

(2) Multi-DOF EE.

Both specific solutions of this category which will be introduced in Sections 6.3.2 and 6.3.3 are rather large in size. Their primary purpose is as end effectors for the RMS; they can be attached to the shuttle standard end effector directly. They could also be fitted to an arm of about 10-12 feet in length.

(3) The Anthropomorphic Hand.

This hand must have its own specially designed arm for the following reasons:

- The strap-on human arm controller needs an equally proportioned mechanical arm.

- As it already extends to the elbow, only a three-DOF shoulder is needed.

- The same active mechanical compliance that is built into the wrist joint must be built into the elbow and shoulder joints too. The upper arm is thus a relatively small additional development item, using the same type of design as the wrist.

- The shoulder will be designed to fit to its symmetric counterpart for two handed operations. The back will be fitted to the RMS EE grapple fixture.

- For OMV operation, the two arm set-up can be mounted onto a baseplate of the OMV vehicle.

- For operations inside the shuttle or on the space station, a self-propelled robot might be needed which can operate independently of the RMS arm. A free flying robot could take advantage of a variant of the Manned Maneuvering Unit (MMU). In some cases, propulsion by thrusters might contaminate the cargo; therefore the propulsion might take place in the same fashion as the astronauts propel themselves in EVA operations: by using tethers and foot restraints. Actually, no human-like legs are needed; a second set of a two arm-hand configuration as a locomotion device to hold on to tethers and handles works better. This locomotion can be compared to tree-living monkeys that also have a second set of hand-like devices as feet to hold on to branches while moving through the trees.

6.2.2   Hand and Arm Control

(1) Smart Hand.

The one-DOF EE can be controlled by any of the many different control means currently available with or without feedback information or automatic control. The arm for this hand can be controlled by several means, for instance, with a six-DOF position control device including a trigger mechanism for clamping control.

(2) Multi-DOF Hands.

As already noted in Section 6.1.2, multi-DOF hands need the proper control so that each joint can be controlled in an easy to identify and user-friendly fashion. There are five or more hand motions to be controlled simultaneously for the suggested solutions with the joints distributed over several fingers, each having individual motion capabilities. The glove-type controller is suggested and will be further described in Section 6.3.4. In addition to joint motion control, compliance control must be provided. Arm control will be as described above under (1).

(3) The Anthropomorphic Hand.

The hand will be controlled through the glove as the only feasible means until automatic controls become available. Arm control will be through a seven-DOF (including wrist) strap-on harness. This allows control of the whole arm/hand with human inputs by simply performing the motion. This also solves the collision avoidance problem as well as the seventh DOF (redundant) arm joint control. As an alternative, the second arm might receive a four-DOF rate controller (x, y, and z plus seventh-DOF redundant control), positioning the wrist behind the wrist joint. (Note that the glove controller already includes the three-DOF wrist.) The rate controller allows removal of the human arm from the controller to handle control panel controls. Both controllers can be zero adjusted, set for fine motion gains, position re-indexed, and slave motion frozen so that the human arm can be repositioned in a relaxed mode or moved without the slave following. Mode selection for individual groups of joints can also be done so that, for instance, the slave arm is frozen above the wrist while the operator is free to move closer to the display screen and activate the end effector only through the wrist and finger sensing glove. These functions will help prevent operator fatigue.

6.2.3   Summary - System Composition

Summarizing the previous analyses, a system integration can now be done:

(1) The single-DOF EE system.

Its components are:

- Smart hands which might include their own force-torque sensors.

- An exchange mechanism either for the whole hand or just for fingers or fingertips.

- Very complex EE stowage, dock, lock, and tether mechanisms.

- An arm with six or seven DOF which is comparable in size with the hand since this non-compliant hand cannot be mounted directly to the RMS EE.

- A controller.

- A complex tool rack with dock, lock, and tether mechanisms.

6 - 12

- The need to develop several more EEs and different types of fingers.

(2) The multi-DOF hand system.

- The proposed hands could be mounted onto the RMS grapple fixture, in which case they would be stand-alone items without an additional arm. The exchange mechanism under this scenario is the grapple fixture itself.

- Needs an EE stowage bin with dock, lock, and tether mechanisms.

- Alternately, an arm with six or seven DOF could be designed to support the EEs for more precise tasks. The EEs would not be exchangeable in this case.

- A glove-type hand controller is needed.

- Needs tools and very complex tool stowage, dock, lock, and tether mechanisms.

(3) The Anthropomorphic Hand.

- It consists of a hand-arm assembly with mounting plate for symmetric arm accomodations and a grapple fixture mounting for the RMS or OMV.

- Needs a glove-type hand controller.

- Needs an arm-hand stowage location.

- Can be built as a multi-arm system with left and right hands.

6.3   PROPOSED END EFFECTOR SOLUTIONS

This section proposes four specific EE solutions. They will be evaluated in Section 7 to determine the most feasible EE to be built.

6.3.1   Improvements for the OMV Smart Hand

Among the eight suggested improvements discussed in Section 6.1.1, four are of questionable feasibility or effectiveness. They are:

- The creation of an exchange mechanism for the whole EE.

- The automation of the exchange operation.

- Reducing the size of the sensors to make the claws less bulky; this can be implemented whenever smaller sensor heads become available.

- Exchangeable fingertips and inserts; these can be manufactured and incorporated when appropriate applications are defined.

One suggestion is avoided because of some disadvantages:

- The springloaded claws, allowing some self-centering and passive compliance. A redesign of the clamping force sensors would be necessary which introduces other disadvantages (See Figure 6-3).

That leaves only two suggestions for implementation which require minor design modifications. The proposed smart hand solution is thus to use the existing design and incorporate:

- Self-centering in the longitudinal axis (See Figure 6-2).

- Design modifications to allow an easy exchange of the two-finger claws manually, prior to or in-between task executions.

6.3.2 Two Opposing Fingers with Multi-DOF

This hand requires a new development. It is a five-DOF hand with a linear motion for gripper opening adjustments and two DOF per finger for clamping. The clamping direction of all joints is unidirectional, enabling a relatively simple design. Finger and rotational joint actuation, including compliance, is contained in the "finger package" that will be further described in section 6.3.4. The linear motion translates both finger packages toward or from the center to create smaller or larger gripper openings (Figure 6-4).

Modified intermeshing claws (see Figure 6-1) could be used that provide enough internal finger space to incorporate tactile sensors. As an alternative, rotating claw sections of the type described in section 6.3.3 could be used instead.

The hand's features are:

- Two fingers with two DOF each.

- Intermeshing or rotating claws can be used as fingers.

- Linear gripper opening adjustment.

- Exchangeable or add-on fingertips possible.

- Modular design with two finger packages.

- Finger joint compliance which is essential for multi-point object contact.

- Strong clamping capabilities.

- Relatively large size.

- RMS shuttle EE compatible adapter (grapple fixture) on back side.

- No force-torque sensor (uses the FTS soon to be built into the shuttle RMS).

- Clamping force sensing, proximity sensing.
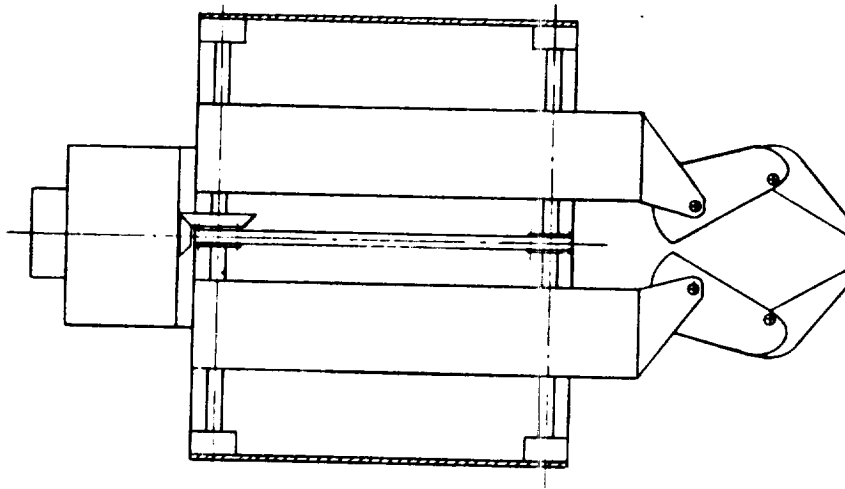
Figure 6-4. Two Opposing Fingers with Multi-DOF

Even though this EE has certain advantages over the OMV hand, some basic disadvantages remain:

- No manipulative capabilties.

- Accurate fine positioning is impossible since it depends on the 50-foot RMS arm.

- It needs a complex tool rack with proper tool orientation, as well as docking, locking, and tethering mechanisms.

- It has no compliance with respect to rotational misalignments which is a potential problem if such things as bar-handles are grabbed with the uniformly concave inside section of the fingers. Large moments will result where something will yield! If the grasped object is free floating, it will have a tendency to rotate to align to the groove. As previously stated, an EE without soft grasping capabilities in all directions might not be permitted to be hard mounted to the RMS since it negates the RMS soft grasping capabilities.

<u>Option</u>:

Since soft grappling is needed if it is used as an RMS hand, an expanded design could be chosen that incorporates active mechanical compliance in the remaining directions, which are two rotational axes and one linear direction. In essence, this requires the construction of a section between EE and arm that provides compliance for the EE. This design, though, would become as complex as a dexterous hand and is thus not recommended.

A controller with at least six DOF is needed for proper hand control. The functions are: two fingers with two DOF each, claw opening, and compliance control. Depending on how many active compliance controls the hand will have, additional DOF might be used for individual compliance control.

6.3.3 Four Fingers in Circular Arrangement

This hand features 10 or more DOF with the following functions (Figure 6-5):

- Four finger packages with two DOF each. Closing motion direction is toward the gripper's roll axis.

- Simultaneous linear gripper opening adjustment (one DOF) toward/from the roll axis.

- Longitudinal motion capability with compliance. This feature enables a very important capability, illustrated by example: In a screw removal operation, the hand could hold a screwdriver and apply a selective force in the forward direction (toward the screw), while the hand simultaneously moves backwards, yielding to the unscrewing screw. This operation can easily be automated by servoing for a constant press-on force.

- Roll motion of the whole EE might also be built-in.

The primary advantages of this design versus the solution discussed in Section 6.3.2 are:

- It has four fingers, allowing grasp of a workpiece in different directions for a better hold.

- The clamping surfaces of two opposing claws can translate laterally or rotate in pairs to accommodate slight misalignments without the need to readjust the arm position. The lateral alignment can be done manually by joystick if fiber-optic vision is provided from the center of the gripper, or even automated if proximity sensors detect the off-center distances of the objects.

- The hand can be used on the RMS directly because it has soft grappling capabilities. The hand could be designed either to be grasped by the standard RMS end effector, or as a replacement for the standard RMS EE.

  If the hand is built as an alternative EE for the RMS, it could mount directly to the soon-to-be-built RMS force/torque sensor (FTS), eliminating the need to use a grapple fixture. Designing the FTS and EE together would allow an improved interface design that would result in much better FTS accuracy. Also, this new hand could secure itself
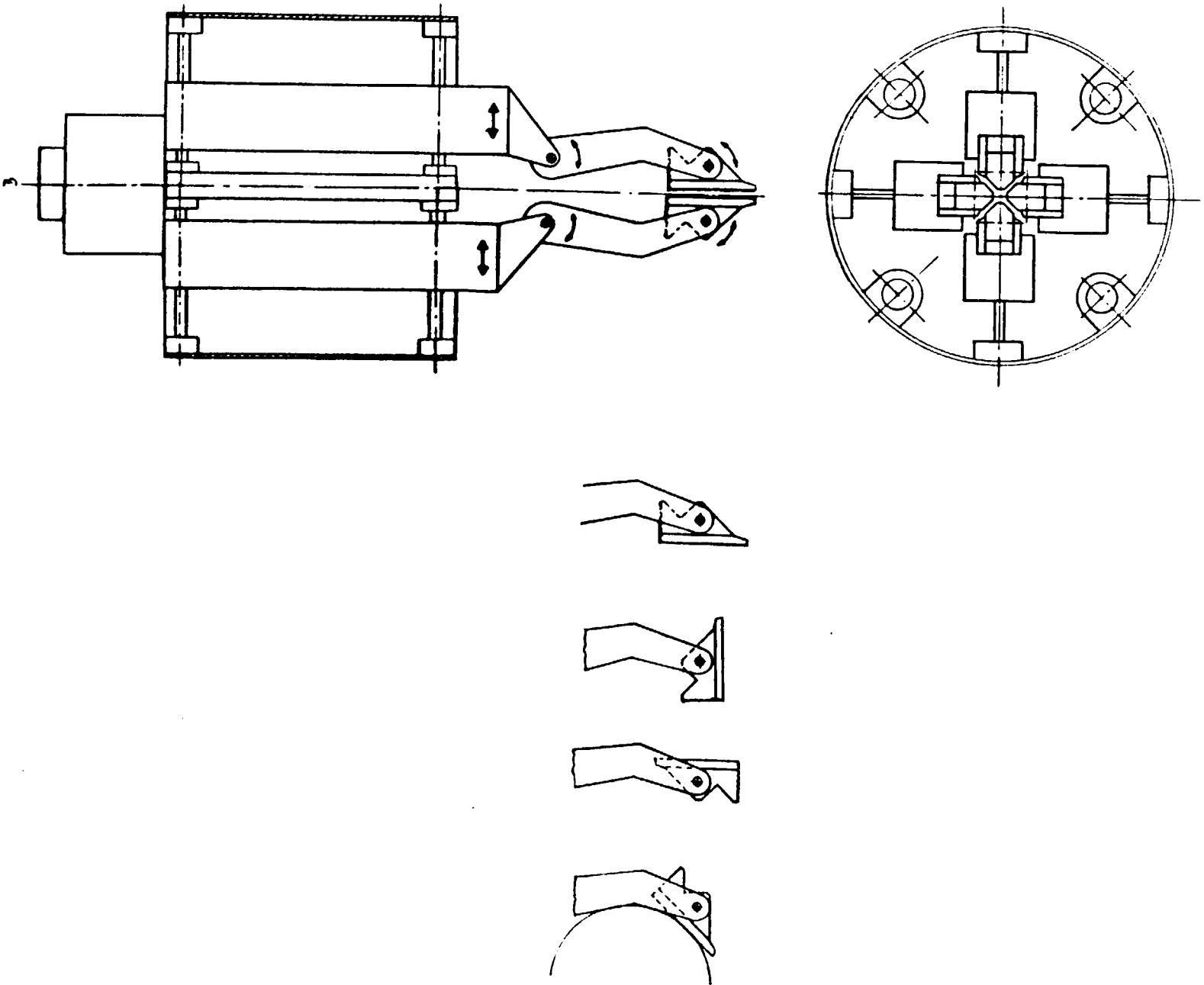
Figure 6-5. Four Fingers in Circular Arrangement

6 - 17

during launch with its claws, thus effectively solving the launch vibration problem. (In the expected near term installation of the FTS into the RMS, the existing EE is cantilevered so that the FTS is required to provide structural stability. This, in turn, renders the FTS unusable for accurate measurements and for measurements of small loads.)

The New Finger Design

Foreseen is a rotating front section (second digit) as can be seen in Figure 6-5. Depending on the orientation of the claw, there are four possible clamping options:

(1) Small object clamping. This orientation allows closing the claws to a near zero center opening gap. Protruding (sharp tip) front ends allow access to recessed parts in small areas. The claw arrangement can be compared to a lathe chuck. Its use is for holding small, round parts in the axial direction.

(2) Large object clamping. By rotating the front section 90° from the above orientation, large face clamping surfaces are facing inward to grasp large size objects.

(3) Concave surfaces. Rotating the front section another 90° aligns concave surfaces that work better for clamping spherical parts or cylinders in a sideways orientation where one opposing pair of claws will do the clamping.

(4) In addition to using the second digit as clamping claw, the whole finger can be used to hold an object with at least two contact points per finger.

A glove-type finger controller (to be described in Section 6.3.4) should be used to control the four independent fingers with two DOF each. In addition, the thumb can control gripper opening adjustment and forward motion. The lateral knuckle joints would be used for compliance control in the rate control mode. A control function that moves all four fingers or two opposing fingers simultaneously will also be provided.

Due to different control modes and non-conforming shape between master and slave, additional control devices, such as joysticks, will be needed so that the most efficient control mode can be chosen for each operation. Centering operations which align opposing claw pairs can best be done with a joystick or even automated if the necessary sensing is provided. It should be noted: The control of this hand could prove to be extremely complicated!

Other important design considerations are:

- Compliance.

- Modularity in design.

- Rotating finger linkages with different clamping surfaces for multifunctional grasping.

- RMS EE compatible adapter (grapple fixture) on back side, or direct mounting to the RMS force/torque sensor.

- Needs no exchange mechanism if used directly on the RMS or any other arm.

- Needs no arm.

- Has clamping force and proximity sensing.

- Can incorporate forward-looking vision (fiber optic camera head or proximity sensors) in the center axis of the gripper.

- Forward facing tools, especially rotational devices, can be handled better.

- Some centering and fine adjustment capabilities.

- Strong clamping capabilities.

- Two to four finger operations possible.

- Bulky, large size.

- No full limber arm control due to lack of wrist.

- The hand has no manipulative capabilities.

- Requires complex hand design.

- No wrist sensor, the RMS force/torque sensor is used.

- May obstruct the global vision system.

- Overload release mechanism.

- Consistent with automation.

- In a two arm configuration, the EE could be used together with a dexterous hand.

- As an RMS EE, the cylindrical shell containing the finger packages could serve as mounting platforms for a set of two anthropomorphic arms that would do the EVA work where this EE would hold the bulk load (i.e., satellite) in combined operations.

6.3.4   The Anthropomorphic Hand

The general features of the anthropomorphic hand include (Figure 6-6):

- Proportional to human hand, with fingernails, four-DOF fingers including two-DOF knuckle joints, a four-DOF thumb, palm, three-DOF wrist, and elbow.

- Active mechanical compliance at nearly every joint.

- Joints can be sealed to keep contaminants out.

- Modular finger packages.

- Exchangeable fingertips with exchange operation done by the other hand.

- Finger packages developed for left- or right-hand thumb compatibility so that a left hand can be built from the same finger packages.

- Thumb can be rotated out so that an open hand configuration is formed.

- Finger actuation located in forearm.

- Wrist actuators near the elbow for weight balance.

- Each joint is directly controlled by one motor alone with no coupling to other drives. Thus, the hand can be directly operated (joint to joint) from the glove controller, without the need for significant time delaying computer computations and coordinate transformations.

- Clamping force is adjustable.

- Overload release mechanisms at every joint.

- Sensors located throughout the hand.

- Can bring a camera and lights to the working area and orient them properly for close-up inspection even when the other hand performs other tasks.

The Controller

The glove-type hand controller is an integral part of the dexterous hand development, to be used for direct control in teleoperation mode, and as a computer input device. Preliminary evaluations have shown the feasibility of this type of device. The capability to direct a dexterous hand to the finger joint level and receive feedback at each finger would certainly be considered a hand control breakthrough. Features of the controller include:

- Glove-type slip-on device for short set-up times.

- Resolution to the finger joint level with control capabilities of up to 23 DOF (including wrist) simultaneously.

- Position sensing at each finger joint.

- Force input sensing for compliance control.

- Position feedback to most joints.

- Tactile feedback of one point per link.

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- Has easy to understand feedback right in the hand, not distracting the operator's attention to the vision feedback system.

- Three-DOF wrist position sensing.

- Wrist position feedback.

- Arm motion sensing harness can be attached.

- The whole control glove and harness and its computer control will require very little volume in the space shuttle flight deck.

Some advantages of this master/slave arrangement are highlighted below:

- Dexterous, manipulative capabilities.

- Tool pick up and orienting capabilities.

- Can use off the shelf tools.

- Can "hug" objects rather than just rely on clamping forces.

- Can reach into smaller spaces.

- Can exchange fingertips using a second hand of the same type.

- Can grasp objects in different modes.

- No prior shape detection required.

- Has multiple levels of operation: fingernails, finger(s), palm, arm surface, two-armed operations.

- Off-line repair possible with exchangeable packages.

- On-line exchange of individual finger packages with the other hand may prove feasible.

- Spare finger packages will be available.

- Hybrid control of force or position.

- Compliant force control with adjustable strength might allow very delicate tasks such as cleaning telescope mirrors.

- The capability to loosen up on joint stiffness will provide the necessary looseness to align a slightly misaligned part to its mate, thus enabling assembly operations.

- Arm compliance enables two-handed operations.

- Clamping force can be maintained indefinitely without additional power supply due to the springloaded and self-locking mechanisms.

- Direct teleoperation control.

- Human factored natural control in which the operator simply performs the motion.

- Human brain can easily relate to this shape for control.

- Reduced operation learning time required.

- Glove can be used in teaching mode to teach the controller basic motions to be recalled by voice commands.

- Automation feasible.

The proposed hand would have a thumb and three fingers since analyses showed that two fingers can do roughly 40% of all hand tasks, three fingers 90%, and four fingers 99% [21]. This shows that adding the little finger would not contribute much.

Automation

Automation features for routine tasks and selected advanced hand operations will be built into the controller to enhance the system's capabilities.

Preprogrammed sequences (robotic tasks). The hand-arm controller allows recording of manipulator motions in a simple, fast, and user-friendly fashion. The hand's feedback enables one to monitor the repetitive autonomous manipulator motions and allows some corrective action.

Automation aids (canned hand motions). The glove serves as a teaching device to teach the controller complex hand motions or small sequences of motions. Executing those functions could be through voice commands with, for example, nouns and modifiers (see Table 6-1).

Automated tasks. Compliance will open the way for automating many hand functions. The most obvious is that the hand can be commanded to close over an object and will align itself to the shape of the object through its fingers and to the orientation of large objects through wrist and arm compliance. Programming for grappling is thus minimized and greatly simplified since the controller reads the configuration of its manipulators through its sensors rather than aligning them through very extensive programming efforts.

Noun	Modifier I	Modifier II
Mode	Manual function, sequence	Start, reset, correct
Control	Position	Touch, hold, release
Hand	Force	Strength increase/decrease
	Close, clamp, pinch	Clamping force
	Grab object, align	Sphere, cylinder, flat surface
Thumb	Move, scan	Direction, distance, over surface
Joint #	Rotate	Direction, amount

Sample Command Sequences

Table 6-1
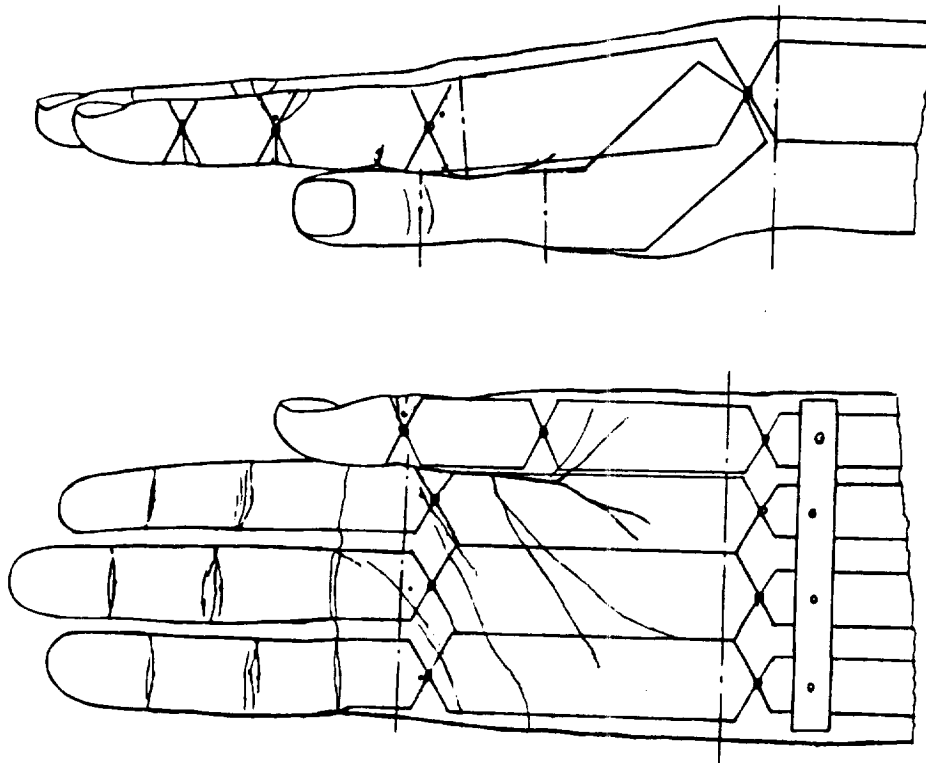
Figure 6-6. Anthropomorphic Hand

6.3.5 Dexterous Hand (Simplified Anthropomorphic Hand)

The space shuttle has an immediate need for an EE to handle loads without having to resort to the cumbersome grapple fixture. The dexterous hand (DH) alternative is presented as an

intermediate end effector with some of the characteristics of the anthropomorphic hand.

The dexterous hand uses a simplified anthropomorphic hand with only two fingers with two DOF each, the fingers being of a simpler design and having no manipulative capabilities. The thumb will have three or four DOF; it has manipulative capabilities and can move out of the way to form an open EE. The palm and the three-DOF wrist will remain as before. The hand will be mounted on a support system similar to that of the end effector with four fingers in circular arrangement; this includes axial motion capabilities and thus needs no arm development. The DH in essence is a combination of a simplified anthropomorphic hand mounted on the support of the four-fingered hand.

The general advantages are as follows:

- Quicker implementation possibilities; further, the EE needs no arm development.

- It has full limber arm control capabilities similar to the currently practiced RMS grappling procedure for safe load handling. This makes it ideal for use with the RMS.

- The development is an intermediate step between the current smart hand and the more capable anthropomorphic hand. With this DH, invaluable experiences on earth and in space could be gained in an early experiment; its evaluation would aid the subsequent construction of the anthropomorphic hand.

There are also some distinct advantages over the circularly arranged hand:

- It has a wrist, allowing much greater flexibility which is essential for operations with the 50-foot RMS arm as well as for aligning and working in constrained spaces.

- The hand is still proportional to the human hand and can thus be directly controlled through the glove controller. Thus, it does not have the control problems of the four fingers in circular arrangement.

- It has some dexterity, allowing more complex operations than just clamping objects. It could be a supplementary EE for the RMS where the current EE handles the big loads, the DH, smaller ones.

The hand is depicted in Figure 6-7. It has most of the functions described in the previous section, including compliance. There are up to 13 DOF: the two fingers have two DOF each, the thumb, three or four. The wrist has three DOF and the hand assembly can also translate in the axial direction. Fine adjust movements for sidewise or up and down motions can also be provided, adding two more DOF.

The controller is the same as for the anthropomorphic hand, but with additional features controlling the translational motions.

Figure 6-7. Dexterous Hand
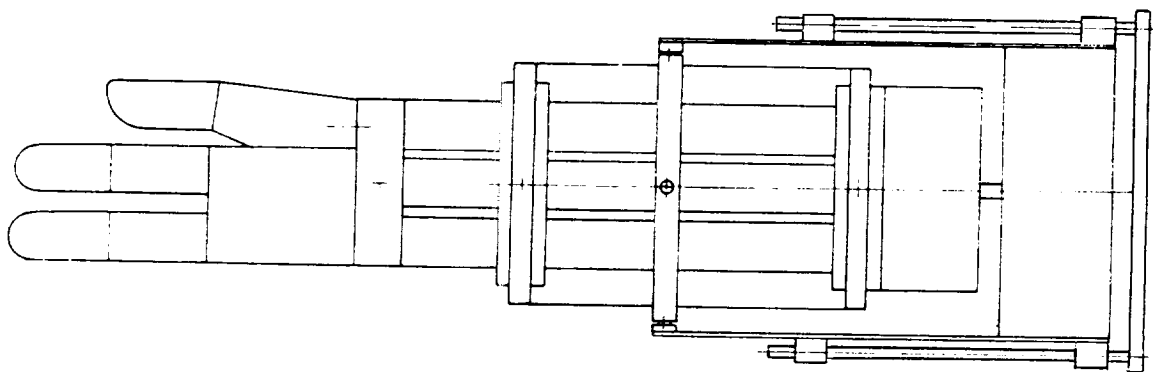
SECTION 7

EVALUATION OF ALTERNATIVE DESIGNS

Due to the disparate requirements for end effector systems intended primarily for fine manipulations or gross load handling, we have chosen to perform two evaluations. The first evaluation, called "EVA Substitution," considers alternative end effectors intended to perform tasks otherwise requiring EVA. These EEs would require an appropriately scaled manipulator arm. The second evaluation looks at end effector configurations that can be used with the RMS arm.

7.1   EVALUATION MODEL

For both evaluations we have employed a simplified multi-attribute value model, sometimes called a "relevance tree." The evaluation criteria for the two evaluations are listed in Figures 7-1 and 7-2, accompanying sections 7.2 and 7.3.

Each of the major evaluation categories has been assigned an appropriate weight representing its overall importance. In weighting the categories, we have placed heavy emphasis on performance (the Function Performance and Task Performance categories combined have a 50% share of total weight). This is consistent with the intent to have teleoperators and telerobots substitute for EVA. Factors related to performance quality have been grouped together as "System Attributes" and given the next highest weight (20%). The other categories are Useability, Robustness/Complexity, and Development Cycle Factors, which have a total combined weight of 30%.

Each criterion within a major category has been assigned equal weight, representing equal importance. A value scale, ranging from 0 to 4, has been defined to evaluate the alternatives against the criteria (see Table 7-1). The values within a category are summed and normalized. The overall rating of a particular end effector is the sum of each normalized category value times its corresponding weight factor.

4	Excellent
3	Good
2	Fair
1	Poor
0	None, no capability

Generic Evaluation Scale

Table 7-1

The relevance tree model has been chosen as appropriate because the alternative EE systems have been defined only at a conceptual level. The uncertainties inherent in the evaluation of conceptual designs does not warrant the additional complexities of a more rigorous model. A more complex model would simply cloak the evaluation results in an illusion of precision.

7.2   EVA SUBSTITUTION EVALUATION

The categories and evaluation criteria for the EVA substitution evaluation are listed in Figure 7-1.

7.2.1 Description of End Effectors to be Evaluated

The alternatives to be evaluated are summarized in Table 7-2. These have been pre-selected as representative of the discussion in Section 6. The evaluation of the EVA substitution end effectors assumes that each is mounted on a manipulator arm of approximately 3 to 6 feet in length. The alternatives are described briefly below:

(1) Improved OMV Hand and Variants (OMV)

OMV-A. The basic model considered here is the single-DOF smart hand with intermeshing claws that is currently under development at JPL. The hand has a force/torque sensor at the base and proximity sensors in the claws or "fingers." We also assume manually exchangeable fingers which incorporate some sensors (e.g., proximity sensors).

OMV-B. The first variation on this design is the addition of manual (astronaut) exchange capability to the basic model. The evaluation assumes there would be three EEs available; one would be equivalent to the OMV-A, with one smaller and one larger.

OMV-C. The second variant upgrades manual exchange to automatic exchange capability. We have assumed five EEs for this option. Three EEs correspond to those for OMV-B, namely intermeshing claws of various sizes. The remaining two EEs are special purpose devices for such tasks as soldering and polishing.

Each of the exchangeable designs allows for replacement of failed units and development of similar but complementary EEs. Multiple end effectors require stowage facilities for the EEs not in immediate use, thus increasing system volume and mass.

(2) Two Opposing Fingers with Multi-DOF (2F)

The models in this category have five DOF. Both have two fingers, each with two DOF. The fifth DOF is in the form of linear lateral translation at the base of the EE; this provides for changing the overall distance between the two fingers. Force/torque sensing can be included in this design. Each design permits manually-attached fingertip add-ons.
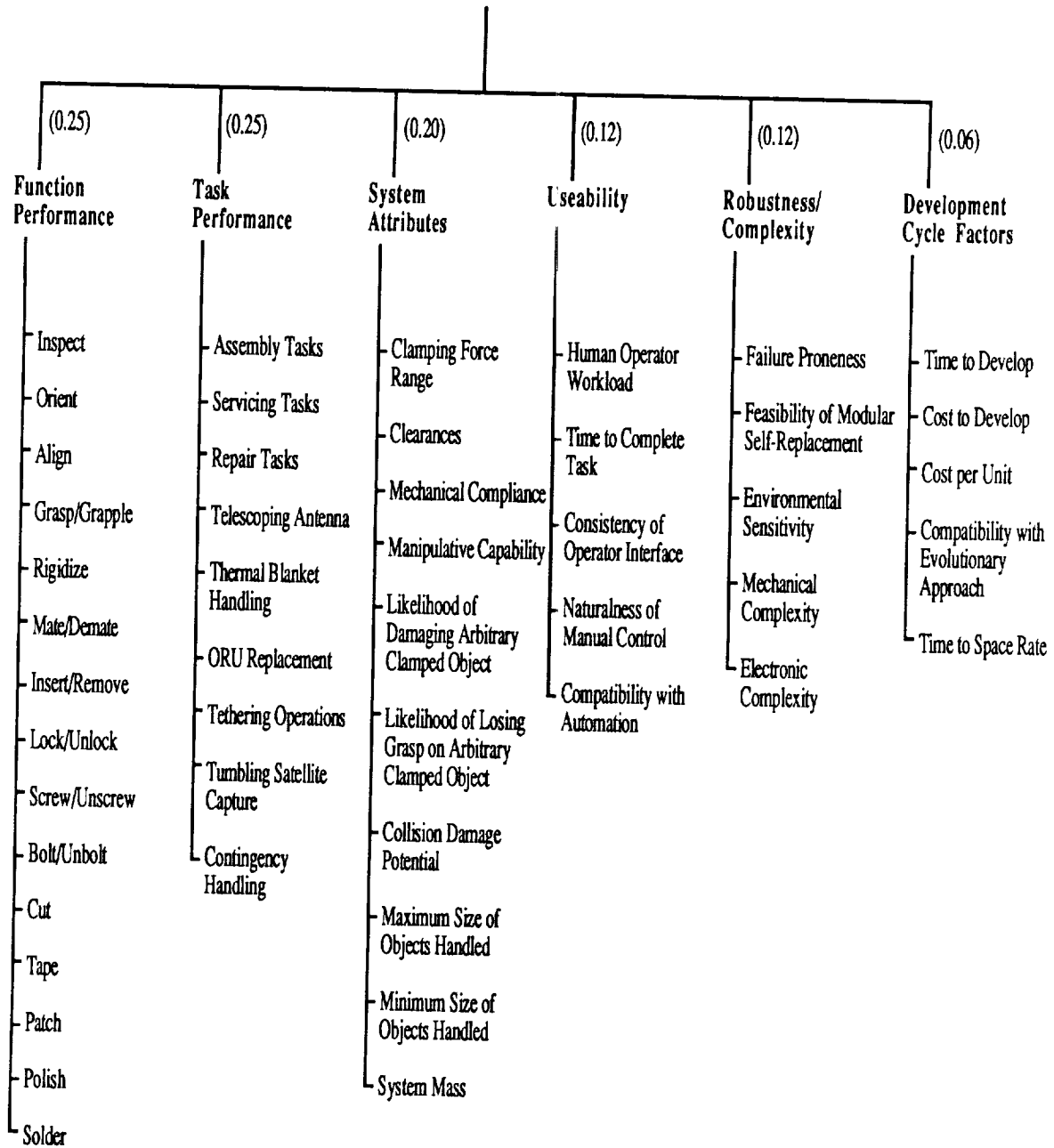
Figure 7-1. EVA Substitution End Effectors Evaluation Criteria

EVA Substitution End Effectors

(0.25) Function Performance
- Inspect
- Orient
- Align
- Grasp/Grapple
- Rigidize
- Mate/Demate
- Insert/Remove
- Lock/Unlock
- Screw/Unscrew
- Bolt/Unbolt
- Cut
- Tape
- Patch
- Polish
- Solder

(0.25) Task Performance
- Assembly Tasks
- Servicing Tasks
- Repair Tasks
- Telescoping Antenna
- Thermal Blanket Handling
- ORU Replacement
- Tethering Operations
- Tumbling Satellite Capture
- Contingency Handling

(0.20) System Attributes
- Clamping Force Range
- Clearances
- Mechanical Compliance
- Manipulative Capability
- Likelihood of Damaging Arbitrary Clamped Object
- Likelihood of Losing Grasp on Arbitrary Clamped Object
- Collision Damage Potential
- Maximum Size of Objects Handled
- Minimum Size of Objects Handled
- System Mass

(0.12) Useability
- Human Operator Workload
- Time to Complete Task
- Consistency of Operator Interface
- Naturalness of Manual Control
- Compatibility with Automation

(0.12) Robustness/ Complexity
- Failure Proneness
- Feasibility of Modular Self-Replacement
- Environmental Sensitivity
- Mechanical Complexity
- Electronic Complexity

(0.06) Development Cycle Factors
- Time to Develop
- Cost to Develop
- Cost per Unit
- Compatibility with Evolutionary Approach
- Time to Space Rate

7-3

2F-I. The first version has intermeshing claws at the ends of the finger packages, which allow for proximity sensing, similar to those in the OMV hands.

2F-R. The second model instead has rotating claws on the finger packages, as used in 4F. Proximity sensing can be incorporated as well.

(3) Four Fingers in Circular Arrangement (4F)

4F. This design possesses 10 or more DOF: two DOF for each of the four fingers, one linear DOF for forward position adjustments, plus one DOF for combined claw opening adjustment in the radial direction. Additionally, wrist rotations could be considered. The EE relies on finger packages with rotating claws, for which manual fingertip add-ons are feasible. Force/torque and proximity sensors are feasible, as in the other designs. The center of the gripper could accommodate a fiber optics camera front-end.

(4) Anthropomorphic Hand (AH)

AH. The anthropomophic hand is very similar in configuration to a human hand. The hand to be evaluated has three fingers and a thumb. To incorporate the actuators, this "hand" extends to the elbow, and includes a total of 20 active joints (four in each finger and thumb, three in the wrist, one in the elbow), plus compliance control. The hand has force, position, compliance, and several single-point tactile sensors. Assuming the existence of a second arm-hand arrangement, the hand supports teleoperated fingertip exchanges.

Alternative Designation	Base Design	Options
OMV-A	Improved OMV Hand	
OMV-B	Improved OMV Hand	Manual EE exchange (with 3 end effectors available)
OMV-C	Improved OMV Hand	Automatic EE exchange (with 5 end effectors available)
2F-I	2 Opposing Fingers, Multi-DOF	Intermeshing claws
2F-R	2 Opposing Fingers, Multi-DOF	Rotating claws
4F	Four Fingers, Circular Configuration	
AH	Anthropomorphic Hand	

Summary of End Effector Alternatives - EVA Substitution

Table 7-2

7.2.2 EVA Substitution Results

The values found for each EE criterion are listed in the tables in Appendix B. The evaluation results are summarized in Table 7-3.

The anthropomorphic hand (AH), with an index of 2.70, is by far the highest ranked alternative. Table 7-3 shows that this hand is strongest in just those areas of the greatest importance: function performance, task performance, and system attributes.

Alternatives

Categories	Weights	OMV Hands			Two Opposing Fingers		Four Fingers	Anthro-pomorphic
		OMV-A	OMV-B	OMV-C	2F-I	2F-R	4F	AH
Function Performance	0.25	1.13	1.47	1.73	1.33	. 1.47	1.87	2.87
Task Performance	0.25	0.89	1.11	1.44	1.33	1.56	1.78	2.67
System Attributes	0.20	1.30	1.90	1.80	2.00	2.20	2.40	3.20
Useability	0.12	3.20	1.40	2.20	2.20	2.20	2.40	3.00
Robustness/Complexity	0.12	2.80	2.60	1.00	2.00	2.00	1.80	1.60
Development Cycle Factors	0.06	3.20	2.40	1.20	2.20	2.20	1.80	2.00

Overall Rating

Σ weight x value:	1.68	1.65	1.61	1.70	1.83	2.00	2.70

EVA Substitution End Effectors - Evaluation Summary

Table 7-3

Since this end effector evaluation was geared to substitution for EVA, the authors performed a rough ranking of an EVA astronaut using the same evaluation model. The evaluation was necessarily rough, since many of the criteria cannot be applied directly to an astronaut. In several cases the evaluation scale was extended to 5 to encompass a human being's additional capabilities. The hypothetical astronaut's rating was 3.8; this places an astronaut roughly as far above the anthropomorphic hand as the anthropomorphic hand is above the current state-of-the-art smart hand. This is not surprising, considering the astronaut's integrated control and sensor systems, and general adaptability. Noteworthy, however, is the fact that two-thirds of the functional capability gap between the current technology and human EVA capability can be closed by a single development effort, by producing an anthropomorphic hand.

These results will be discussed further in Section 8.

7.3 RMS END EFFECTOR EVALUATION

The categories and evaluation criteria for the RMS configured EEs evaluation are listed in Figure 7-2.

7.3.1 Description of End Effector Configurations to be Evaluated

The end effector (and arm) designs evaluated below have been selected as potentially effective when configured with the RMS manipulator arm. Most of the alternatives discussed in the EVA substitution evaluation are inappropriate for use with the RMS in their original form. Some have been modified for inclusion in this evaluation.

Note that the first end effector (STD) is the currently used RMS EE. As such, it automatically ranks quite high in the "Development Cycle Factors" category, since the develoment cycle is already complete. This has a tendency to inflate the overall rating of this alternative relative to the proposed options.

Each of the designs that are grappled by the RMS standard EE is mounted on the RMS grapple fixture and is assumed to receive power and communicate through the Special Purpose End Effector electrical connector. We have assumed that mating and demating of the electrical connectors are reliable operations.

The five RMS configured alternatives are listed in Table 7-4, and described in the following paragraphs:

(1) Existing RMS End Effector with Force/Torque Sensor (STD)

This design is the current Standard End Effector in use on the space shuttle RMS. We have assumed that it has been outfitted with the JPL wrist-located force/torque sensor (currently scheduled for flight testing in 1991). This EE was not designed to be multifunctional; its sole purpose is to grasp a specially-designed grapple fixture that has been previously mounted on satellites, astronaut restraints, etc. However, it is the only existing teleoperator end effector for space operations.

RMS Configured End Effectors

(0.25)	(0.25)	(0.20)	(0.12)	(0.12)	(0.06)
Function Performance	**Task Performance**	**System Attributes**	**Useability**	**Robustness/ Complexity**	**Development Cycle Factors**

Function Performance
- Inspect
- Orient
- Align
- Grasp/Grapple
- Rigidize
- Mate/Demate
- Insert/Remove
- Lock/Unlock
- Screw/Unscrew
- Bolt/Unbolt
- Cut
- Tape
- Patch
- Polish
- Solder

Task Performance
- Assembly Tasks
- Servicing Tasks
- Repair Tasks
- Telescoping Antenna
- Thermal Blanket Handling
- ORU Replacement
- Tethering Operations
- Tumbling Satellite Capture
- Contingency Handling
- Auxiliary Equipment Holding Capability
- Bulk Item Holding (e.g., grapple, EVA platform)

System Attributes
- Clamping Force Range
- Clearances
- Mechanical Compliance
- Manipulative Capability
- Likelihood of Damaging Arbitrary Clamped Object
- Likelihood of Losing Grasp on Arbitrary Clamped Object
- Collision Damage Potential
- Maximum Size of Objects Handled
- Minimum Size of Objects Handled
- System Mass
- Necessary Volume for Control Station
- Danger to EVA Astronaut
- Obstruction at Worksite for EVA Astronaut
- Power Consumption
- FTS Precision Capability
- Launch Restraint Requirement
- Enhanced Multifunctionality through Multiple Grippers

Useability
- Human Operator Workload
- Time to Complete Task
- Consistency of Operator Interface
- Naturalness of Manual Control
- Compatibility with Automation

Robustness/ Complexity
- Failure Proneness
- Environmental Sensitivity
- Mechanical Complexity
- Electronic Complexity

Development Cycle Factors
- Time to Develop
- Cost to Develop
- Cost per Unit
- Compatibility with Evolutionary Approach
- Time to Space Rate

Figure 7-2. RMS Configured End Effectors Evaluation Criteria

7-7

(2) Four Fingers, Grappled by Existing End Effector (STD+4F)

This is essentially the "Four Fingers in Circular Arrangement" option. Its design includes an RMS grapple fixture on the back of the end effector mounting plate. The EE is exchangeable in the sense that it can be picked up by the RMS end effector (STD), used as an extension of the RMS, and then set down. This EE may rely on the JPL force/torque sensor at the RMS wrist for force/torque feedback.

(3) Anthropomorphic Manipulator Arms, Grappled by Existing End Effector (STD+2AH)

This design builds on the anthropomorphic hand (AH) design up to the elbow and adds upper arms with three-DOF shoulders. Two symmetrical hand/arms are mounted onto an RMS grapple fixture from the back of the shoulders. The entire arrangement is grasped by the RMS end effector (STD).

(4) Dexterous Hand, Grappled by Existing End Effector (DH)

This hand consists of a simplified AH mounted on the support of the 4F hand which in turn is mounted to a grapple fixture that is grasped by the RMS EE.

(5) Four Fingers plus Anthropomorphic Manipulator Arms (4F+2AH)

The Four Finger End Effector just described in (2) is combined with two anthropomorphic hand/arms. In this arrangement, the Four Finger EE can hold an object in place while the anthropomorphic hands manipulate the object.

Alternative Designation	Description
STD	Existing RMS End Effector with force/torque sensor
STD+4F	Four Fingers, grappled by existing EE
STD+2AH	Anthropomorphic Manipulator Arms, grappled by existing EE
DH	Dexterous Hand, grappled by existing EE
4F+2AH	Four Fingers plus Anthropomorphic Manipulator Arms

Summary of End Effector Alternatives - RMS Configuration

Table 7-4.

7.3.2 RMS Results

The values found for each criterion are shown in the tables in Appendix B. The results are summarized in Table 7-5.

The alternative built of three end effectors, one of four fingers circularly arranged and two of anthropomorphic design (4F+2AH), was rated most highly. As with the EVA substitution evaluation, this option was strongest in performance and weakest in reliability and development areas.

The ratings of all RMS configured end effectors are shown in Table 7-5. Note that the current RMS end effector has the greatest robustness and highest development cycle rating. These strengths arise from the fact that the effector is already extant (introducing a bias in its rating), and from a relative simplicity of design that results in the lowest performance rating.

The results of the evaluation will be interpreted, and recommendations made, in Section 8.

	Weights	**Alternatives**				
Categories		STD	STD+4F	STD+2AH	DH	4F+2AH
Function Performance	0.25	0.73	1.20	2.47	1.40	2.87
Task Performance	0.25	0.55	1.00	2.36	1.18	3.09
System Attributes	0.20	2.41	2.35	2.18	2.24	2.47
Useability	0.12	2.80	2.60	2.60	2.80	2.40
Robustness/Complexity	0.12	4.00	2.75	2.00	2.50	1.50
Development Cycle Factors	0.06	3.40	2.60	1.40	3.00	1.60

Overall Rating

	STD	STD+4F	STD+2AH	DH	4F+2AH
Σ weight x value:	1.81	1.85	2.28	1.91	2.55

RMS Configured End Effectors - Evaluation Summary

Table 7-5

SECTION 8

EVALUATION INTERPRETATION AND RECOMMENDATIONS

8.1 INTERPRETATION OF EVALUATION RESULTS

8.1.1 EVA Substitution

The anthropomorphic hand has been evaluated as the best EE system for EVA substitution. It is the most complex of the EEs, but also the most functionally capable. The anthropomorphic hand is the only alternative suggested that possesses full manipulative capability, which is mandatory for completing EVA tasks in realistic time frames. Clearly, an end effector that moves like a human hand, and can be controlled by analogous motions of a human hand, is likely to be well-equipped to do the work of a human hand.

Conclusions pertinent to this hand are:

- A dexterous hand is needed in order to perform EVA tasks. The AH and DH hands are the only alternatives evaluated that can be classified as dexterous hands. Other dexterous EEs can be imagined and will come into existence once AI control is developed. They will have a comparable number of DOF, but are without the built-in human control simplification of the anthropomorphic and simplified anthropomorphic hands.

- The anthropomorphic and simplified anthropomorphic hands are the only configurations capable of advanced manipulations that are inherently consistent with the glove-type controller. The glove controller will be adaptable to other dexterous hand designs, but this will require additional development effort.

- Even though much effort is undertaken to control common EEs through advanced computer methods and AI, those methods are still years away from controlling even simple tasks, whereas contingency operations will have to be controlled by a human in the control loop for an even longer time. Thus, the AH is currently the only real choice for advanced manipulations: having an AH where the operator simply performs the desired motion manually is bringing the state-of-the-art of man-machine interfaces and teleoperations to a never-before-achieved level. Limited and canned automation tasks are aided by the built-in compliance control and the glove as a control input device. Other automation features can always be incorporated into the hand as they become available.

- The AH scored consistently higher than the other hands in all major categories, clearly demonstrating its capabilities beyond the mere clamping and grasping of objects.

- The anthropomorphic hand combines what would otherwise be several EE constructions into one development. Thus, this design is more capable and should be more economical and cost effective in the long run than the alternative of developing exchangeable end effectors, and their auxiliary equipment.

- Tool usage through the AH will further enhance the hand's overall capabilities.

8-1

General conclusions from the analysis of EVA substitution evaluation include:

- Two-fingered hands rated the lowest which shows that they are not sophisticated enough for multifunctional EVA tasks.

- The final score clearly reveals that exchangeable EEs or any exchangeable parts are just not worth the effort. The more sophisticated hands will have the capabilities to handle special purpose equipment without exchangeability needs.

- Very critical are the aligning and grappling capabilities, calling for a combination of the following elements: good wrist motion capabilities, an arm that is appropriate to the EE, compliance, and dexterity.

- The 4F hand has some advanced functions and task capabilities well above the two-fingered hands and could be utilized well in a variety of special tasks. Its overall rating is second, behind the AH. It certainly warrants further consideration.

- Several multi-DOF dexterous fingers together with compliance clearly enhance multifunctional capabilities. Current robots are limited to pick and place operations because of the limitations of their EEs. The above mentioned attributes could break through this barrier!

Employing telerobots will be necessary for EVA activities and space station work in the 90s, which in turn depends on the availability of a space robot hand capable of EVA activities. It is therefore essential that the EVA capable anthropomorphic manipulator is developed now since its deployment will require several years of development effort. It will then be available and ready for use in the 90s, during early space station operations.

A word of caution: It would be very foolish to seek a simpler solution than the best one due to fiscal and time constraints. Reality would soon reveal that a simpler hand is not capable of achieving its intended purpose, could not bring relief for EVA operations, and might be so cumbersome to use that nobody would want to take it into space. This would mean that much of the effort and its fundings would be wasted and new grants would have to be provided to do what should have been done in the first place. We strongly recommend taking the extra step needed to create the hand that will do the work. Its development already pays off by not having to develop all the auxiliary equipment needed with simpler hands.

8.1.2 RMS Configuration

The highest rated alternative (4F+2AH) among the RMS configured end effector systems actually has three EEs. It includes two anthropomorphic manipulator arms for fine manipulations, and a four-fingered hand in circular arrangement for less dexterous gripping tasks. The 4F EE attaches to the RMS or might be on a separate arm where all three EEs mount on a baseplate that attaches to the grapple fixture. This combination has many of the characteristics of the smart front end proposed for the OMV. This is not surprising, considering the similarity in tasks to be performed and the constraints imposed by the RMS.

This alternative allows objects to be grappled (by whatever combination of the three end effectors is appropriate). A grappled object can then be rigidized to the work site by the non-anthropomorphic EE, so that the anthropomorphic arms can perform precision operations on the object without significant concern for the dynamics of the 50-foot RMS. The two anthropomorphic arms can work cooperatively, carrying out tasks otherwise infeasible.

This alternative (or even a further extension to four anthropomorphic arms) can be viewed as an outgrowth of the anthropomorphic hand, providing the environment in which the hand can best perform EVA substitution tasks. As such, the alternative is quite complex, and we do not envision it as the initial incarnation of an anthropomorphic EE system.

An early experiment could be done with either the full AH or the simplified AH as described under the dexterous hand (DH). It would push the state-of-the-art of dexterous hand capabilities, provide an early experiment, and the evaluation of it could significantly improve the full anthropomorphic arm development.

Among the general conclusions from the RMS EE evaluations are:

- The standard RMS EE's strengths lie in its capabilities to handle big loads.

- An EE capable of precise small load handling is needed but must be built on an arm comparable in size to the new EE. Manipulating the 50-foot RMS arm into place for accurate operations or in constrained space is impossible.

- Even though an RMS-size EE need not necessarily be a manipulative type arm for payload handling, the evaluation shows that the 4F non-manipulative hand does not have the functional and task capability needed for tasks beyond pick and place operations. Its weaknesses and strengths greatly overlap the STD RMS EE and will not add many new capabilities. An EVA astronaut would be needed to assist in almost every operation!

- The DH, even though equal in the final score to the 4F hand and considered an intermediate development, has some distinct advantages that make it clearly superior: it has better limber arm control, better alignment and control capabilities and even some manipulative capabilities because of its wrist, human shape, and the dexterous thumb.

- A definite increase in capabilities clearly occurs in all major scores if a second EE is used. Obviously, two hands can do more than one; third or fourth EEs can serve as holders or as vises.

8.2   DEVELOPMENT APPROACH

Finger Packages: The preceding analyses and evaluations revealed that both the EVA substitution as well as the RMS configurable front end require more advanced general purpose EEs of very similar configuration: their core will be self-contained finger package units, complete with actuators, compliance control, local sensing, and electronics. With these modular packages, different hand configurations can be formed, the packages can be

exchanged in the field and, due to largely overlapping development efforts, the once designed finger package can easily be reconfigured for subsequent hand constructions, especially where the electronic design is concerned. It is therefore imperative in the short term as well as for long range planning that a thoroughly designed finger package with the above described characteristics be developed and tested. The economic advantages of this approach are substantial since both dexterous hands as well as bulk load EEs are needed and will spring off from this core design in the form of modified finger packages.

Anthropomorphic Hand: The evaluation proved that the anthropomorphic manipulator arm is far superior in task handlings both as an EVA substitute and on the RMS. It is thus strongly recommended as the next development item in either the simplified form first or as full anthropomorphic manipulator.

Developing the 4F hand prior to the AH is absolutely inappropriate since even the most sophisticated capabilities that could be built into this hand would be nullified by the RMS 50-foot arm's inability to properly move into position and do the necessary fine adjustments needed for grapplings. This EE configuration could perform only the most primitive tasks in its stand-alone configuration on the RMS EE. It needs either an arm by itself and/or the anthropomorphic manipulators to guide aligning and grappling. (Note that the DH has at least a wrist to fine adjust.) Besides, there are the control problems of the 4F hand due to mutating master-slave configurations that would require further investigation prior to the design phase.

Thus, the development is suggested as follows:

(1)   Selection of either the full AH or the simplified version must be made.

(2)   Develop design for finger and thumb packages tailored to AH chosen.

(3)   Develop the glove controller.

(4)   Design electronics in modular form for individual finger packages for teleoperation mode with automation features to be added later.

(5)   Choose to build either the support system described in DH, or the upper arm of the AH. If the upper arm of the AH is chosen for development, a corresponding master arm would need to be built as well.

(6)   Develop flight hardware for an early flight experiment with the DH or go to Step 7.

(7)   Develop flight hardware for an AH with a cooperating dual arm/hand anthropomorphic manipulator system to conduct an advanced flight experiment.

(8)   Implement automation features.

(9)   Determine future developments to construct a telerobotic space servicer.

Time Schedule. The development effort of Steps (1) to (5), leading to a prototype master/slave arm-hand system will take approximately three years to complete. One year must be allocated to test, evaluate, and modify the base technology items. It should then be possible

to carry out a simple flight experiment (Step 6) within three years following the test phase of the prototype. An advanced flight experiment as described in Step (7) will require two more years for duplicating the arm-hand system and to gain confidence in operating a cooperating dual arm teleoperator.

8.2.1 Conceptual Design of Recommended Core Technology Development

Based on the evaluation in this report, the following choices were made for core technology development for FYs 1988-90:

- An anthropomorphic four-finger hand with its finger packages and wrist actuation extending to the elbow, having a total of 19 active joints (including wrist).

- An elbow joint specifically designed to accommodate the anthropomorphic hand.

- A three-DOF shoulder joint to complete the anthropomorphic seven-DOF arm.

- A master controller, consisting of an exoskeleton arm controller and a glove controller. The master arm has a total of 23 DOF.

The following figures show the anthropomorphic arm-hand concept. Figures 8.2-5 show the teleoperator system in its subsequent expanded version as a dual arm-hand system adapted for space shuttle usage.

4 DOF PER FINGER, 3 FINGERS
4 DOF THUMB
3 DOF WRIST
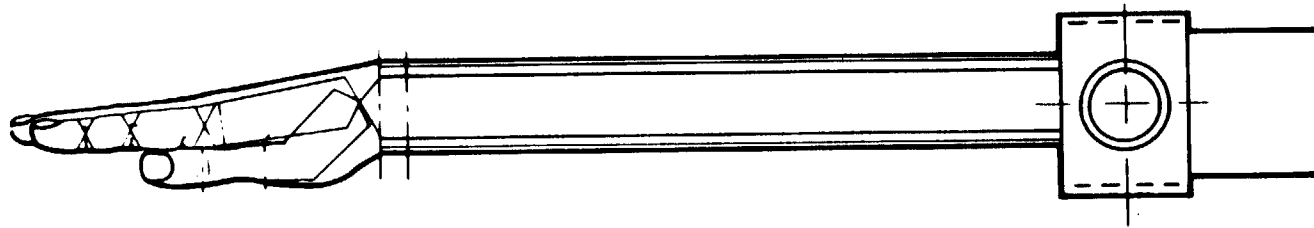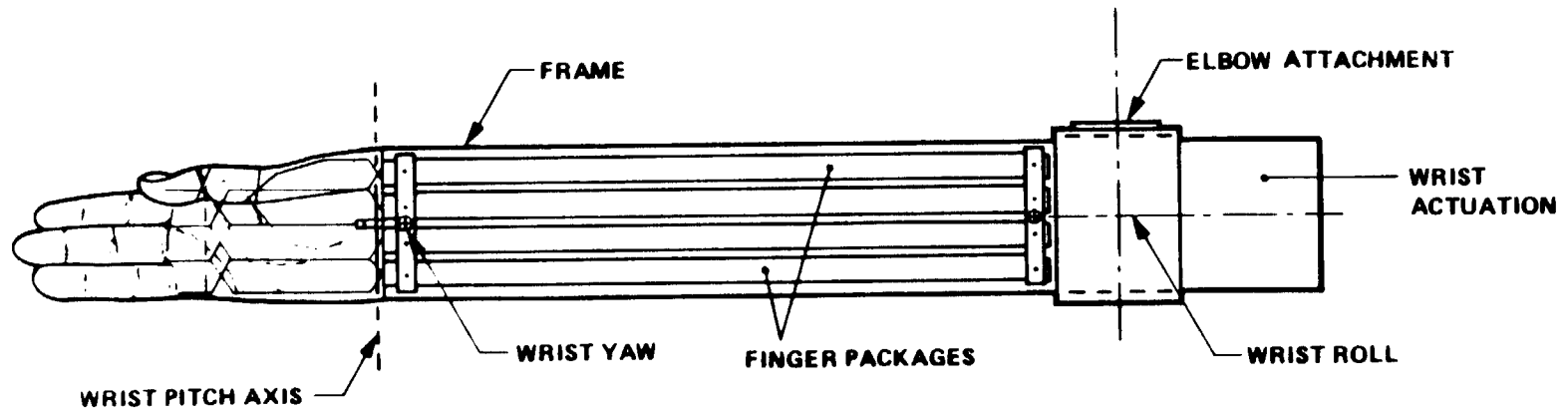
Figure 8-1. The Jau Anthropomorphic Hand

GRAPPLE FIXTURE

INTEGRATED
SYSTEM

ROTATING
PLATFORM

EQUIPMENT
AND
TOOL BOX

VISION SYSTEM
AND LIGHTS
ATTACHMENT

AUXILLIARY
SYSTEM
ATTACHMENTS

BMJ
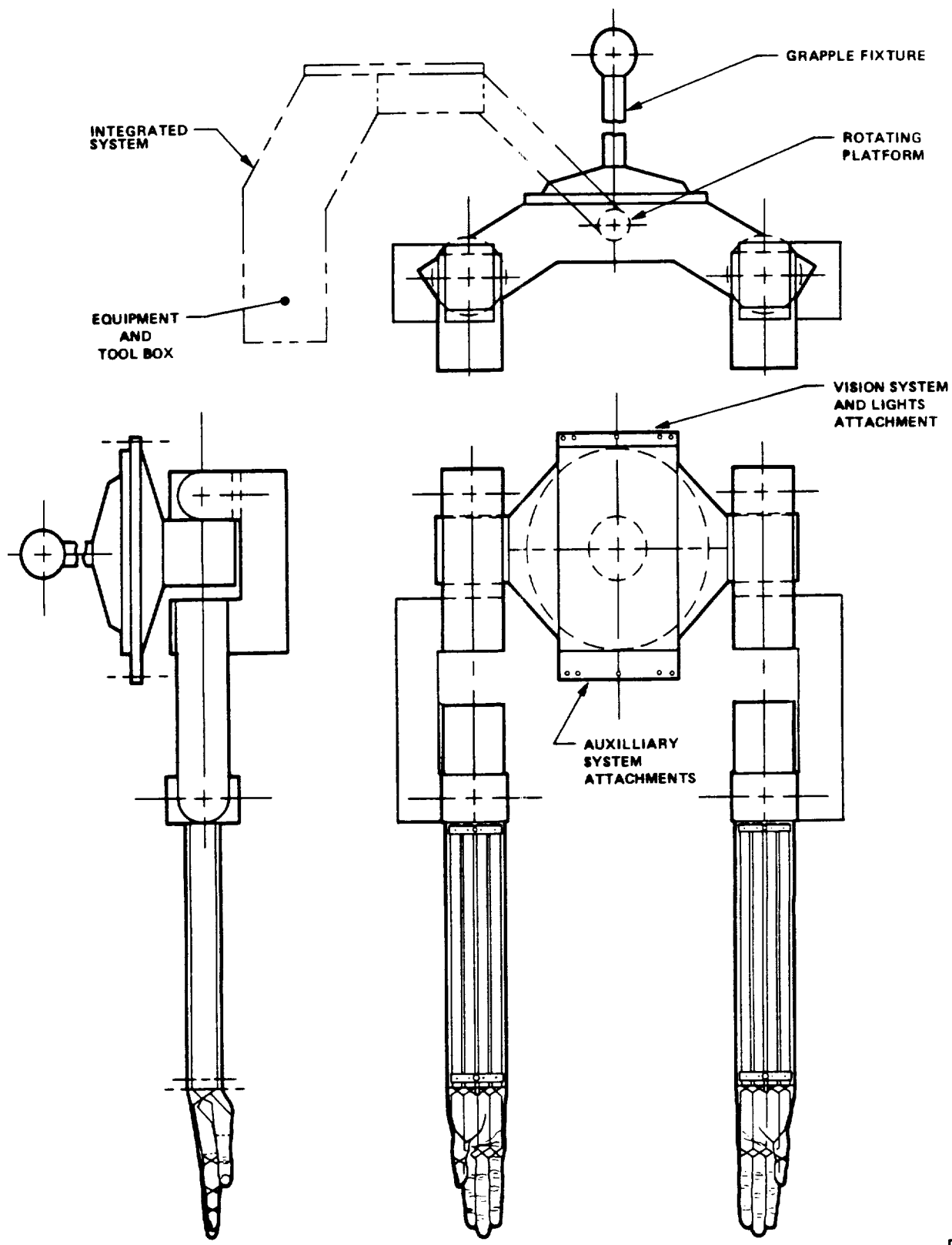
Figure 8-2. Anthropomorphic Telerobot for Shuttle Arm Attachment

HARNESS
WEIGHT
SUPPORT
OPTION

ARM
COUNTER-
BALANCING

ARM
ATTACHMENT
STRUCTURE

INTERSECTING SHOULDER JOINT AXES

MASTER ARM CONTROL HARNESS

- ADJUSTABLE FOR DIFFERENT BODY SIZES
- SEPARABLE ABOVE WRIST AND ABOVE ELBOW
- BACKDRIVEN AT 7 ARM JOINTS, THUMB AND 3 FINGERS WITH 4 D.O.F. EACH
- HARNESS WEIGHT: 8-10 kg PER ARM

SLAVE ARM

- ANTHROPOMORPHIC SHAPE, APPROX. 25% LARGER THAN THE ARM OF A 6 ft. TALL MALE
- SEPARABLE AT ELBOW
- 7 D.O.F. ARM, THUMB AND 3 FINGERS WITH 4 D.O.F. EACH
- ARM WEIGHT: APPROX. 25 kg PER ARM

BMJ

Figure 8-3. The Jau Anthropomorphic Telerobot

AI COMPUTER
CONTROL FOR
AUTONOMOUS HAND/
ARM CONTROL

LOCAL MASTER
ARM ELECTRONICS
A/D CONVERSION

CONTROL
ELECTRONICS

LOCAL
ROBOT ARM
ELECTRONICS
A/D CONVERSION

CONTROL PANEL

PARAMETER SETTING
FUNCTION EXECUTION

MASTER CONTROLLER

SENSOR STATUS DISPLAY,
VISION SYSTEM FEEDBACK ETC.

ROBOT ARM

BMJ
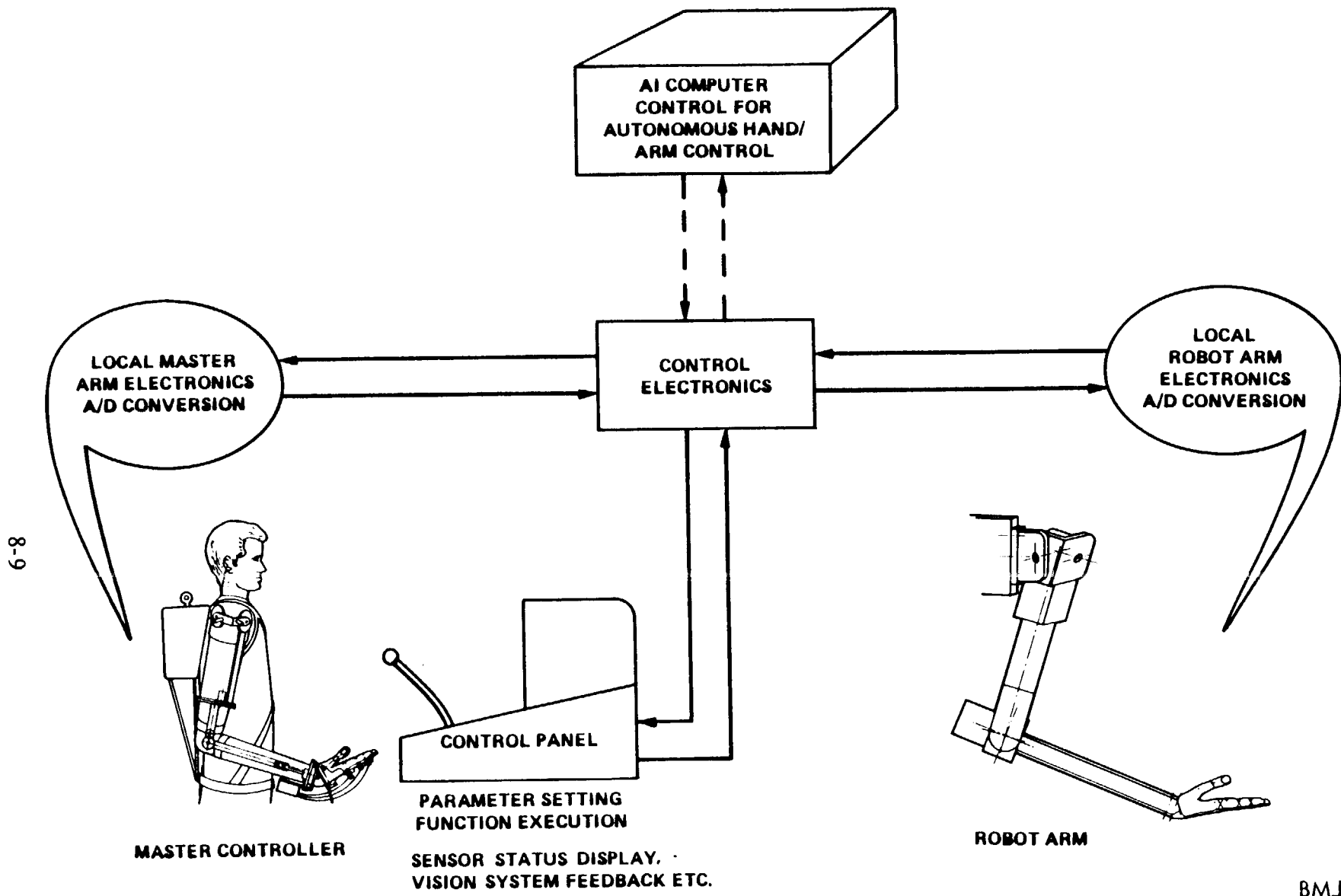
Figure 8-4. Anthropomorphic Robot Arm-Hand Overall System

Labels within figure: TELEROBOT COMPUTER, TELEROBOT ELECTRONICS, BMJ

Figure 8-5. Anthropomorphic Telerobot Control from Shuttle Aft Flight Deck

SECTION 9

SUMMARY

Over the next decade, operations in space will become more common, less extensively simulated and rehearsed, and of significantly greater diversity.

Increasingly common space missions will include inspection, servicing, and repair of space station systems and satellites in both low earth orbits and geosynchronous orbits. Additional operations will involve assembly and construction of large space structures, and handling of unplanned contingencies.

A reliance solely on EVA astronauts would severely limit the range of possible missions for reasons of accessibility, safety, and availability. The overhead associated with life support will limit access by human beings to structures in geosynchronous orbit. Many tasks would put a space-suited astronaut in a state of unacceptable risk. The number of astronauts available for all missions will be very few. The capability is needed to extend the reach of humans working in space.

These types of tasks must depend heavily on teleoperators and semi-autonomous telerobots in order to be practical. Use of teleoperators and telerobots will allow for the best combination of men and machines to achieve the greatest flexibility in carrying out myriad space-based tasks.

The principal goal in the development of teleoperators and telerobots is to provide the equivalent functional capability of an EVA astronaut. A major barrier to achieving this equivalency is the current state-of-the-art of robotic end effectors; the end effector is the "hand" at the end of a teleoperator arm. Current robotic end effectors are generally two-clawed grippers with none of the manipulative capability inherent in the human hand. Improvements in end effector system dexterity are clearly essential for teleoperators and telerobots to substitute for EVA astronauts in space tasks.

We have defined the functional requirements for multifunctional space end effectors. The capabilities of EVA astronauts were used as the basis for the end effector functional requirements. The end effector must be small enough to reach into areas an astronaut's gloved hand can access, strong enough to apply controlled forces up to 30 lb and an instantaneous force of 36 lb, and compliant enough to avoid damage to itself or objects in the workplace. The end effector must incorporate the appropriate 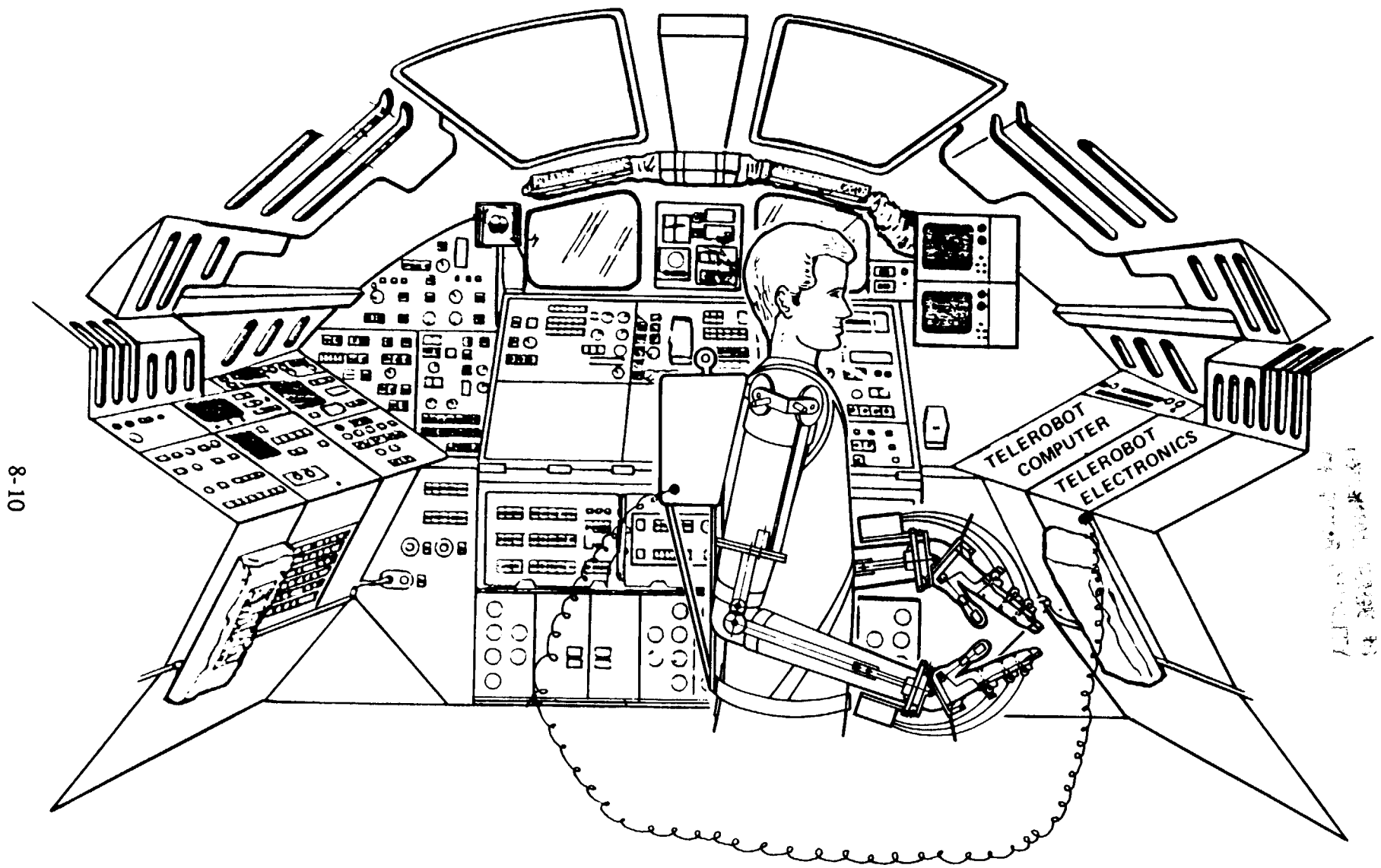combination of sensors, which may include those for vision, force/torque, grasp, tactile, temperature, proximity, position, and motion sensing.

The end effector system (consisting of the end effector and the tools it uses), in addition to its functional capability, must be robust in design, adapted to the human operator, and consistent with sensory and control needs. It must be modular in design, relatively insensitive to its hostile environment, and safe. Further, it must be adaptable to increasing levels of automation and autonomous control.

These functional and other overall system requirements not only impact the design of the end effector itself, but also the entire teleoperator system of which it is a part. End effector design influences the control station, information processing, and tool and equipment stowage subsystems.

The job the end effector must do influences the design and configuration of the mechanical arm that holds it. The arm must be of appropriate size, mass, and have enough degrees-of-freedom to support the optimal performance of the end effector. For EVA substitution, the arm (excluding the end effector itself) should be approximately 3 to 6 feet in length; it should possess at least seven DOF so as to be able to reach around obstructions. The use of two or more arms is suggested for multiple reasons: symmetric arm (left- and right-handed) cooperative manipulations, improved bulk load handling, self-replacement of failed end effectors, and grappling and rigidizing at the work site.

Three categories of possible end effectors have been defined: single-DOF hands, multi-DOF hands, and anthropomorphic hands. Proposed end effector concepts within these categories include:

(1) Improved OMV Smart Hand. This one-DOF end effector consists of intermeshing claws, with manual exchange of the claws. The end effector may be designed for complete manual or automatic exchange capability.

(2) Two Opposing Fingers with Multi-DOF. Each finger has two DOF. Alternate designs have either intermeshing claws or rotating claws with multiple contact surfaces for holding objects.

(3) Four Fingers in Circular Arrangement. The four fingers have rotating claws and a total of two DOF each. The four fingers allow for grasping of objects in multiple orientations.

(4) Anthropomorphic Hand. The anthropomorphic design has three fingers, a thumb, and a three-DOF wrist for a total of 19 active joints.

(5) Dexterous Hand (Simplified Anthropomorphic Hand). This hand has most of the characteristics of the anthropomorphic hand, but is mounted on a simple base support. It is therefore appropriate for use with the current shuttle remote manipulator system (RMS), without needing development of its own arm.

Options 1-4 were compared for their appropriateness in EVA substitution situations. The evaluation considered six major categories (function performance, task performance, system attributes, useability, robustness/complexity, and development cycle factors), each including several criteria. The anthropomorphic hand rated best of the alternatives, due to its far superior functional capability. It is the only one of the alternatives with the ability to manipulate objects, rather than merely clamp them.

A second evaluation considered configurations of options 3-5 and the current RMS end effector that would be appropriate for mounting on the 50-foot RMS. The same six categories used for the first comparison were applied to this RMS configuration evaluation with some changes to the specific criteria due to the lower precision of tasks performable with the RMS. The highest

rated alternative in this case was a combination of two symmetric anthropomorphic arms (left- and right-handed) with the four fingers in circular arrangement as a grappling end effector. This alternative may also be similar to the proposed "Smart Front End" for the Orbital Maneuvering Vehicle.

An evolutionary development approach has been suggested that will lead to the anthropomorphic hand, with its associated arm, glove-type hand controller, and master arm controller. The approach emphasizes development of modular finger packages, which are similar for both the anthropomorphic hand, and the circularly arranged end effector. Flight experiments with end effectors practical for EVA substitution are envisioned as feasible within six years of the start of the development effort.

The report ends with the conceptual design of the anthropomorphic arm-hand system that is recommended for the core technology development effort for 1988-90.

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APPENDIX A

EVA TASKS, TOOLS, AND EQUIPMENT

A.1   EVA TASKS PERFORMED TO DATE

Stow/unstow equipment and tools

Use hand tools and power tools

Remove/install threaded connectors
- 3/4" hex bolts
- hex allen screws
- shrouded screwdriver screws

Mate/demate D-connectors

Grasp: screws, grommets, washers, knobs, tape,
          handrails, restraints, closeouts, ORUs, etc.

Fold, wrap, and tape thermal blankets

Flip switches, turn knobs

Use MST (Module Servicing Tool)

Rendezvous and dock with satellites

De-spin, spin, and grapple satellites

Mate/demate umbilicals

A.2 EVA TOOLS AND EQUIPMENT [22]

Screwdriver (shrouded)

Probe

Hammer

Forceps

Power Tools
  EVA Power Tool (screwdriver/wrench)
  MST (Module Servicing Tool)

Wrenches/Pliers
  Adjustable wrench
  Vise grips
  Lever wrench
  Allen wrench w/movable sleeve
  Open-end wrench (1/2-inch)
  Ratcheting box wrench (1/2-inch)
  Ratchet drive (3/8-inch)
  EVA ratchet drive (3/8-inch)
  1/4-inch hex Allen, 19.5-inch drive extension
  7/16-inch socket / 4-inch extension / 3/8-inch ratchet drive
  90° needle nose pliers

- Cutting Devices
  EVA scissors
  Diagonal cutters
  Tube cutter

Pry bar

Bolt puller (crowbar)

Loop pin extractor

EVA Winch
Winch rope reel
Snatch block

Restraints/Containers:
  Tethers
  Portable foot restraint
  Manipulator foot restraint
  Tape set - duct tape
  Velcro strap set
  Payload retention device
  Trash container
  Provisions stowage assembly
  Modular equipment stowage assembly
  Mini-workstation
  Tool caddy

Manned Maneuvering Unit (MMU)

Special Purpose Tools
  3-Point tool
  Centerline latch tool

EMU Devices
  Glove hot pads
  EMU battery
  EMU LiOH cannister
  EMU lights
  EMU light battery
  EMU TV system
  EMU TV battery pack

APPENDIX B

EVALUATION TABLES

B.1   EVA SUBSTITUTION END EFFECTORS EVALUATION TABLES

Table B.1-1. EVA Substitution End Effectors - Function Performance

	Alternatives						
	OMV Hands			Two Opposing Fingers		Four Fingers	Anthropomorphic
	OMV-A	OMV-B	OMV-C	2F-I	2F-R	4F	AH
Inspect	2	1	3	2	2	2	3
Orient	1	1	1	1	1	2	4
Align	1	2	2	2	2	2	3
Grasp/Grapple	1	2	2	3	3	3	3
Rigidize	3	3	3	2	2	3	3
Mate/Demate	1	2	2	1	1	1	3
Insert/Remove	1	1	1	1	2	3	3
Lock/Unlock	1	1	1	1	1	1	2
Screw/Unscrew	1	3	3	1	2	3	4
Bolt/Unbolt	1	1	1	1	1	2	3
Cut	1	1	1	1	1	1	2
Tape	0	0	0	0	0	0	2
Patch	1	2	2	2	2	2	3
Polish	1	1	2	1	1	2	3
Solder	1	1	2	1	1	1	2
TOTAL	17	22	26	20	22	28	43
NORMALIZED TOTAL	1.13	1.47	1.73	1.33	1.47	1.87	2.87

Criteria

Table B.1-2. EVA Substitution End Effectors - Task Performance

Alternatives

Criteria	OMV Hands			Two Opposing Fingers		Four Fingers	Anthro-pomorphic
	OMV-A	OMV-B	OMV-C	2F-I	2F-R	4F	AH
Assembly Tasks	1	2	2	2	2	3	3
Servicing Tasks	1	1	1	1	2	2	3
Repair Tasks	1	1	1	1	1	1	2
Telescoping Antenna	1	1	2	2	2	2	3
Thermal Blanket Handling	0	1	1	0	1	1	2
ORU Replacement	1	1	2	2	2	2	3
Tethering Operations	0	0	0	0	0	0	2
Tumbling Satellite Capture	2	2	2	2	2	3	3
Contingency Handling	1	1	2	2	2	2	3
TOTAL	8	10	13	12	14	16	24
NORMALIZED TOTAL	0.89	1.11	1.44	1.33	1.56	1.78	2.67

Table B.1-3. EVA Substitution End Effectors - System Attributes

Alternatives

Criteria	OMV Hands			Two Opposing Fingers		Four Fingers	Anthro-pomorphic
	OMV-A	OMV-B	OMV-C	2F-I	2F-R	4F	AH
Clamping Force Range	2	3	3	2	2	3	2
Clearances	1	2	2	1	2	2	3
Mechanical Compliance	0	0	0	2	2	3	4
Manipulative Capability	0	0	0	0	0	1	3
Likelihood of Damaging Arbitrary Clamped Object	1	2	2	2	2	2	3
Chance of Losing Grasp on Arbitrary Clamped Object	2	3	3	3	3	3	3
Collision Damage Potential	2	2	2	3	3	3	4
Maximum Size of Objects Handled	1	2	2	2	3	3	4
Minimum Size of Objects Handled	1	3	3	2	2	2	3
System Mass	3	2	1	3	3	2	3
TOTAL	13	19	18	20	22	24	32
NORMALIZED TOTAL	1.30	1.90	1.80	2.00	2.20	2.40	3.20

Table B.1-4. EVA Substitution End Effectors - Useability

	Alternatives						
Criteria	OMV Hands			Two Opposing Fingers		Four Fingers	Anthro-pomorphic
	OMV-A	OMV-B	OMV-C	2F-I	2F-R	4F	AH
Human Operator Workload	3	1	2	2	2	2	2
Time to Complete Task	2	0	1	2	2	3	4
Consistency of Operator Interface	4	3	3	3	3	3	3
Naturalness of Manual Control	4	3	3	3	3	2	4
Compatibility with Automation	3	0	2	1	1	2	2
TOTAL	16	7	11	11	11	12	15
NORMALIZED TOTAL	3.20	1.40	2.20	2.20	2.20	2.40	3.00

Table B.1-5. EVA Substitution End Effectors - Robustness/Complexity

Alternatives

Criteria	OMV Hands			Two Opposing Fingers		Four Fingers	Anthro-pomorphic
	OMV-A	OMV-B	OMV-C	2F-I	2F-R	4F	AH
Failure Proneness	4	4	1	3	3	2	2
Feasibility of Modular Self-Replacement	0	0	0	0	0	0	1
Environmental Sensitivity	4	3	2	3	3	3	2
Mechanical Complexity	3	3	1	2	2	2	2
Electronic Complexity	3	3	1	2	2	2	2
TOTAL	14	13	5	10	10	9	8
NORMALIZED TOTAL	2.80	2.60	1.00	2.00	2.00	1.80	1.60

Table B.1-6. EVA Substitution End Effectors - Development Cycle Factors

Alternatives

Criteria	OMV Hands			Two Opposing Fingers		Four Fingers	Anthro-pomorphic
	OMV-A	OMV-B	OMV-C	2F-I	2F-R	4F	AH
Time to Develop	4	3	1	2	2	1	1
Cost to Develop	4	3	1	3	3	2	2
Cost per Unit	3	2	1	2	2	1	1
Compatibility with Evolutionary Approach	1	0	2	1	1	3	4
Time to Space Rate	4	4	1	3	3	2	2
TOTAL	16	12	6	11	11	9	10
NORMALIZED TOTAL	3.20	2.40	1.20	2.20	2.20	1.80	2.00

B.2 RMS CONFIGURED END EFFECTORS EVALUATION TABLES

Table B.2-1. RMS Configured End Effectors - Function Performance

Alternatives

Criteria	STD	STD+4F	STD+2AH	DH	4F+2AH
Inspect	1	2	3	2	3
Orient	2	2	4	3	4
Align	1	2	3	2	3
Grasp/Grapple	2	2	3	3	3
Rigidize	4	2	3	3	3
Mate/Demate	0	1	2	1	3
Insert/Remove	1	2	3	2	3
Lock/Unlock	0	1	2	1	2
Screw/Unscrew	0	1	3	1	4
Bolt/Unbolt	0	2	3	2	3
Cut	0	0	1	1	2
Tape	0	0	2	0	3
Patch	0	1	2	0	3
Polish	0	0	2	0	2
Solder	0	0	1	0	2
TOTAL	11	18	37	21	43
NORMALIZED TOTAL	0.73	1.20	2.47	1.40	2.87

Table B.2-2. RMS Configured End Effectors - Task Performance

Alternatives

Criteria	STD	STD+4F	STD+2AH	DH	4F+2AH
Assembly Tasks	0	1	2	1	3
Servicing Tasks	0	1	2	1	3
Repair Tasks	0	1	2	1	3
Telescoping Antenna	0	1	3	1	3
Thermal Blanket Handling	0	0	2	1	2
ORU Replacement	0	1	2	1	3
Tethering Operations	0	0	3	1	3
Tumbling Satellite Capture	1	2	3	2	3
Contingency Handling	1	2	3	2	4
Auxiliary Equipment Holding Capability	0	1	2	1	4
Bulk Item Holding (e.g., grapple, EVA platform)	4	1	2	1	3
TOTAL	6	11	26	13	34
NORMALIZED TOTAL	0.55	1.00	2.36	1.18	3.09

Table B.2-3. RMS Configured End Effectors - System Attributes

Alternatives

Criteria	STD	STD+4F	STD+2AH	DH	4F+2AH
Clamping Force Range	1	3	2	2	3
Clearances	1	2	3	1	3
Mechanical Compliance	3	3	4	3	4
Manipulative Capability	0	1	3	2	3
Likelihood of Damaging Arbitrary Clamped Object	1	2	3	2	3
Chance of Losing Grasp on Arbitrary Clamped Object	4	3	3	3	3
Collision Damage Potential	2	2	2	2	2
Maximum Size of Objects Handled	4	2	3	1	4
Minimum Size of Objects Handled	1	2	3	2	3
System Mass	4	3	1	2	1
Necessary Volume for Control Station	4	3	1	3	1
Danger to EVA Astronaut	4	2	1	3	1
Obstruction at Worksite for EVA Astronaut	4	4	2	4	2
Power Consumption	3	3	2	3	2
FTS Precision Capability	1	1	1	2	2
Launch Restraint Requirement	1	1	1	3	1
Enhanced Multifunctionality through Multiple Grippers	0	0	3	0	4
TOTAL	38	38	37	38	42
NORMALIZED TOTAL	2.24	2.24	2.18	2.24	2.47

Table B.2-4. RMS Configured End Effectors - Useability

Alternatives

Criteria	STD	STD+4F	STD+2AH	DH	4F+2AH
Human Operator Workload	4	3	2	3	2
Time to Complete Task	1	2	3	2	3
Consistency of Operator Interface	4	3	3	3	2
Naturalness of Manual Control	4	3	3	3·	3
Compatibility with Automation	1	2	2	3	2
TOTAL	14	13	13	14	12
NORMALIZED TOTAL	2.80	2.60	2.60	2.80	2.40

Table B.2-5. RMS Configured End Effectors - Robustness/Complexity

Alternatives

Criteria	STD	STD+4F	STD+2AH	DH	4F+2AH
Failure Proneness	4	2	2	2	1
Environmental Sensitivity	4	3	2	3	2
Mechanical Complexity	4	3	2	3	1
Electronic Complexity	4	3	2	2	2
TOTAL	16	11	8	10	6
NORMALIZED TOTAL	4.00	2.75	2.00	2.50	1.50

Table B.2-6. RMS Configured End Effectors - Development Cycle Factors

Alternatives

Criteria	STD	STD+4F	STD+2AH	DH	4F+2AH
Time to Develop	4	2	1	3	1
Cost to Develop	4	2	1	2	1
Cost per Unit	3	3	1	3	1
Compatibility with Evolutionary Approach	1	3	2	4	4
Time to Space Rate	4	3	2	3	1
TOTAL	16	13	7	15	8
NORMALIZED TOTAL	3.20	2.60	1.40	3.00	1.60

APPENDIX C

ACRONYMS USED IN TEXT

CCD   -   Charge Coupled Device

CID   -   Charge Injected Device

DH   -   Dexterous Hand

DOF   -   Degree Of Freedom

EE   -   End Effector

EMU   -   Extra-vehicular Mobility Unit. A space shuttle astronaut's spacesuit.

EV   -   Extra-Vehicular

EVA   -   Extra-Vehicular Activity

IOC   -   Initial Operational Capability

MMU   -   Manned Maneuvering Unit

MST   -   Module Servicing Tool. A power tool used by astronauts to aid module changeout on certain types of satellites.

OMV   -   Orbital Maneuvering Vehicle. A future unmanned space vehicle, fitted with a manipulator system for servicing and repair of satellites and other space structures.

OMV Hand   -   JPL experimental "smart" end effector, possibly to be developed for eventual use with the OMV.

ORU   -   Orbital Replaceable Unit. Modular units for use in satellites and other space structures, designed to be replaced easily by an EVA astronaut.

PFMA   -   Proto-Flight Manipulator Arm

RMS   -   Remote Manipulator System. The 50-foot manipulator system used onboard the space shuttle.

SFE   -   Smart Front End. The proposed manipulator system to be fitted to the OMV for satellite servicing and repair operations.