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INTRODUCTION

Extravehicular activity (EVA) is crucial to the success of both current and future space operations. As space operations have evolved in complexity so has the demand placed on the EVA crewman. In addition, some NASA requirements for human capabilities at remote or hazardous sites have been identified. One of the keys to performing useful EVA tasks is the ability to manipulate objects accurately, quickly and without early or excessive fatigue. The current suit employs a glove which enables the crewman to perform grasping tasks, use tools, turn switches, and perform other tasks for short periods of time. However, the glove's bulk and resistance to motion ultimately causes fatigue.

Due to this limitation it may not be possible to meet the productivity requirements that will be placed on the EVA crewman of the future with the current or developmental Extravehicular Mobility Unit (EMU) hardware. In addition, this hardware will not meet the requirements for remote or hazardous operations.

In an effort to develop new ways for improving crew productivity, NASA's Johnson Space Center awarded a contract to Arthur D. Little, Inc., to develop a prototype anthropomorphic robotic hand (ARH) for use with an extravehicular space suit (contract #NAS9-17454). The first step in this program was to perform a design study which investigated the basic technology required for the development of an ARH to enhance crew performance and productivity. This paper summarizes the design study phase of the contract and some additional development work which has been conducted at Arthur D. Little, Inc., after the conclusion of the Phase I effort.*

OBJECTIVE

The study had three major objectives. They were:

- To characterize the EVA environment and develop the operational requirements placed on the gloved hand which could be performed by an ARH.
- To survey the technology relevant to developing an ARH.
- To develop a concept which satisfies the requirements within both overall NASA and ARH program constraints.

The subsequent development work objectives were:

- To build a test bed for analyzing the study recommendations.

*The majority of this work was conducted under contract no. NAS9-17454 for NASA Lyndon B. Johnson Space Center and reported in the report entitled "Design Study of a Prototype Anthropomorphic Robotic Hand for Use with an Extravehicular Space Suit." This report was submitted in September 1986. The report contains a reference list with 196 titles.

- To utilize the prototype hardware to refine the concepts and improve our understanding of hand master and slave design.

DESCRIPTION OF STUDY METHODOLOGY

The first step in this project was to develop the operational requirements placed on the gloved hand in past, current and projected future EVA's by analyzing the tasks that comprised six representative scenarios (Figure 1). Following the development of the operational requirements, both bare-handed and suited data were compiled to quantify each requirement. From these requirements and other relevant data, the design goals and constraints were developed. These were divided into two categories: improvement to be maximized over the gloved hand (e.g., dexterity, range of motion and comfort) and degradation to be minimized over the gloved hand (e.g., safety, mental load, and training).

After the design goals and operational requirements were developed, the technology which might be used to fulfill those requirement and goals was surveyed. The design of an ARH shares many of its goals and constraints with other manipulator program in robotics, teleoperation, prosthetics and orthotics. In addition to surveying previous experience in these areas, a study of individual technologies for major system components (e.g., transmissions, actuators, sensors) was also performed. This study was aimed at uncovering technologies but, which for one reason or another had not previously been used in manipulator systems but which, on the basis of our goals and requirements, could be applicable to the ARH.

Finally a number of ARH concepts were developed, analyzed and optimized for fulfillment of the design goals within the NASA and ARH program constraints. From this trade-off analysis an optimized concept was produced, and a set of development steps required to yield a device which could enhance EVA performance and productivity was formulated.

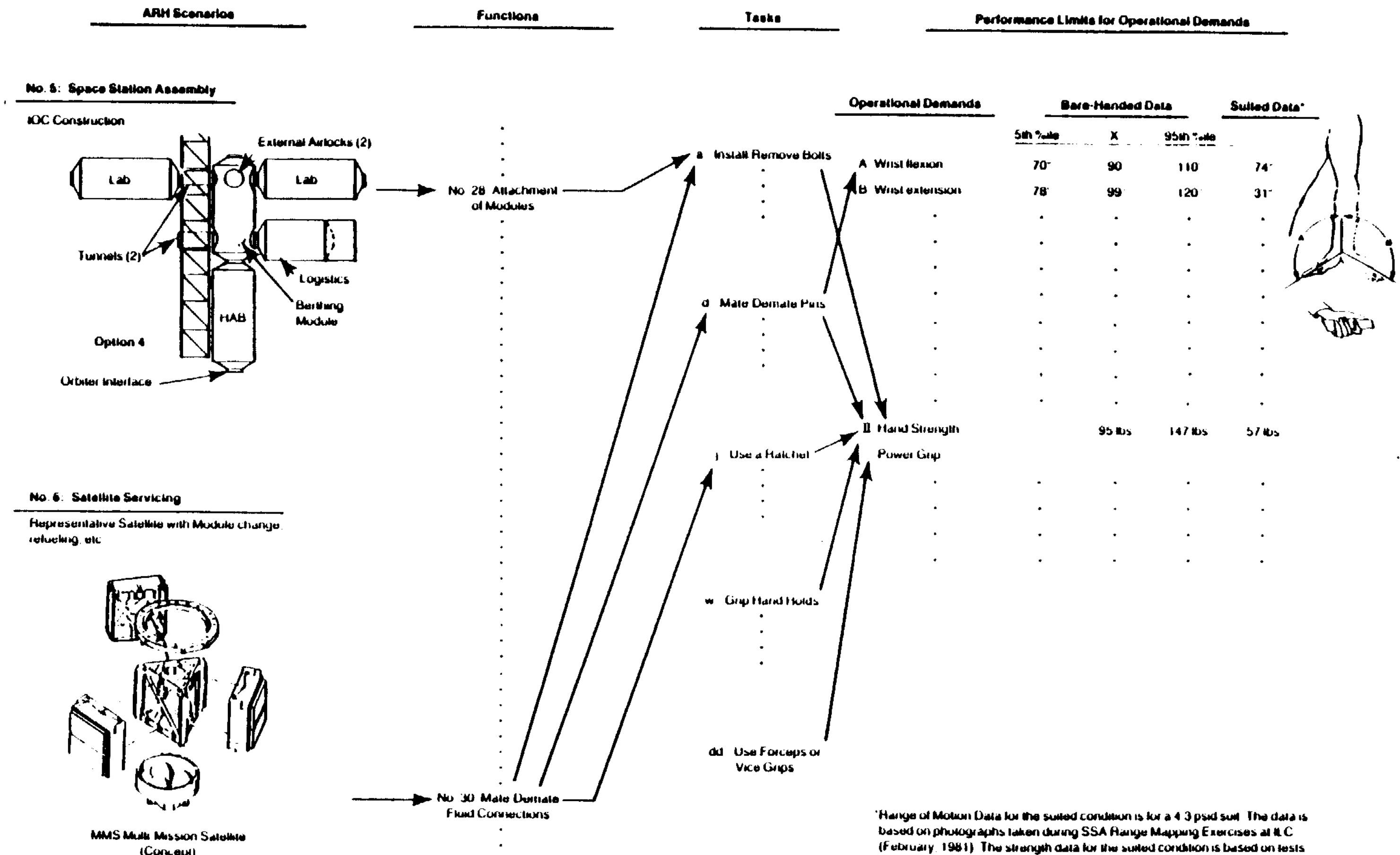
SUMMARY OF STUDY RESULTS

Operational Requirements Development

The task analysis showed that for the six chosen EVA scenarios the most prevalent operations were:

- forearm supination/pronation
- finger motion
- power grip
- palmer grip
- finger pull

FIGURE 1 ARH TASK ANALYSIS APPROACH



*Range of Motion Data for the suited condition is for a 4 3 psid suit. The data is based on photographs taken during SSA Range Mapping Exercises at ILC (February, 1981). The strength data for the suited condition is based on tests performed in 1984 by ILC. The tests were conducted using seven subjects and a vacuum glove box.

- shoulder medial/lateral rotation, and
- wrist adduction/abduction.

These operations were seen as essential to successfully performing EVA tasks.

Technology Survey

From the technology survey on manipulator programs in robotics, teleoperation, and prosthetics and orthotics we learned that:

- Several dexterous hands which might meet the ARH operational requirements had been built but none of them were suitable or easily modifiable for this application.
- Autonomous control of these hands for a range of tasks had not been accomplished.
- No kinematically correspondent master for teleoperated control of these hands had been used in performing useful tasks.
- A large number of important tasks can be accomplished with less than anthropomorphic hands.

From the survey of individual technologies for system components we learned that:

- Actuators with appropriate frequency response and output forces and torques have been demonstrated or can be reasonably expected to meet the requirements.
- A variety of transmission methods exist which could be used for an ARH.
- A wide variety of sensors are available for providing data about the ARH and the environment around it.
- Display of sensory information has been achieved and successfully used in a variety of methodologies.

Thus we concluded that although there was no similar system already in existence, the available technology could be used to create a system which would meet the goals within the constraints.

Concept Development

A variety of options ranging from simple to complex were developed and studied (Figure 2). These options ranged from ARH designs which attached to the space suit arm in place of the glove to Third Arm configurations which attached to the torso or life support system and employed control systems and end effectors with various degrees of complexity. From these options, seven were chosen for their potential performance and to span the range of options. They were developed and designed in sufficient detail to permit performance prediction and trade-off analysis.

Concurrently a trade-off analysis methodology was developed utilizing the operational requirements and design goals and constraints. An equation was developed for each design goal and constraint, relating data describing each design to the bare hand and 3000 series gloved hand. The goals and constraints were ranked by NASA personnel and the ADL team, and weightings were developed (Table 1). From these weightings, the equations, and the design data developed for each of the seven concepts, overall scores were obtained (Table 2). The scoring results indicated that the following features were primary discriminators between concepts relative to enhancing EVA performance and productivity:

- o wrist degrees of freedom (DOF) and range of motion
- o grasp and wrist lock
- o number of fingers and DOF of each
- o mechanism complexity
- o feedback of ARH status to the operator.

Using the results of this analysis, a design was formulated that could be built during the time allocated to the prototype phase of this contract. This device, the optimized displaced fingers (ODF), was a direct mechanically linked master/slave that would be worn on the end of the suit arm. It had three, three jointed fingers, a 2 DOF thumb, a locking wrist, grasp lock and a 3 DOF wrist co-located with the operator wrist (Figure 3). This design as then evaluated using the trade-offs methodology and received the highest score of all the designs considered.

STUDY CONCLUSIONS

Based on the results of this study, we have concluded that the "optimized, displaced fingers" (ODF) design is the approach which best meets the requirements for an ARH as defined in this project. The device would have good dexterity, mobility, and fatigue characteristics and would provide improved performance over the present glove for the EVA tasks selected as typical for this study.

FIGURE 2 Design Options

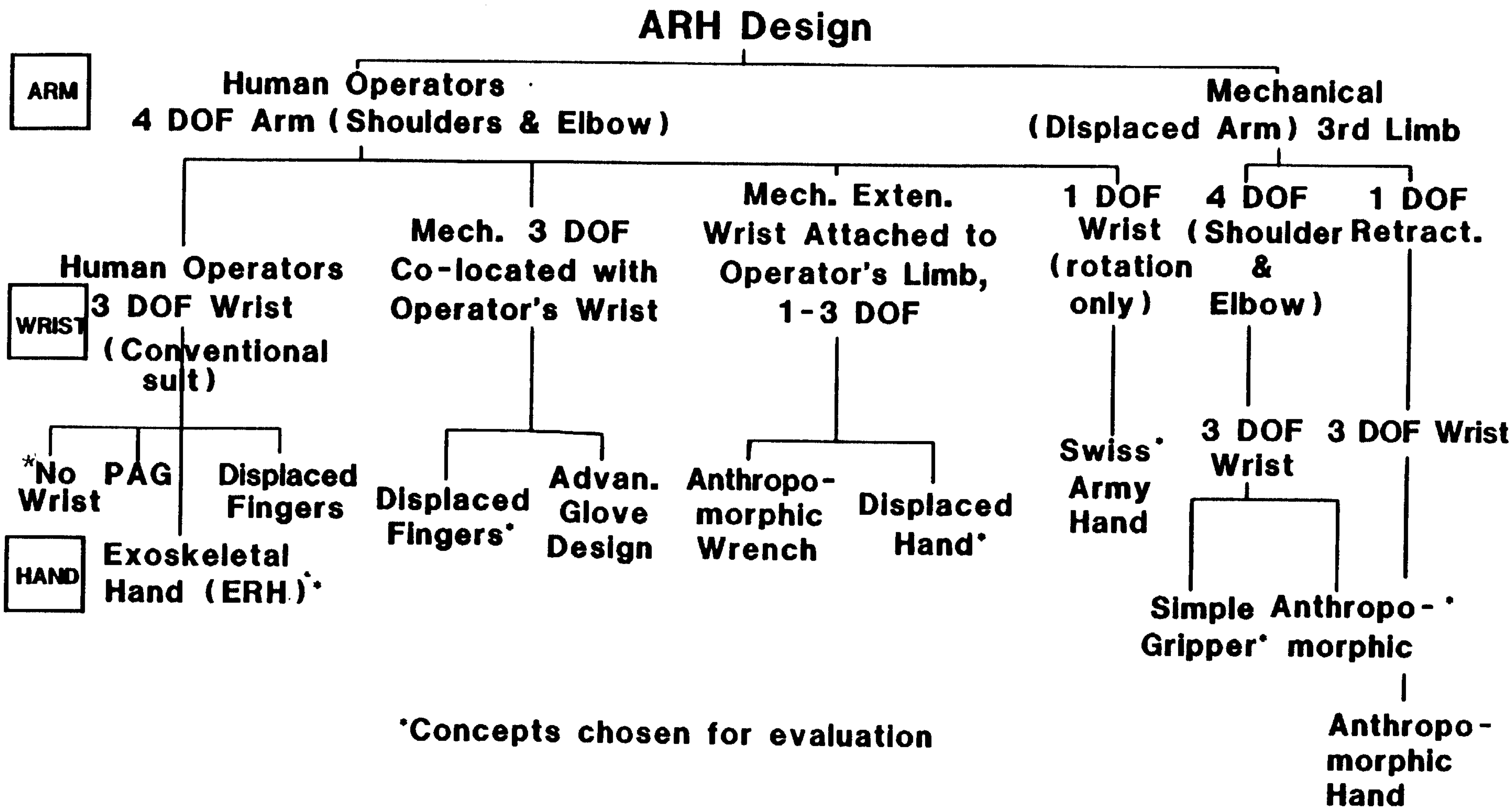


TABLE 1 RANKING OF DESIGN GOALS & CONSTRAINTS

Improvement to be Maximized Over Gloved Hand:

		Weight (%)
1.	Dexterity	9.0
2.	Maximum Force	5.3
3.	Maximum Torque	6.0
4.	Range of Motion	6.2
5.	Arm Dynamics	4.5
6.	Feedback	7.6
7.	Muscle Fatigue	7.7
8.	Comfort	6.7
9.	Impact Tolerance	5.2

Degradation to be Minimized Over Gloved Hand:

10.	Safety (during operation)	11.0
11.	Training	3.4
12.	Mental Load	7.6
13.	Failure	11.4
14.	Maintenance	2.5
15.	Power Required	3.2
16.	Cost	2.7
TOTAL		100

TABLE 2 FINAL DESIGN SCORES

	Displaced Fingers	Displaced Hand	Third Arm/Simple	Third Arm/Complex	No Wrist	Swiss Army Hand (SAH)	Exoskeletal Robotic Hand (ERH)	Optimized Displaced Fingers
DESIGN GOALS	1	2	3	4	5	6	7	8
Subtotal for Maximized:	83.72	71.96	-151.05	-48.24	67.69	-4.23	11.19	131.70
Subtotal for Minimized:	-83.22	-96.25	-56.02	-210.20	-28.00	-109.23	-34.16	-81.81
Total Score	0.49	-24.29	-207.07	-258.44	39.70	-113.46	-22.97	49.89

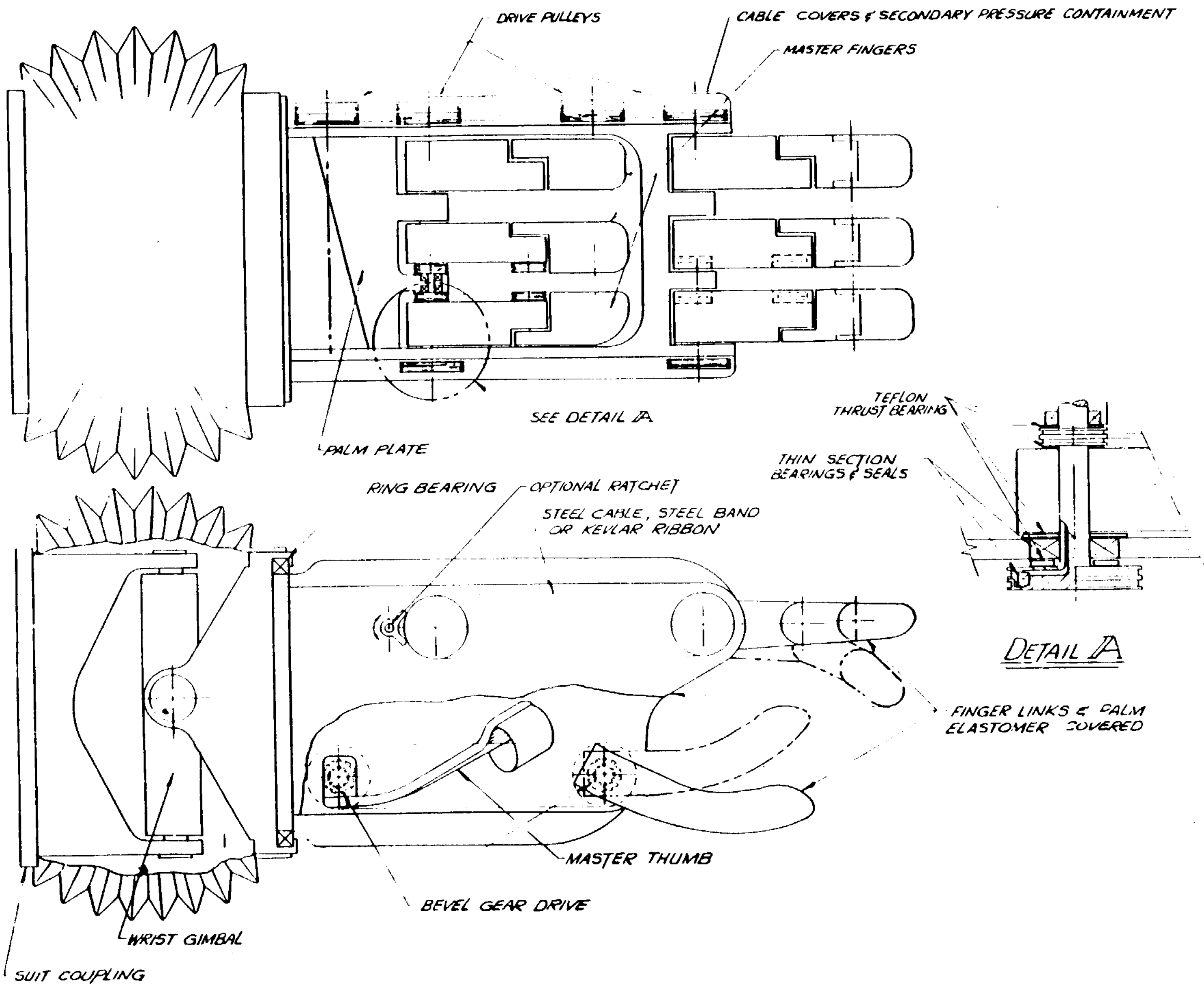


FIGURE 3 OPTIMIZED DISPLACED FINGERS

An important consideration in the evaluation of design alternatives was an assessment of the state of development of dextrous manipulators. Thus, the recommended design represents, in a way, a compromise between a device which could be developed to provide enhanced performance drawing on demonstrated technology and the ultimate advanced, powered, dextrous manipulator. The approach does, however, provide a basis for making significant advances in the state-of-the-art and is a logical first step in the development of the advanced design. Specific advances include:

- Direct feedback: The design incorporates direct feedback and will allow a determination of how the information is used and how much feedback is desirable for future systems.

- Master-slave design: The design of a kinematically correspondent directly coupled master for an anthropomorphic end effector has not been done. This device requires a master which tracks individual fingers to operate the slave. The master would be linked mechanically to the slave in this case, but in advanced designs the master could be equipped with kinesthetic transducers and force reflection coupled with sensors on the slave to provide remote operations.

- Task performance: The device will permit evaluation of the usefulness of an ARH in performing specific tasks and therefore will be useful in developing design specifications for more advanced systems.

For this device to fulfill the objective of enhancing EVA crew productivity, it must be acceptable to the crew and must operate safely in the EVA environment. The ODF is inherently less acceptable and arguably less safe than the third arm options (Figure 2) considered because it seeks to replace the human hand function and also modifies the pressure suit. The human hand is a very complex and well designed device. Even with the mobility, dexterity and fatigue limitations imposed by the current EMU gloves it provides a wide range of capabilities essential to EVA including adaptability to unforeseen conditions.

A perfect ARH would be as flexible and adaptable as the human hand and would not fatigue. This type of device is not currently within the state-of-the-art and could not be developed for space applications in the near term (2 - 3 years). The ODF provides the closest approximation to that capability compatible with the current state-of-the-art while providing a basis for developing future hands which approach the capability of the human hand.

Even with this first step, the development of the ultimate hand system which would be safe and acceptable would not be possible until the 1990's. In the meantime, EVA crewmen will need productivity aids, and therefore, a short-term, safe, acceptable solution should also be developed. We believe that the best alternative is a version of the simple third arm

(Figure 4). This device could be safely interfaced with a crewman and does not require the loss of use of the gloved hand. If powered or manually locked it provides a three arm working capability. It would provide near term operational experience with robotics in EVA.

The Third Arm design should have the following characteristics. It should be simple to use and capable of performing a limited subset of tasks reliably and effectively. It's end effector should provide only grasping and limited manipulations. Therefore, in the short term, dexterous operations would continue to be performed by the gloved hand.

If gloves improve significantly, this simplified ARH (Third Arm) may be the only capability required. If suits go to higher pressures, gloves do not improve sufficiently, or the ODF leads to a highly dexterous ARH with capabilities approaching the human hand, an ARH attached to the suit arm may become desirable.

In summary;

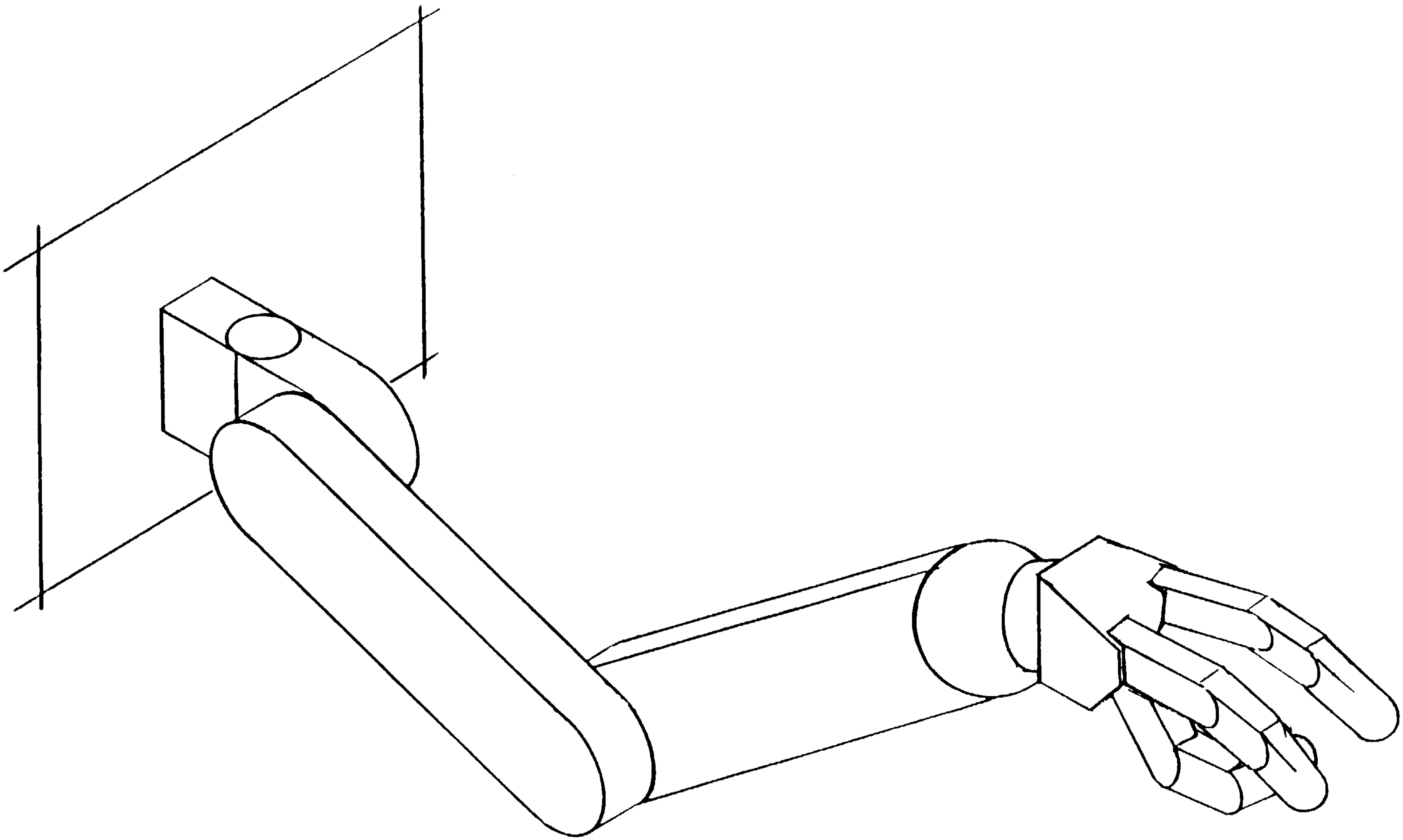
- o The ODF is a useful ARH and can provide information crucial to future hand developments which could be applicable to an advanced ARH or Third arm.
- o A highly dexterous hand/arm system requires significant R&D to become an operational space tool.
- o A simple Third arm is an acceptable short term EVA productivity aid.
- o The Simple Third arm could evolve to a useful complex device or be replaced by an advanced ARH depending on parallel developments in other areas.

METHODOLOGY OF ADDITIONAL IN-HOUSE DEVELOPMENT WORK

In the course of studying hand function, robot hand design and developing the previously described concepts, we identified a number of important design issues requiring further work prior to entering a complete system hardware development. They were:

- o Design of a master to interface with a human hand without severely restricting its motion.
- o Stiff transmission design to minimize friction and backlash.
- o The utility of the overall link configuration including the function of the passive third link.

FIGURE 4 Simple Third Arm Concept



Arthur D. Little, Inc.

To study approaches to these issues, we designed and built a two-finger master/slave test bed (Figure 5). We chose this particular configuration to fully test the finger kinematics, test the thumb position and allow simple grasping to be able to assess potential performance. The system was designed so that additional fingers could be accommodated to allow us to examine the feasibility of a nested shaft design and evaluate the lateral placement of the pulleys. The design approach selected was similar to that shown in Figure 3.

PRELIMINARY RESULTS OF DEVELOPMENT WORK

The hand test bed as originally conceived utilized what we considered to be a near anthropomorphic thumb placement. Once the device was built and testing began, we realized that one seldom utilizes the thumb in its relaxed orientation (Figure 6a). We found for grasping a range of objects the effective degrees of freedom provided by the palm and thumb together allow a more useful configuration (Figure 6b). As our designs do not have these degrees of freedom, we modified the geometry to reflect this more useful hand configuration. Further testing will determine whether this provides sufficient capability for the desired tasks.

In building the hand master for the test bed, we found that packaging the linkage to be compatible with a range of human hands with the volume allocated is a difficult problem. The center of rotation of the links should be at the center of rotation of the finger joints. If not, relative motion between the master and the human hand will result. For a small number of fingers (1-3) for a particular person matching the centers of rotation of the joints may be achievable in a system employing rigid links, but, with hand size variation and larger numbers of fingers, it becomes difficult. One solution which makes use of the human sensory motor adaptability is to design to permit a certain amount of relative motion. Preliminary findings show that this is a useful methodology, and further development will explore the limitations of this approach.

The passive third link was constructed and has been found, as predicted, to be useful in grasping a variety of objects. In the configuration we tested, its motion is directly proportionate to the proximal link. This configuration may not be optimal for grasping oddly shaped objects, but may be excellent for the tasks of interest. Further testing will lead to a better understanding of these issues, and perhaps the application of a certain degree of compliance to this linkage.

The initial transmission configuration used, tensioned cables. This increased bearing friction and presented some operational problems. Other cable materials maximizing stiffness while minimizing the required pretensioning and other transmission concepts are currently being evaluated to improve this situation.

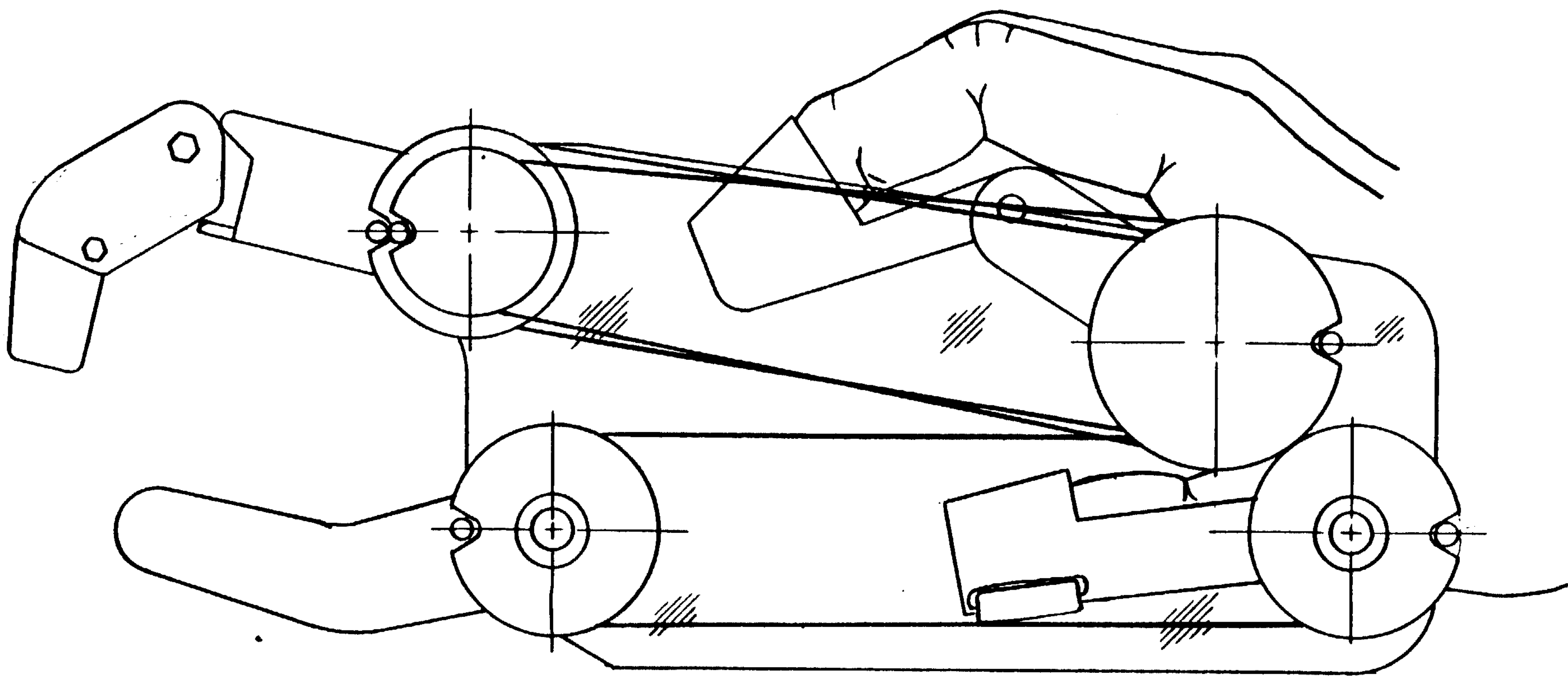


FIGURE 5 2 FINGER TEST BED

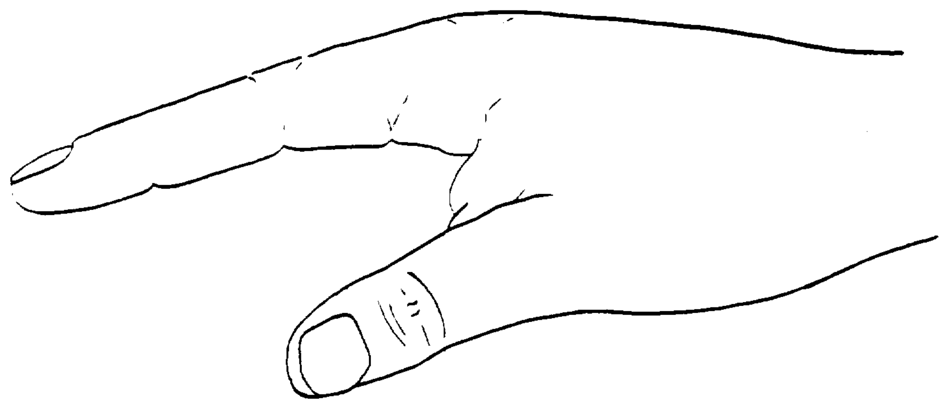


FIGURE 6A

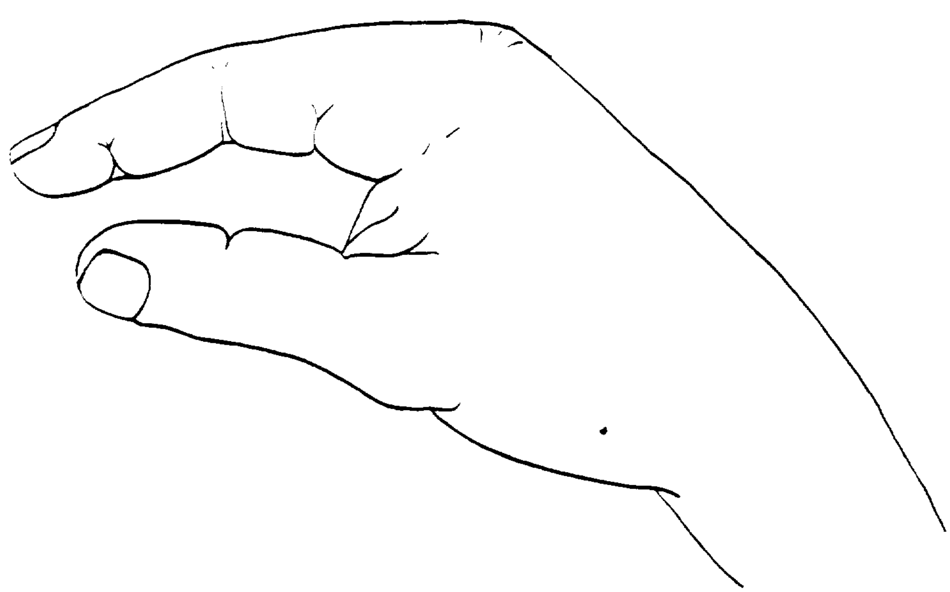


FIGURE 6B

Conclusions of Developmental Work

Although the work described is still in progress, the objectives of the work have been achieved. This work has shown the utility of studying simple devices, such as our test bed, to provide a solid foundation for future complex systems. Before dexterous hands can be designed for remote operation much more of this type of experimentation needs to be accomplished.