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# NASA RESEARCH ANNOUNCEMENT PHASE I REPORT AND PHASE II PROPOSAL FOR THE DEVELOPMENT OF A POWER ASSISTED SPACE SUIT GLOVE ASSEMBLY

**Submitted by ILC Dover, Inc. as part of a contract in response to NASA Research announcement 95-OLMSA-01.**

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## 1.0 Abstract

In July of 1996, ILC Dover was awarded Phase I of a contract for NASA to develop a prototype Power Assisted Space Suit glove to enhance the performance of astronauts during Extra-Vehicular Activity (EVA). The contract was awarded in response to a proposal submitted by ILC Dover in April of 1995 for NASA Research Announcement 95-OLMSA-01. Congressional budget conflicts delayed the award of the contract until July of 1996 from the original letter of intent to award from NASA in November of 1995, resulting in compression of a ten (10) month program into a four (4) month program. This report summarizes the work performed to date on Phase I, and details the work to be conducted on Phase II of the program.

Phase I of the program consisted of research and review of related technical sources, concept brainstorming, baseline design development, modeling and analysis, component mock-up testing, and test data analysis. ILC worked in conjunction with the University of Maryland's Space Systems Laboratory (SSL) to develop the power assisted glove.

Phase II activities will focus on the design maturation and the manufacture of a working prototype system. The prototype will be tested and evaluated in conjunction with existing space suit glove technology to determine the performance enhancement anticipated with the implementation of the power assisted joint technology in space suit gloves


## 2.0 Phase I Introduction, Study Results, and General Design Objectives

This section provides an overview of the objectives for the Phase I Power Assisted Space Suit Glove development program. The specific rationale behind the design evolution is discussed in detail in the sections which follow.

State of the art space suit gloves place substantial torque loads on the astronaut's metacarpophalangeal (MCP) joint throughout the normal range of motion. The high torque is a result of the large area which is deformed during MCP joint extension, and is very similar to the conditions discussed with **Figure 3**. The task of the power assist glove is to counteract these torques, relieving the astronaut's muscles from the burden of continually compensating for these torques, thereby reducing fatigue and enabling near "nude body" hand motion. The power assist system thus acts as an "active spring," which counterbalances torque loads due to the glove.

With the Power Assisted Glove design, the MCP joint is patterned to add the required run length to the back of the glove. When pressurized, this gore area will expand to take up this run length, resulting in a steady state, glove closed condition. The forces required to counterbalance these loads, or open the hand, are exerted by means of a cable(s) attached to the glove just under the base of the four fingers. The cable runs over the dorsal surface of the MCP joint, past the palm bar strap, where the cable is attached to the shaft of a DC motor (See **Figure 1**). Rotation of the motor winds the cable onto the shaft, thereby applying torque about the glove MCP joint. The magnitude of the forces required at a particular time will depend upon experimentally determined values of the glove stiffness (its tendency to return to the closed position) and damping (its tendency to dissipate rotational energy) as functions of the MCP joint angle and rotation rate. By keeping the cables in tension, there is a one-to-one relation between the MCP angle of the glove and the angle through which the motor shaft has rotated. A similar relation exists between the shaft and MCP joint rotation rates. Thus measurements of the motor shaft angle can be used to determine MCP joint deflection. These measurements will be accomplished using a digital optical encoder mounted on the shaft of the motor. Shaft angular velocity will be determined from the encoder output using digital signal processing algorithms. The motor assembly will be low-friction and back-driveable, so that cable can be taken up or released by the motor in response to MCP joint opening or closing.

Experimental glove data obtained on concept mockups was used to determine the exact stiffness and damping properties of the glove as a function of the shaft rotation (which corresponds one-to-one with the MCP joint angle) and rotation rate. The motor torque required to implement compensating torques about the glove MCP joint will then be computed from this data and the models and the instantaneous motor state using an embedded microprocessor. The microprocessor will also perform the computations needed to extract MCP joint angle and rotation rate from the readings on the optical encoder.

Several design iterations were conducted in an effort to reduce the torques in the space suit glove MCP joint, prior to the addition of the actuation system. Reducing MCP joint torque reduces the size of the actuation system required, minimizes the power requirements of the actuation system, and improves the reaction rate of the joint. All of these attributes are desirable for a system where packing volume, profile, and weight are required to be minimized.

TUCKED FABRIC MCP

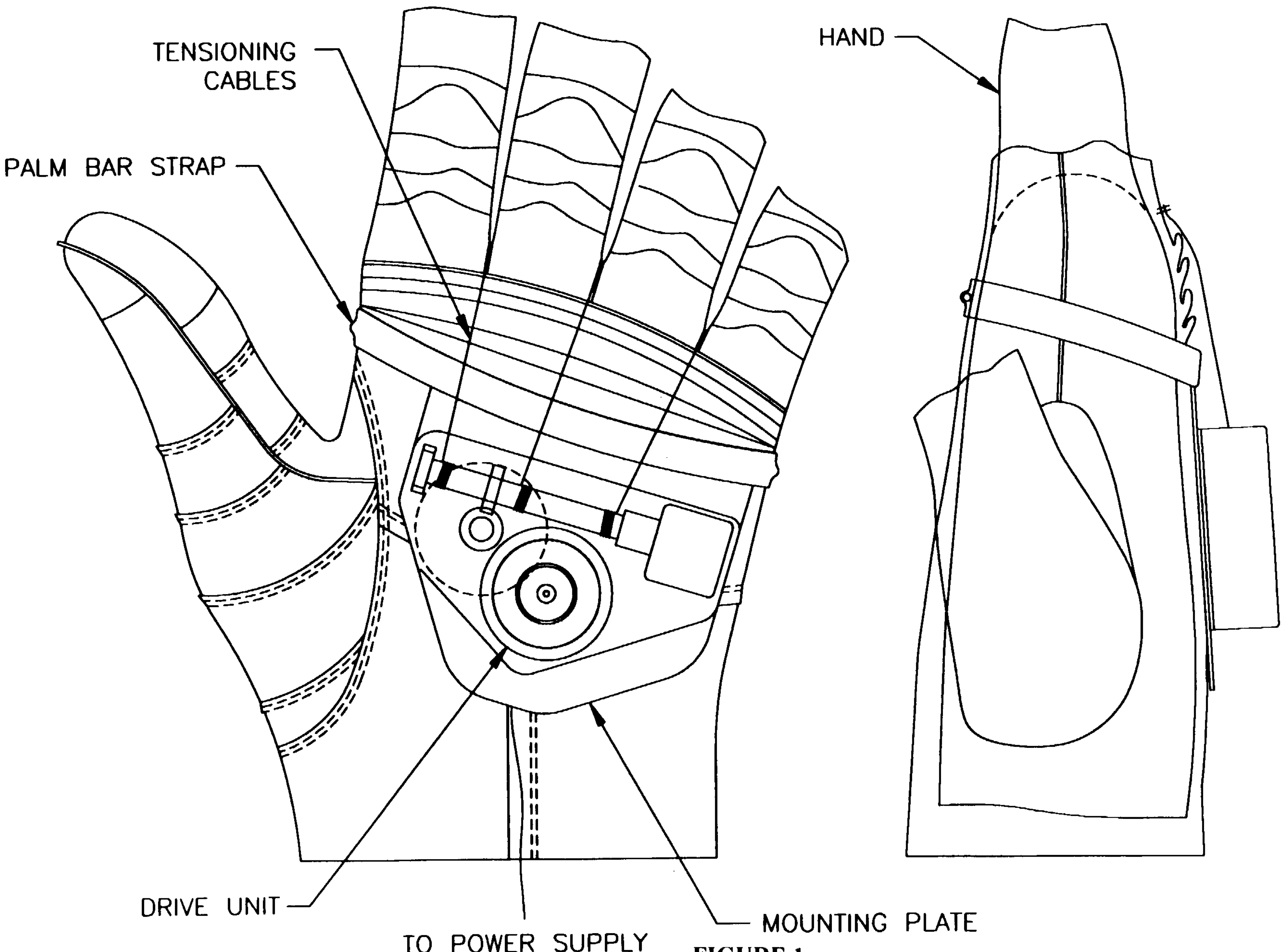


FIGURE 1

## 2.1 Glove MCP Joint Conceptualization

As part of the initial design process, a brain storming session was held at ILC to identify potential MCP joint design concepts. The thrust of the effort was centered on the softgoods aspect of the glove and methods to reduce MCP joint torques. One baseline, Tucked Fabric concept was identified, with three additional concepts identified as potential improvements upon the baseline concept. Each of the concepts is described in detail below, with drawings of each also attached.

Common to all investigated MCP joint concepts:

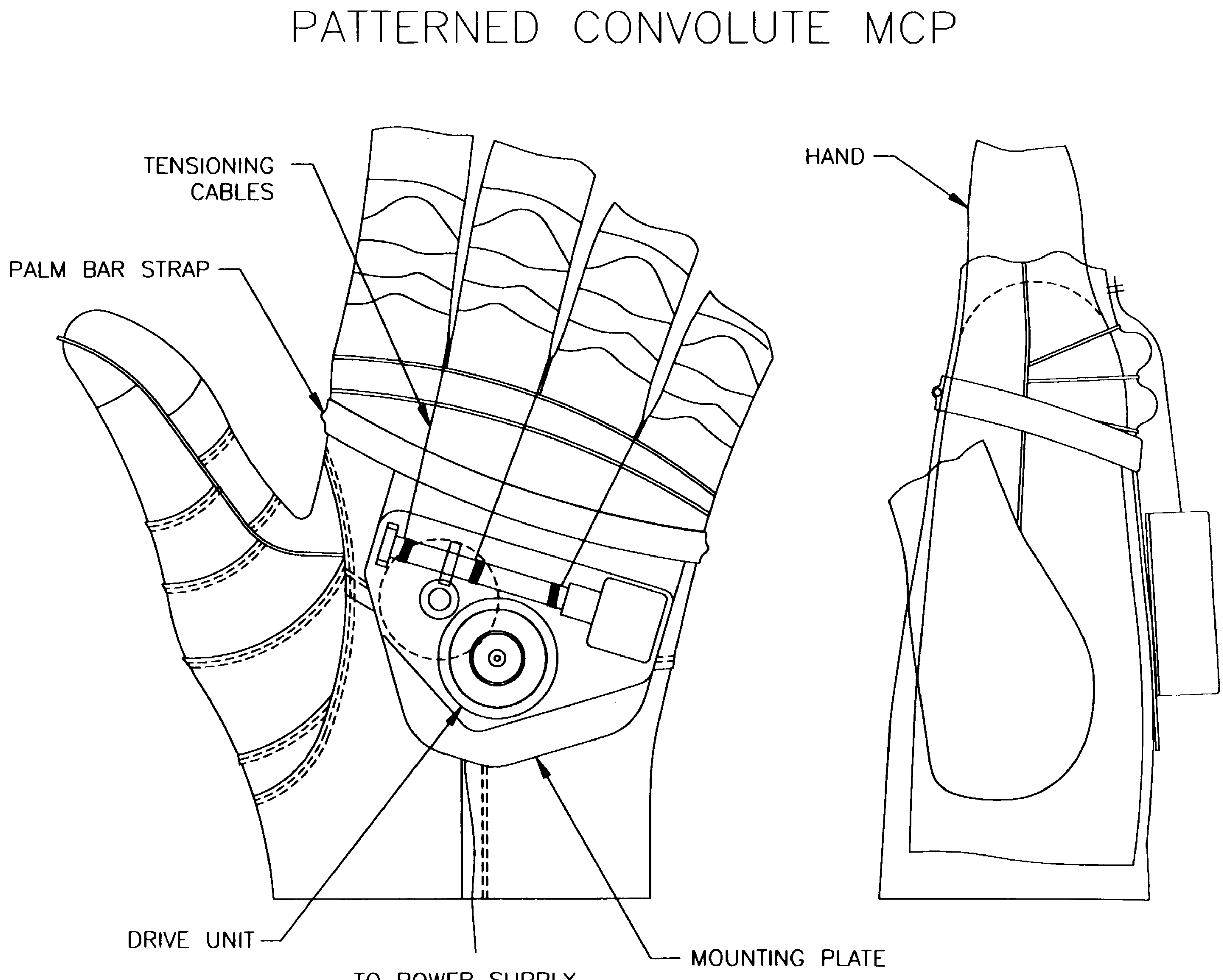
1. The MCP joint is patterned to give the proper run length when the joint is in a closed position (approximately 45° flex).
2. A composite plate is used on the dorsal side of the restraint to mount the actuation system to the glove, and transfer MCP joint loads into the gimble rings and wrist disconnects.
3. Composite plates are attached to the restraint rip-stop material via whip stitching around the perimeter of each plate.
4. For this effort, the actuation system power supply and digital control circuitry are located in a location remote to the glove.
5. Loads from the actuation system are transferred to the top of the MCP joint by means of low profile, low elongation cords.
6. Composite plate forming tools were generated using the stereolithography dip molds from the phase VI glove. These forming plates were then used to fabricate the finger and hand back composite plates.
7. The bladder was properly shaped and indexed in the MCP joint area to prevent increased joint torques from being created by the bladder.

### 2.1.1 Tucked Fabric MCP (Baseline Concept) - see Figure 1

The back surface of the MCP joint is patterned as a series of gores made by tucking the fabric under itself and stitching it to the neutral axis. Load from the actuation system is transferred across the MCP joint by means of three cords attached to the crotch seams. This concept is very simple to design and build, and established a baseline, upon which design improvements were made. However, due to the generally uncontrolled nature (i.e. ballooning effect) of this type of joint, torques can be relatively large. Additionally, the ballooning of this concept forces the fingers to move out of plane, creating potential comfort and fatigue problems.

### 2.1.2 Half Rolling Convolute MCP -see Figure 2

A rolling convolute (RC), which is a gore structure that rolls over top of itself, is used to form the MCP joint. One composite plate forms the upper surface of the convolute, and runs completely around the circumference of the palm area. The other plate forms the lower surface of the convolute, and pivots around a point located approximately on a line passing through the center of rotation of the MCP



PATTERNED CONVOLUTE MCP
TENSIONING CABLES
PALM BAR STRAP
HAND
DRIVE UNIT
TO POWER SUPPLY
MOUNTING PLATE


FIGURE 2

joint. No convolute is formed in the palm area of the hand, therefore the name "half" rolling convolute.

A complete RC was designed and fabricated on a previous NASA contract and demonstrated reduced MCP torque. However, the concept demonstrated stand off problems in the palm and sides of the glove due to the hardware used to create the RC. This situation will reduce tactility of the crewmember in the areas surrounding the hardware and may, in a worst case condition, prevent the crewmember from properly grasping an object.

The half convolute concept promises reduced MCP joint torques similar to the complete RC due to the controlled action of the rolling convolute design and the reduction in the effective volume of the joint. This reduces pressure loads (see **Figure 3**), but eliminates some of the hardware encumbrance. However, the concept still requires the added RC pivot hardware along the neutral axis of the index finger and little finger. The hardware on the index finger side creates a stand off in the area between the thumb and index finger and, as a result, creates difficulties when trying to grasp objects within the palm of the hand.

**Figure 3** graphically demonstrates the differences between a simple gore MCP and an RC MCP. The gored MCP bends around a line that is approximately in the palm of the glove and, therefore, changes the shape of "Area 2" shown in the figure. Conversely, the RC changes the shape of a relatively small area, "Area 1". "Area 1" is approximately 25% the area of "Area 2", which means roughly that the RC should offer MCP joint torques that are 25% of those seen with a gored MCP design. In practice, this level of torque reduction is not obtainable due to frictional effects in the RC materials, but the analysis does clearly demonstrate that RC's have the potential to offer joint torques that are substantially lower than standard gored joint designs.

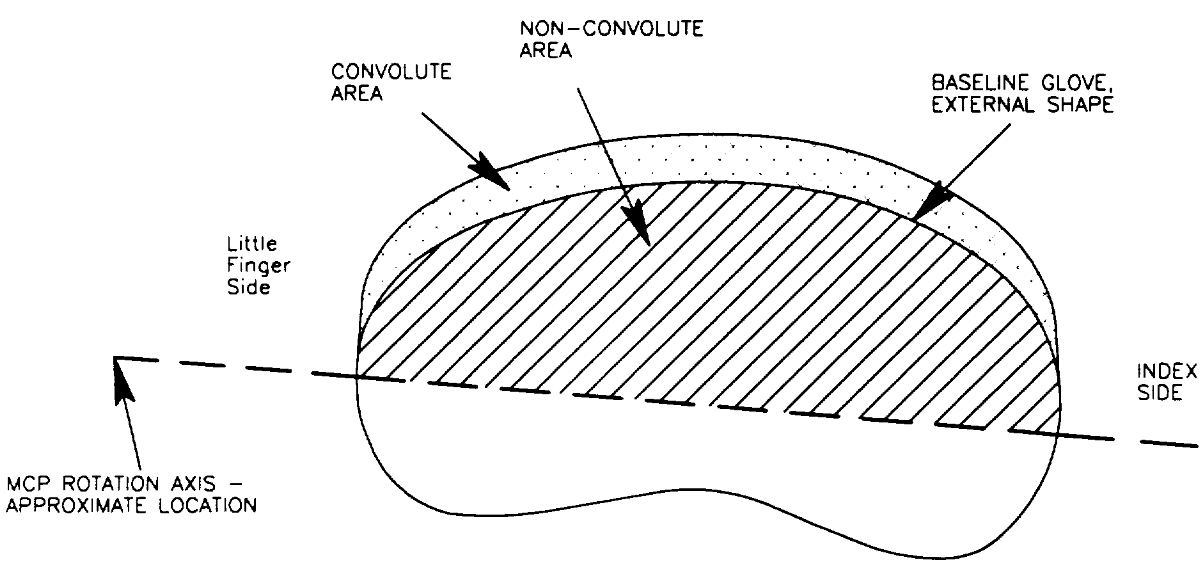



**Figure 3 - Glove MCP Cross-Sections**

### 2.1.3 Patterned Convolute MCP - see Figure 4

With this concept, the MCP joint is patterned as a series of gores that form convolutes when assembled. Webbings are used to create "tight lines" to stabilize the gores in three locations. The theory behind this concept is to create the extra run length required for MCP joint extension, while controlling the break points of the MCP convolute and preventing bulging of the softgoods. Both of these characteristics will reduce joint torques. This concept has been successfully demonstrated in the Phase VI wrist restraint joints.

### 2.1.4 Unjoined Rolling Convolute MCP - see Figure 5

This concept is a hybrid of the half rolling convolute and the tucked fabric concept. In this concept, a rolling convolute is created in the MCP joint area by using two composite plates which move relative to one another, with the restraint material and bladder material forming a convolute between the two. The composite plate used at the base of the fingers is also used to transfer the loads from the actuation system to the top of the MCP joint. As with the half rolling convolute concept, the controlling effect of the convolute reduces joint torques. This concept lacks the hardware standoff in the palm and side of the hand, and is expected to have low joint torques as previously described and shown in **Figure 3**.

## 2.2 Materials Issues

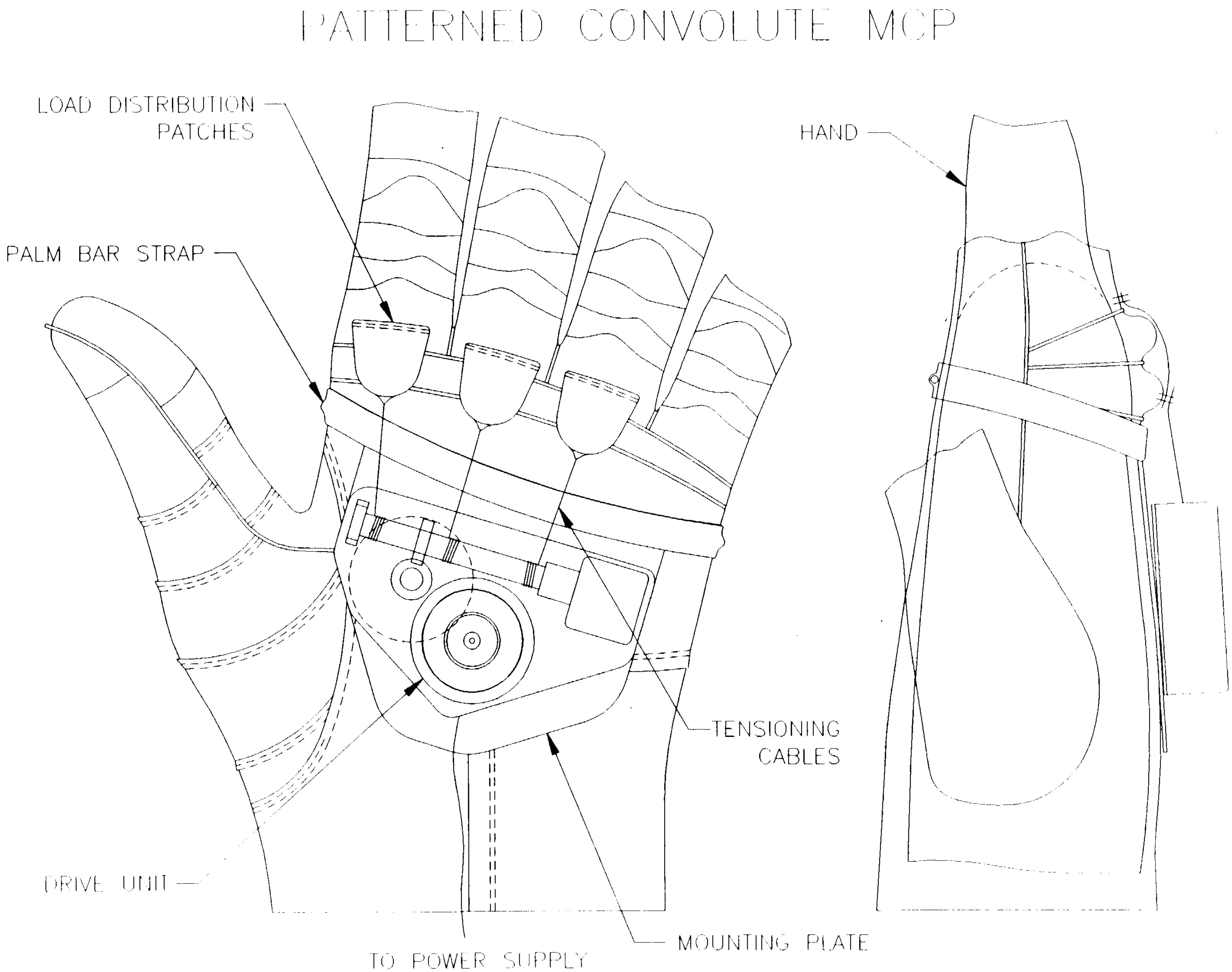
High stiffness to weight ratio, high tech composite materials were investigated for use in the mounting hardware and plates used to transfer loads across the MCP joint. Composite materials offer very low weight and low profile as a result. Graphite epoxy is a candidate material that will meet the high stiffness, low profile and weight requirements.

High modulus, low elongation materials are proposed for use in the tension cords which connect the actuation system to the glove. These materials store very little strain energy and, as a result, will not create oscillations or instability in the control system. Vectran cord is one material that is being considered for this application.

All materials, including the ones listed above, will also be selected based on no toxicity, no off-gassing characteristics.

## 2.3 MCP Joint Development and Test

Following the brainstorming efforts, design layouts each of the identified concepts were generated, analyzed, and tested to determine feasibility and MCP joint torques, and to provide a database for downselection to an optimal design.



PATTERNED CONVOLUTE MCP
LOAD DISTRIBUTION PATCHES
PALM BAR STRAP
HAND
DRIVE UNIT
TENSIONING CABLES
TO POWER SUPPLY
MOUNTING PLATE


**FIGURE 4**

# UNJOINED ROLLING CONVOLUTE MCP

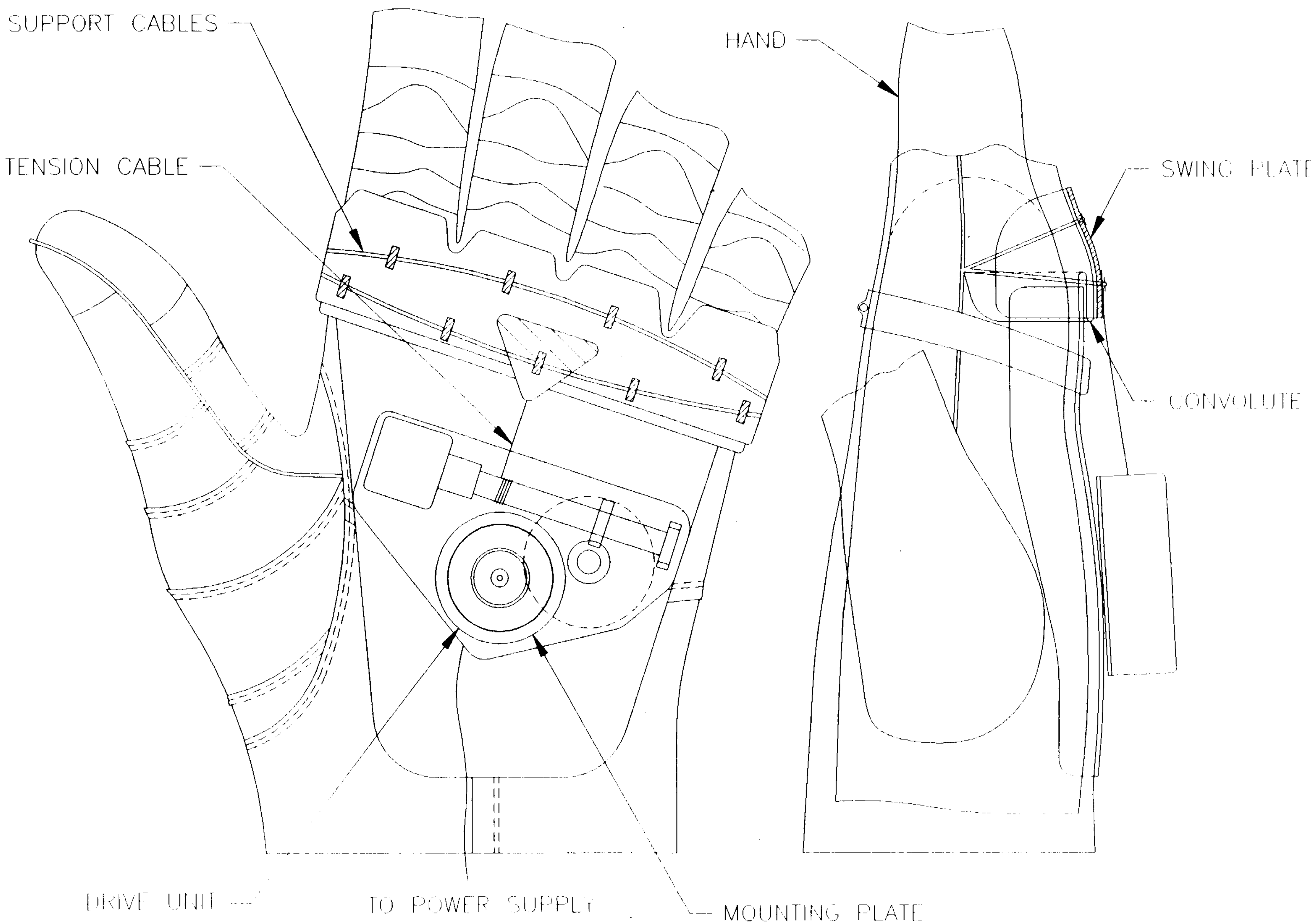



**FIGURE 5**

A test apparatus was designed and built in order to obtain an MCP torque comparison between each concept (see **Photo 1**). This apparatus allows the MCP resistive forces to be plotted vs. linear travel of the cable(s) which attach to the actuation system. The test apparatus also allows the rate of joint opening and closing be varied such that velocity effects can be studied. **Figure 6** shows a sample of the data generated with the test apparatus. The Y-axis shows load at the given X deflection of the Instron cross heads (deflection of the MCP joint is approximately 80% of this value). The top portion of the curve corresponds to movement from a hand closed to a hand open position, with the lower portion of the curve going in the opposite direction. The system currently demonstrates hysteresis, which is accommodated by the control software.

### 2.3.1 Tucked Fabric MCP Testing

The tucked fabric concept demonstrated very high torques required to extend the MCP joint. Testing of this concept revealed MCP loads of approximately 20 pounds in a full open position (approximately 45° of rotation). See **Figure 7**, which shows the actual test data obtained for this concept.

### 2.3.2 Half Rolling Convolute MCP Testing

The basis for the design of this concept was a rolling convolute MCP that was fabricated on another ILC/NASA contract. The MCP joint design demonstrated controlled operation and low torque MCP values. Due to the encumbrance of the hardware required in the palm of the glove and the pivot hardware required, this concept was not considered feasible for EVA use and therefore was not fully mocked-up for testing . However, the basic concept of this type of joint design was used to baseline the unjoined rolling convolute design.

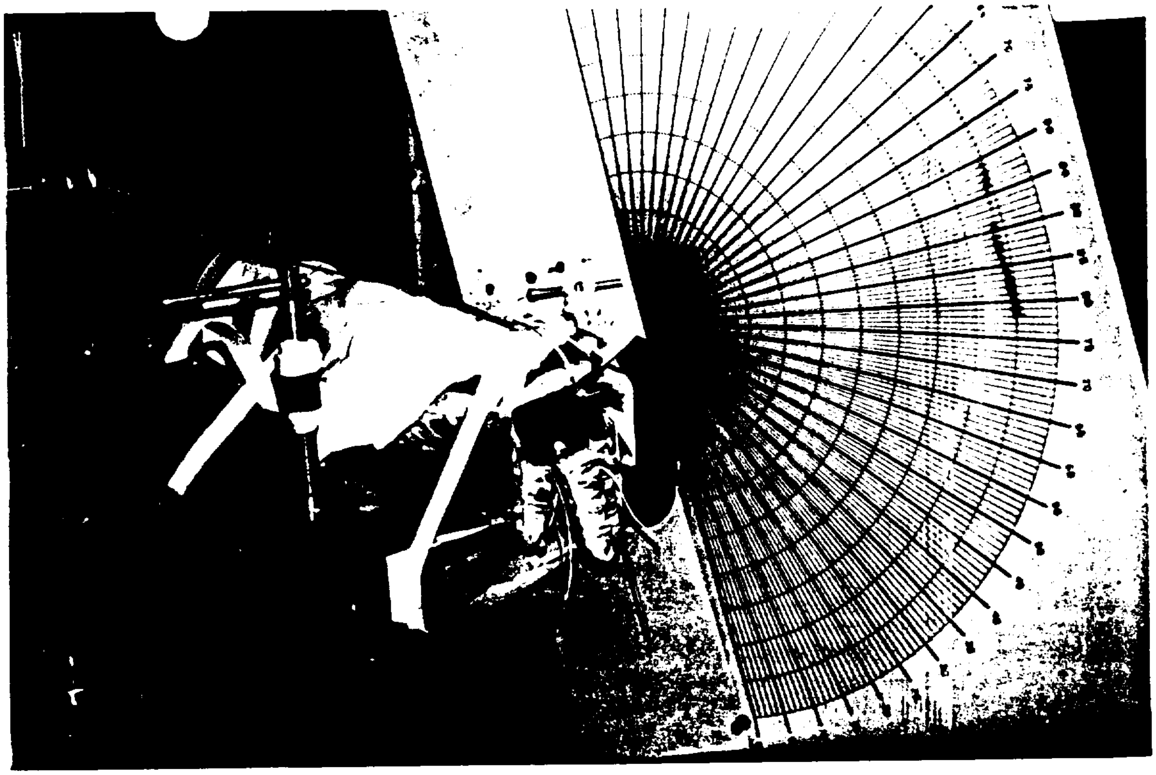
### 2.3.3 Patterned Convolute MCP Testing

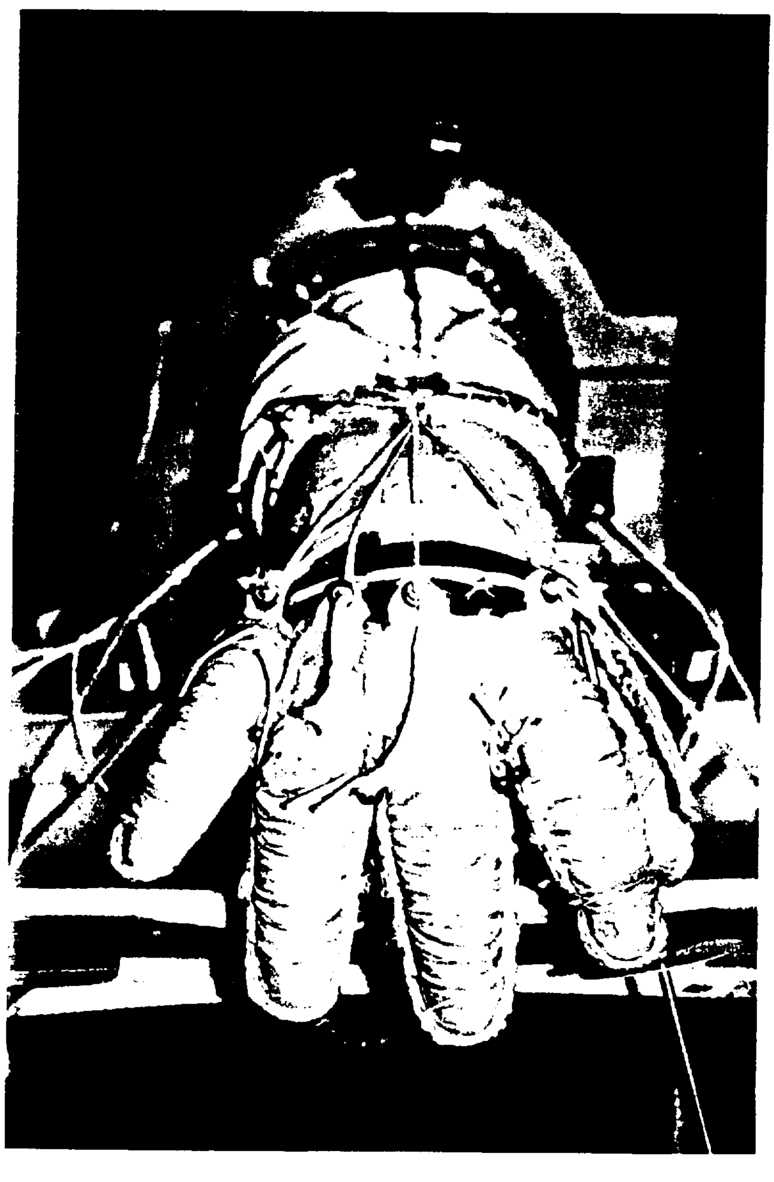
As previously mentioned, a design similar to this is used in the Phase VI restraint wrist joint, and has demonstrated low torque operation. This concept has not been fabricated and tested at present, but will be as part of Phase I on-going activities.

### 2.3.4 Unjoined Rolling Convolute MCP Testing

An initial prototype of this concept was built and tested as shown in has revealed **Photo 2**. Testing showed a maximum load of 13 lbs required to fully open the MCP joint (see **Figure 6**, which shows the actual data). This value, which is 65% of the maximum load value measured for the tucked fabric concept, demonstrates a substantial improvement in MCP joint performance. There are areas of improvement with this concept that are currently being studied, including:

1. Stiffening the composite plates used to minimize restraint ballooning.
2. Reducing the profile and weight of the composite plates used to maximize comfort and minimize encumbrance of the system.





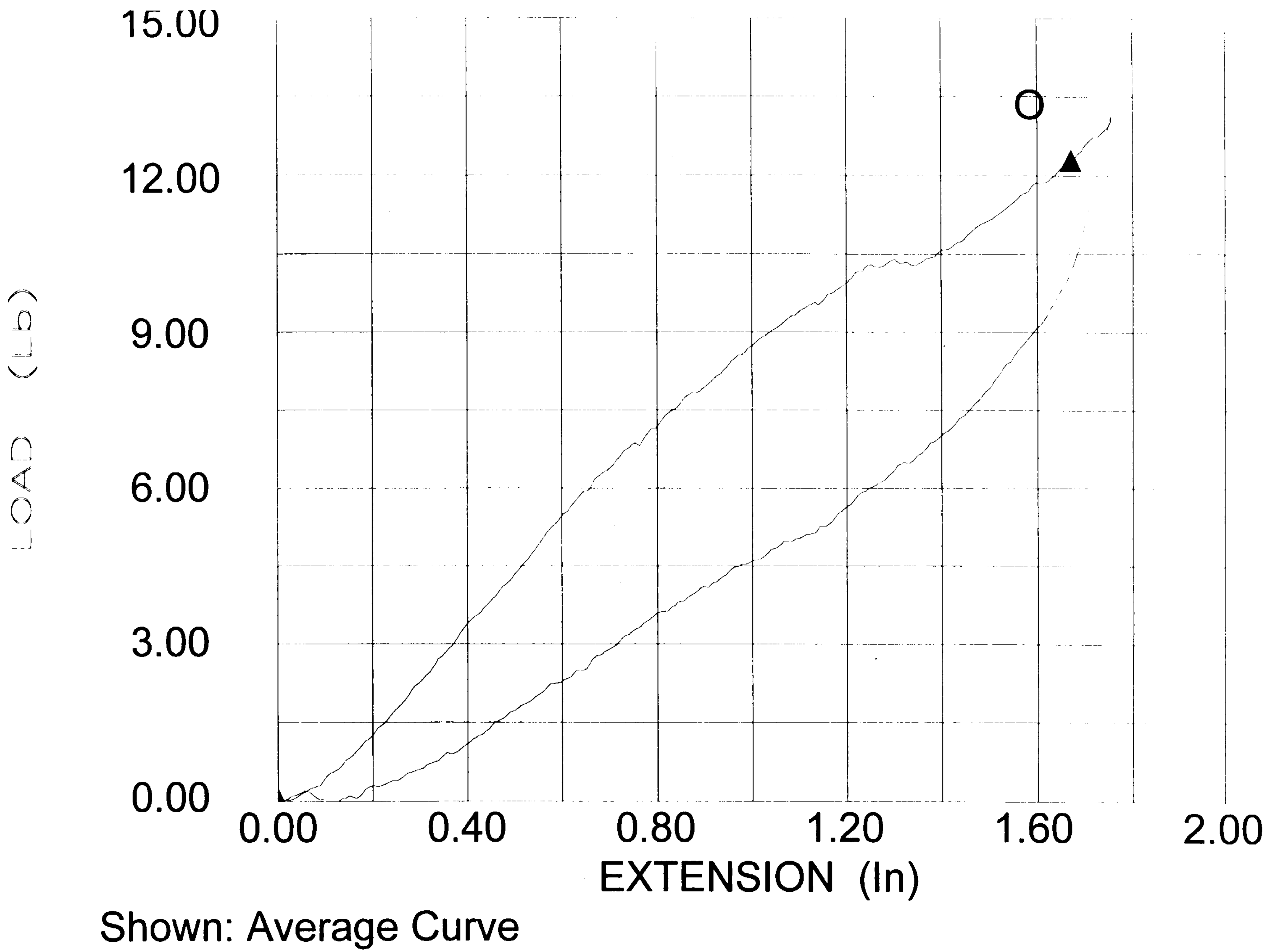
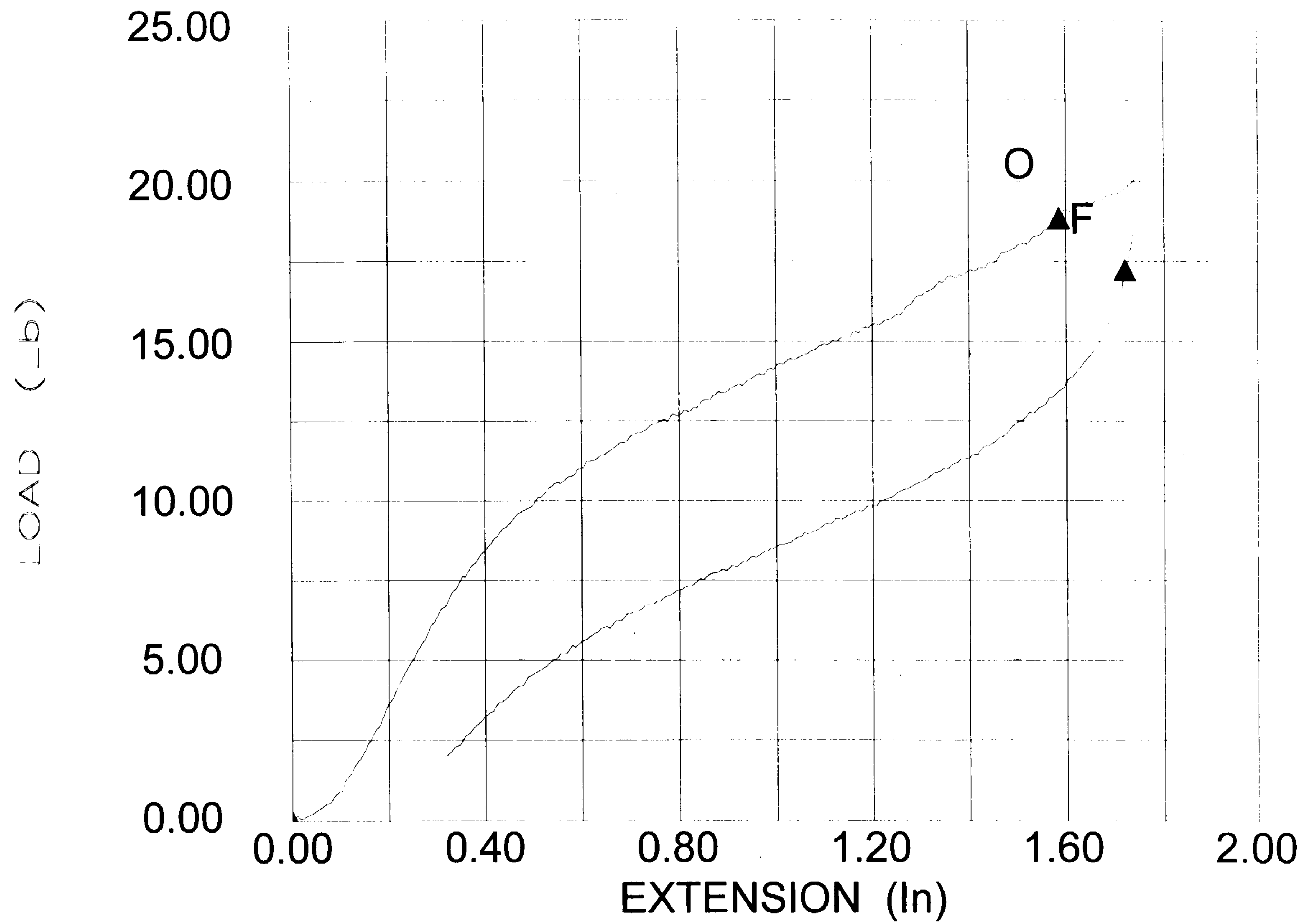

15.00
12.00
9.00
6.00
3.00
0.00
LOAD (Lb)
0.00
0.40
0.80
1.20
1.60
2.00
EXTENSION (In)
O
Shown: Average Curve

FIGURE 6


25.00
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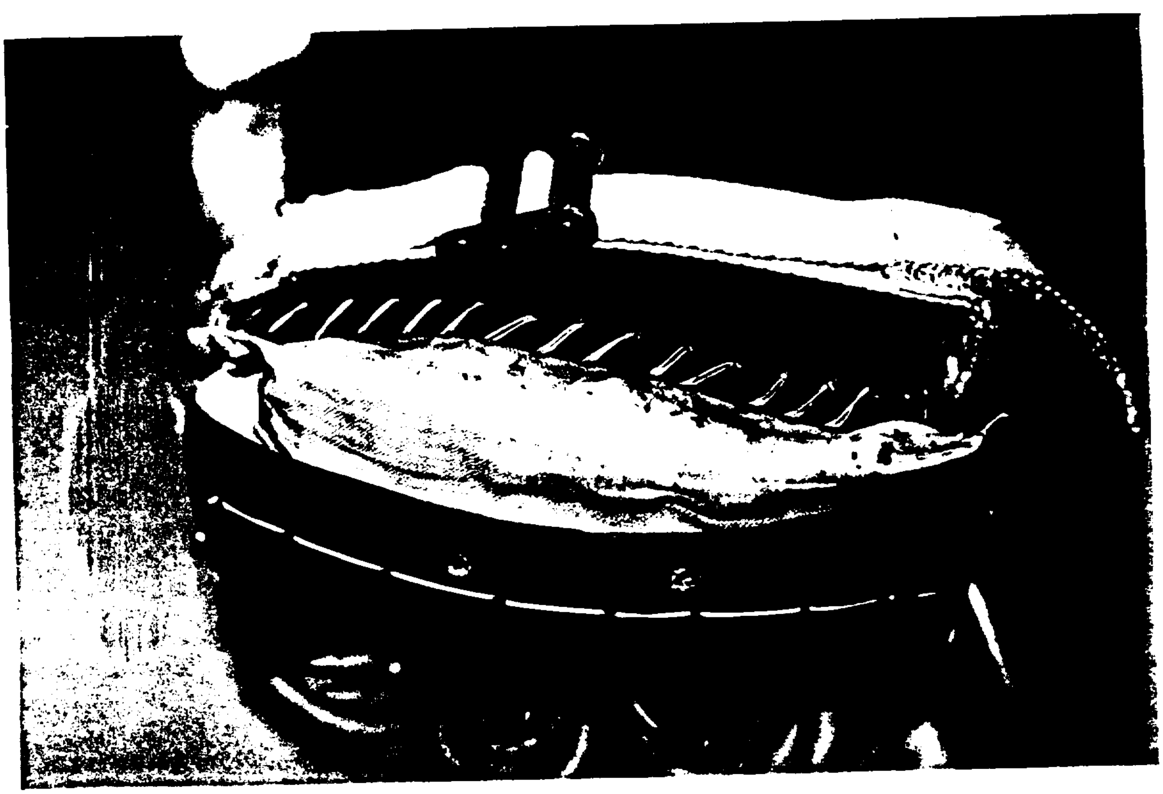
EXTENSION (In)

FIGURE 7



3. Improving the geometry of the composite plates to more closely match the profile of the pressurized restraint, thereby reducing MCP joint torque.
4. Repatterning the bladder in the convolute area to give better restraint/bladder interface to reduce MCP joint torque.
5. Improving the transition of the convolute into the neutral axis to make MCP joint movement low torque and smooth.

All items listed above will reduce MCP joint torques. ILC anticipates that MCP joint loads (and subsequent torques) can be reduced to a value below 10 pounds. This is within the performance abilities of the baseline design of the actuation system.

### 2.3.5 Tucked Fabric Concept With Passive Actuation System Testing

The tucked fabric concept was built and tested using the aforementioned test apparatus. Additionally, a passive coil spring system was built per the work of J. Main (see reference section) and was qualitatively evaluated. The theory behind the system is to use springs, or similar, to counteract the torque loads in the MCP joint. The system works independently of any type on control system and is, therefore, designated as a passive system. The design of a passive system is very simple relative to an active system, and, if made to work, would provide a low cost, simple solution to the problem. For that reason, the system was prototyped and tested to determine its applicability for this program.

However, as demonstrated by subjective torque data obtained for this concept, the passive system demonstrated poor performance in trying to simulate "nude" hand performance. This lack of performance can be attributed to the fact that the maximum force from the "actuation" system is required when the MCP joint is in a fully open position, but that the coil springs exert their minimum force in that position. This requires a compromise where the zero load (neutral position) is chosen to be somewhere between a completely open and completely closed position. Near nude hand performance is, therefore, not obtainable with this type of passive system. But, this system provides better MCP joint performance than one without it, and it is very simple and cost effective. Therefore, it will be investigated further in Phase II of the program.

### 2.3.6 Glove Testing Conclusions

Based on the evaluations described above, the unjoined rolling convolute was chosen for further development and testing. This conclusion was based on the reduced MCP joint torques (approximately 65% of the baseline concept torques) obtained with this concept. Additionally, since the concept does not have any hardware in the palm of the hand, the concept does not interfere with normal glove operation, including grasping of objects in the palm of the hand.

Other benefits of the half rolling convolute system include its compatibility with the baselined, low profile actuation system. Namely, the actuation system required for actuation of such a low torque joint design allows it to fit within the available real estate on the back portion of the restraint. Reducing actuation system profile minimizes the chances of the system impairing EVA activities, such as placing the hand inside of a relatively confining area. A lower profile actuation system and lower torque MCP joint will also have lower inertial forces, meaning that response times can theoretically be increased. As can be seen, lower MCP joint torques affect a wide range of performance areas crucial to satisfactory EVA activities.

The passive system demonstrated limited effectivity with the tucked fabric concept. However, the passive system will be revisited with the half rolling convolute since RC joint torques can be made to be more linear in nature and, as previously mentioned, do demonstrate lower torque values. These two desirable characteristics make passive systems, which tend to be linear or constant in nature, more feasible for counteracting MCP joint torques.

## 2.4 System Modeling

### 2.4.1 Requirements:

The modeling task must provide an accurate account of the relation between glove properties and applied external forces or torques, and the resulting motion of the glove MCP joint. It must also provide a specific characterization of the physical properties of the pressurized glove and the actuators used in the control system. The resulting model must be expressed in a manner which allows the specification of a compensating control strategy employing the selected actuators and sensors.

### 2.4.2 Candidate technologies:

Elementary physics can be used to develop a lumped parameter dynamic model of the motion of the MCP joint, and of the interaction between the glove and the specific actuator technology chosen. Additional degrees of freedom can be incorporated into such a model as needed using the same principles. A variety of data fitting and system identification techniques, such as least mean square (LMS), autoregressive moving average (ARMA), nonlinear ARMA (NARMA), and adaptive Kalman filtering algorithms, can be used to estimate static and dynamic parameters within the assumed model using experimental glove and actuator data [Eubank, Lyung, Goodwin & Sin].

### 2.4.3 Selected technology:

*Physical Modeling:*

As a first iteration, it is assumed that a one degree of freedom model of the motion of the MCP joint will be sufficient. This assumption will be modified in subsequent iterations depending upon the outcome of the initial system identification process. The single degree of freedom corresponds to ideal rotation of the MCP joint; that is, to a first approximation, it is assumed that the astronaut's hand is snugly encased in the glove of a pressurized spacesuit and that the fingers move in unison. This results in a second order model of the form:

$$(J_g+J_h)\, d^2/dt^2(q(t)) + b(d/dt\, q(t))+B'(d/dt\, q(t)) + k(q(t)) + K'(q(t)) = \tau(t)$$

where b and k are damping and elastic properties of the unencumbered (nude body) MCP joint rotation, q(t), with angular velocity d/dt q(t), K' is an additional restoring spring-like torque due to the pressurized glove, corresponding to its tendency to return to a closed position, while B' is a glove-induced damping torque. Finally $\tau(t)$ is the torque generated by the astronaut's muscles, while $J_h$ is the unencumbered rotational inertia of coordinated MCP joint motion and $J_g$ is similarly the rotational inertia of the glove MCP joint.

The task of the controller will be to provide an external "power assist" torque, to remove the need for the astronaut's muscles to counteract the torques associated with the physical properties of the pressurized glove, potentially reducing fatigue. In order for the controller to properly execute this function, an accurate model of the physical properties of the glove must be obtained: that is, the system identification subtask must provide accurate characterizations of the spring-like and damping torques, K' and B', as a function of the displacement of the MCP joint away from its nominal equilibrium.

The model used for developing this control strategy, however, must take into account the specific method by which the power assist torques are implemented. Taking into account the dynamic and kinematic relations imposed by the selected actuation and sensing technologies, the lumped second order model becomes:

(1) $$(I_m+I(\theta))\, d/dt\, (\omega) + K(\theta) + B(\omega) + f(\omega) = \tau_m$$

where now K and B are the spring-like and damping torques due to the glove, reflected at the motor shaft, $\theta$ is the motor shaft angle, measured by the digital encoder, $\omega$ is the shaft rotation rate, and f is a friction torque due to the gearing of the motor assembly. $I_m$ and $I(\theta)$ are, respectively, the motor inertia, and inertia due to the glove reflected at the motor shaft.

*System Identification:*

The final downselect of a system identification strategy will be highly dependent upon the nature of the data collected, and will focus separately on glove properties and actuator properties. The specific glove properties which must be identified are B and K, while the actuator properties which must be identified are $I_m$ and f. Manufacturer's specifications for these latter two quantities will be initially used, and system identification techniques similar to those described below will be used if the initial performance of the system is unsatisfactory.

To characterize the glove properties, initially static torque-displacement data will be collected using an unpowered glove, attempting to measure directly the variations of $K(\theta)$ with the rotation $\theta$. This data can be collected early in the system development process, using a glove equipped with actuator cables connected to an (unpowered) shaft equipped with a digital encoder. Known constant torques will be applied about the encoder shaft, and the resulting shaft rotation recorded. Samples corresponding to MCP deflections ranging from 0 degrees to 45 degrees, spaced 5 degrees apart, should be sufficient to accurately determine K. Several measurements of the MCP angle resulting from a specific torque will be taken, and the variance of the measurements assessed. The resulting data will then be fit using a covariance weighted LMS technique, first using a linear model, then using first and second order fixed knot spline models. The model with the smallest LMS deviation will be considered a nominal candidate for use in the controller design.

Depending upon the nature of the "damping" term B, however, these measurements may not be sufficient to accurately identify K. For example, if there are significant Coulombic friction effects, i.e. $B=B_0\ \mathrm{sign}(\omega) + B_1(\omega)$, then the static torque-displacement relations may contain errors of magnitude $2B_0$ in the amount of torque required to produce a given MCP deflection. If $B_0$ is substantial, the resulting model inaccuracy may contribute to poor performance in the powered system. To determine the contribution of such effects to the model, additional dynamic data will also be collected from the unpowered glove, by varying the applied torque as a known function of time, and measuring the resulting time histories $\theta(t)$, $\omega(t)$ The resulting data will be fit using adaptive Kalman filtering techniques using ARMA and NARMA models: first order spline basis functions will be used in the NARMA modeling. As with the static data, the model with the smallest LMS deviation from the observed dynamic data will be considered a nominal candidate for use in the controller design.

Figures 1-3 in attachment A summarize an example of reducing noisy, time-varying torque displacement relations from simulated glove MCP dynamics using an adaptive NARMA model; that is, assuming that $I(\theta)=I$ (a constant), $K(\theta)=K\theta^3$, $B(\omega) = B\mathrm{sign}(\omega)\omega$, where K and B are constants The plots show the asymptotic convergence of estimates, $I_e$, $K_e$, and $B_e$ to values very near those used in the glove simulation model.

### 2.4.4 Outstanding issues:

A high quality model requires high quality (low noise) data, and samples of the dynamic properties of the glove at a rate corresponding to the rate at which active control system will operate. Accordingly, the system identification data should be collected using the same high resolution encoders used in the final actuation system, and at the same rate (100Hz) at which the controller will operate.

Another issue is the degradation of the model when non-coordinated finger motions occur. There are two possibilities: first, the motions may produce only small discrepancies from the lumped second-order model. In this case, these independent motions may be left "unmodeled", or rather considered as small magnitude disturbance torques influencing the dynamics (1). Such small perturbations should have minimal impact on the closed-loop motion of the glove using the nominal control strategy described below The second possibility is that independent finger motions will create significant changes in both the effective inertia I, as well as in the glove stiffness and damping characteristics. This situation would require that the position of each finger of the glove be independently sensed, and the model adjusted to allow for variations in I, K, and B with each potential finger pose.

## 2.5 Range of Motion Sensing System Development

### 2.5.1 Requirements:

A sensing system needs to be developed that can accurately sense the position of the joint or force initiators indicating the desire to move the joint.

The feedback from the joint angle sensor provides the input for the control system. Since a single joint is controlled, the minimal system requires one angle sensor. The baseline sensing system will measure the joint angle of the metacarpophalangeal (MCP) joint.

Two approaches can be taken; the angle can be measured at the hand internal to the suit or at the actuator external to the suit. Sensing the actuator angle instead of the hand angle avoids interfacing with suit internal and external electronics. Both of these measurement schemes are valid if all four fingers are modeled to rotate at the same time and same rate.

Another possibility exists where each finger is sensed and actuated independently. This would be a much more complicated design approach, and is one that will be explored in the future.

The motion sensing system needs to be capable of including the full range of motion of the MCP joint (approximately 0 to 45 degrees) at maximum MCP flexion/extension speed. Although the glove slows the hand's speed of motion, the sensor system should be capable of accurately measuring the angle during nude body performance.

Packaging should be designed to minimize interference with the glove's normal operation. In particular, the palm and fingertips of the glove should be free of external hardware.

Low power requirements will reduce power system size, but no specific standards are set for the prototype system.

For final production, the sensor system needs to meet the pressure suit lifetime requirement of 461 operational hours. Although the prototype system doesn't need to meet this requirement, it will be a design goal.

### 2.5.2 Candidate Technologies:

The candidate sensor systems can be divided into three categories: internal to the suit, either internal or external to the suit, and external to the suit. Internal sensors have the advantage of sensing the actual hand position rather than the glove position. With the goal of nude body performance, this angle is a more accurate representation of the desired suit angle. However, mounting electronics inside the suit is more problematic than an external system. Additionally, the signal needs to be transmitted to the motor and processor which are external to the suit. Two candidate sensors that could potentially predict motion before the glove moves are also discussed. The EMG and force sensors must be mounted internal to the suit. Although these sensors don't measure the MCP joint angle, they could be used to measure precursors to movement. Movement intention and direction could be used in a feedforward loop for the control system. Although the baseline control strategy only requires a feedback loop, the feedforward loop is an outstanding issue in the control system design.

#### 2.5.2.1 Internal:

These sensor systems must be mounted internal to the suit. Since these sensors don't measure the MCP joint angle an additional sensor would be required, increasing the complexity of the system.

Electromyography (EMG) sensor:

EMG sensors measure the electrical signal produced by muscles during contraction. The electrodes are mounted to the subject's skin above the muscle of choice. For the power assisted joint the onset and direction of motion could be determined. An advantage of this sensor is the ability to predict the onset of motion before it occurs. However, EMG signals vary significantly with electrode placement and individual characteristics so implementation would be difficult.

Force sensor inside glove:

Force sensors at the fingertips can measure the initial pressure between the hand and the suit before the hand actually moves the glove. However, correct glove fit requires some static pressure at the fingertips to maximize tactile feedback to the suit subject. This pressure may be hard to distinguish from the additional pressure during motion. Additionally, electronics or sensors at the fingers or palm may interfere with glove performance, limit dexterity, or cause discomfort.

#### 2.5.2.2 Internal/External:

These systems may be mounted either inside the glove or external to the glove. However, they are designed to measure a bend along an arc (rather than at a joint center) so a precise mounting system is difficult.

Fiber optic sensors:

*In-house JAMS:* A fiber optic joint angle sensor has been developed by the University of Maryland Space Systems Laboratory. The system includes a transmitter with an LED as a light source, a fiber optic cable, a receiver, and associated electronics. This sensor system measures light loss across the fiber optic cable as the cable is bent. The cable is etched over a small angle so the sensitivity is much greater over a reduced area of interest. Advantages of this system include a small, flexible sensor and the option of locating electronics at a distance from the joint (reducing bulk near the hand). However, this system has a deadband near the zero angle, and is currently only accurate for a fairly small angle range (45 degrees). Additionally, the fiber optic sensor is difficult to mount precisely to a rotary joint.

*5th glove:* The 5th glove is an off-the-shelf fiber optic glove marketed by General Reality Inc. The system includes a glove with a fiber optic sensor for each digit, LEDs as transmitters, receivers, and a signal conditioning box. The individual sensors are read through a standard serial link. This system is currently in use for JAMS testing. Initial testing shows a good sensitivity over the entire range of motion. However, this system is shipped configured for five joint angles so significant modifications need to be made for this application. Also, each sensor measures total finger bend rather than isolating a specific small arc along the fiber. Therefore, the angle measured by the 5th glove may not accurately correspond to just the MCP joint position.

Force sensing resistors:

Force sensing resistors are also sensitive to bend. These sensors have two conductive strips running the length of the sensor separated by an air space. Either pressure or flexure causes the conductive strips to touch which decreases the resistance across the sensor. Since these sensors are sensitive to pressure, mounting them without pressure points is difficult. The sensors also exhibit a substantial deadband in the low angle range and hysteresis.

Bend sensors:
The bend sensor is a flat 1/4 inch wide film that can be cut to the required length. The sensor consists of an outer covering, a carbon-based ink layer and conductive silver bands. As the sensor is bent, microfissures in the carbon layer increase the resistance. These sensors are not sensitive to pressure; a sample is on order. Sensor deadband and repeatability need to be tested.

#### 2.5.2.3 External:
These sensors must be mounted external to the glove, they are too cumbersome to fit inside the glove, and they need to be mounted to a joint center. Either sensor would be mounted to the motor drive shaft. The prototype system is designed such that the rotation of the drive shaft varies linearly with the MCP joint angle.

Potentiometers:
A rotary potentiometer can be mounted to the motor shaft to measure the angle. The feedback is an analog signal proportional to the rotation angle of the shaft. Advantages of this system include simplicity, off-the-shelf hardware, and reliability. Several concerns exist including some variance in linearity, temperature dependence, noise, and additional electronics for A/D conversion.

Optical encoders:
Encoder packaging is similar to potentiometers, but the signal is digital. Position and direction are measured via two output channels in quadrature (90 degrees out of phase). These sensors are not sensitive to temperature, and are more accurate than potentiometers. However, since the encoder is incremental, absolute position cannot be determined.

### 2.5.3 Selected Technology:
The baseline design for the power-assisted joint includes a single external joint angle sensor. This design doesn't require interfacing internal and external suit electronics. Mechanically, the potentiometer and encoder are the easiest sensors to interface with the actuator. Since the encoder is digital and more accurate it is baselined for the system.

### 2.5.4 Outstanding Issues:
The prototype design includes a single sensor for the MCP joint. Since the glove torque versus MCP angle curve may depend upon individual finger orientation, additional joint angle sensors may improve the system performance.

## 2.6 Control System Development

### 2.6.1 Requirements:
The control system must generate, via the chosen actuators, the external "power assist" torques required to compensate for the physical stiffness and damping of the pressurized glove. More specifically, the control system must compute, from

the measurements provided by the chosen sensor technology, the specific commands which will cause the selected actuators to create the required torques about the glove MCP joint. These calculations must be accomplished at a rate which will maintain satisfactory operation across the nominal, "nude body", performance envelope. Properly tuned, the control system should generate torques which render the glove almost imperceptible; that is, ideally an astronaut should not perceive that any additional effort is required to accomplish rotation of the MCP joint when the glove is pressurized and the control system is active.

### 2.6.2 Candidate technologies:

The control task breaks into two components: the control *algorithm* and the controller *implementation.* The control algorithm can be either feedforward or feedback, linear or nonlinear [Ogata, Slotine & Li]. The controller implementation can be either analog, constructed from conventional op-amp circuits, or digital, requiring software and an embedded microprocessor.

### 2.6.3 Selected technology:

*Control Algorithm:*

The first decision in the selection of the control algorithm is between a feedforward or feedback design. Feedforward control requires sensors which can predict in which direction the system will be required to move in the near future [Ogata]. In the current setting, this would require complex biomonitoring of the astronaut together with identification of appropriate neuromuscular precursors of MCP joint motion. Fortunately, inspection of the assumed dynamic model (1) shows that, assuming the glove stiffness and damping terms, B and K, are sufficiently smooth (no jump discontinuities), the motor torques, $\tau_m$, required to offset their effects on the motion of the MCP joint can be computed by a feedback control strategy which uses instantaneous measurements of the current MCP joint angle and velocity (or equivalently, the motor shaft angle and speed, $\theta$ and $\omega$). The actuator friction torque, $f(\omega)$, can be similarly offset by a feedback control strategy.

The baseline control strategy may thus be written as

$$\tau_m = K_e'(\theta) + B_e'(\omega) + f_e(\omega),$$

where $K_e$ is an estimate of the glove stiffness, $B_e$ is an estimate of the glove damping, and $f_e$ is an estimate of the actuator friction. This control algorithm attempts to keep the glove "neutrally stable" about each possible MCP joint angle, balancing the torques generated by the glove with the net torque generated by the actuators. The estimates used in the above control law will be determined by the outcome of the system identification subtask. In particular, the choice between a linear or nonlinear control strategy will be determined by the nature of the estimated stiffness and damping: if the data collected during the glove testing indicates significant nonlinearities in either of these terms, then these nonlinearities will be incorporated into the feedback control computations.

*Control Implementation:*

If the estimates $K_e$, $B_e$, and $f_e$ in the above control law are linear in their arguments, this feedback control strategy could be easily implemented using an analog electric circuit. Such an implementation has three main drawbacks: First, since the effectiveness of the chosen control strategy will be highly dependent upon the extent to which it negates the effects of the corresponding physical torques K, B, and f, precise, very low tolerance components would be needed in the analog circuit. Second, the exact values of the components which would be needed will depend upon the corresponding physical glove parameters, which may change either with time or with glove dimensions, requiring a component change in the circuit. Finally, it is possible that the system identification subtask will determine that K, B, and f are nonlinear, resulting in a feedback control law which is not well suited for an analog implementation.

Digital implementation of the controller allows precise, complex calculations to be performed, and accommodation of changing glove properties is easily accomplished by a small change in software (in fact, this accommodation can be made automatic, by making the control law adaptive [Slotine & Li], but this avenue will not be explored in the baseline controller implementation). Digital control of a continuous-time system, however, introduces specific constraints on the rate at which control calculations must be performed to assure satisfactory performance. A standard rule of thumb is that the sample rate must be 10-20 times the bandwidth of the controlled system [Franklin, Powell, &Workman]. Since the above control strategy will theoretically allow near nude body motion of the MCP joint, the controller should have a loop rate 10-20 times faster than the maximum frequency of unencumbered MCP joint rotations. Assuming a maximum frequency for these rotations of 4-5 Hz, the controller must make new calculations approximately 50-100 times per second.

With currently available microprocessors, processing speed does not drive CPU choice. Primary considerations for the production system CPU include low power, and small size. Although these parameters don't drive the prototype design, a portable system is preferred. The baseline CPU is a 68332 Tattletale board by Onset Computer Corporation. This board is 2" by 3" by 0.5" and requires 100 mA at 7-15 volts.

### 2.6.4 Outstanding issues:

The feedback control strategy above may not produce the desired results if the glove damping term contains significant Coulombic friction effects, i.e. if $B(\omega) =$

$B_0$ sign($\omega$)+$B_1(\omega)$, where $B_1(\omega)$=0. In this case, whenever the glove is motionless ($\omega$=0), the astronaut would need to apply a torque of magnitude at least $B_0$ before the joint would begin to rotate, defeating the desired "imperceptibility" of the glove. A feedback control strategy like that above is ineffective in this situation, since it can apply a compensating torque only after the joint has begun to rotate. Effective compensation for this kind of nonlinearity in the glove damping properties would require a feedforward of desired MCP joint rotation, and would thus require the more sophisticated biosensing and motion prediction indicated above.

## 2.7 Actuator Configuration

The EVA glove used for the prototype power augmentation system has been modified to incorporate a mobility joint at the MCP location. The glove restraint is patterned to maintain a closed (grasped) neutral position of this joint when pressurized. The power-assist actuation system consists of up to three cables attached to the glove restraint lines (seams) that terminate just above the MCP joint in the area of finger crotches. The cables connect to an actuator mounted on a conformal composite plate attached to the glove restraint layer on the dorsal side of the glove, just below the MCP joint. Tension in the cables applies an opening torque to the MCP joint. The actuator applies force only in the opening direction; sufficient closing forces are inherent in the glove design. This design keeps the palm area of the glove clear of extra mechanisms, to avoid interfering with dexterity, palm tactility, and mobility.

### 2.7.1 Requirements

The actuator system must meet a variety of requirements. Performance requirements derive from the goal of nude-body equivalence for the MCP joint. Safety requirements derive from established EVA hardware guidelines.

These requirements must be met simultaneously. For instance, the actuator must be capable of producing the peak force required while at the maximum acceleration and velocity. Thus, the actuator must be able to sufficiently accelerate its own inertia and overcome internal friction with enough excess force capability to apply to the glove.

*Peak Force:*

A preliminary estimate of the maximum restoring force provided by the EVA glove being developed for this application is 13 lbf. Testing of the actual hardware will refine this value, but this is the working figure used in the design of the prototype actuator. The prototype system is not intended to compensate for the inertia of the EVA glove, just the restoring force, so 13 lbf is the required value at all velocities and accelerations.

*Range of Motion:*

Based on the proposed geometry of the prototype actuation system, the range of motion of the cables required is 1.25 inches. Maximum extension occurs in the fully-grasped glove position.

*Maximum Acceleration and Velocity:*

Acceleration and velocity requirements for the prototype system are derived from a nominal quickest closure time for the MCP joint of 1/8 second. This value corresponds to a typical nude-body maximum performance rate of 4 cycles per second from fully open to fully closed and back. In this motion, the actuating cable traverses its full range of 2.5 inches in 1/8 second. Assuming constant acceleration for 1/16 sec, and constant deceleration for 1/16 sec, the acceleration value required at the cable is 320 in/sec$^2$. The maximum velocity required for the cable is 20 in/sec.

The implications for actuator design are to require low actuator inertia and friction, and rapid response to a commanded force. Overall force control bandwidth must be above 4 Hz to follow the maximum performance trajectory. If an actuator has significant internal dynamics, they must have a bandwidth at least an order of magnitude above this value. The force rise time of any acceptable actuator must therefore be less than 25 milliseconds.

*Packaging:*

The prototype actuator is intended to point the way to a feasible production system, so packaging constraints are stringent. The actuator and sensor are located on the dorsal side of the EVA glove, outside the pressure bladder. To avoid interfering with dexterity, these mechanisms must not extend beyond the edges of the hand. This restricts their usable footprint to a trapezoidal area roughly 3 inches on one side and 2 inches on the opposite (parallel) side, separated by 2.5 inches. Overall height should not exceed 1 inch. The power supply and microprocessor can be located remotely, and the prototype may use larger components than would be selected for a production system. See **Figure 8** for details.

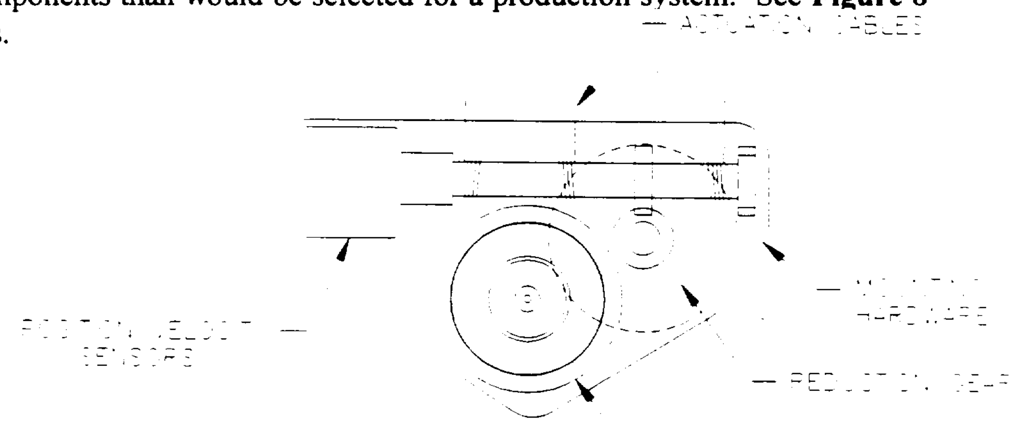


**Figure 8 - Actuation Hardware**

*Power Consumption:*

No specific limits on total power consumption can be stated initially. Any viable system must provide sufficient power for a six-hour EVA duration, and provide for the rejection of heat dissipated in operation. Voltages may not exceed 30 volts, for reasons of operator safety.

*Reliability:*

The actuation system must be designed to fail safe. Specifically, no failure mode can compromise the integrity of the pressure suit or prevent the operator from performing the manual tasks needed to ingress the airlock.

*Lifetime:*

The basic lifetime requirements for a production actuator system correspond to the design requirements for the rest of the pressure suit, with a minimum useful life of 8 years, and minimum operational life of 461 hours. The prototype system need not meet these requirement, but the technology involved must be compatible with them.

### 2.7.2 Candidate Technologies

*Pneumatics and Smart Gels:*

Pneumatic actuators, including "artificial muscles" or smart gels, have some advantages in this type of application. They exhibit an inherent roughly-linear stiffness which depends on the pressure of the gas supply. For the Power Assisted Glove, the actuator is required to track a force/displacement curve derived from the measured EVA glove stiffness. It may be possible to approximate this curve with a few piecewise linear segments, allowing a pneumatic actuator to operate over a significant range of its motion at a constant pressure. This would reduce the control activity required, and decrease power consumption.

Practical problems arise with this approach, however. It is unlikely that the entire range of required motion vs. force can be approximated adequately by a pneumatic actuator at one supply pressure. Thus, rapid motions would require changing pressures quickly. This can be accomplished with a high-pressure reservoir, a low-pressure reservoir, and a plenum (possible just the actuator itself). Fast-acting valves between the plenum and the reservoirs would be controlled by a microprocessor, using data from a pressure sensor in the plenum and a glove position sensor. A fast response time is needed to meet the glove motion requirements--actuator force must be capable of changing from 0 to the 13 lbf maximum in less than 25 milliseconds. This requires a very small plenum and very high gas supply pressure, to reduce the needed flow rate through the valves to a feasible level. Unfortunately, valves with high flow rates (large orifices) or high working pressures (powerful solenoids) are too bulky, too slow, and consume quite a bit of power. Locating the valves away from the glove is not practical because the volume of the gas lines to the actuator increases the effective plenum volume and slows response due to the finite propagation time of a pressure wave.

There is also the undesirable safety issue of attaching a high-pressure gas supply to the pressure suit. Reliability and system cost also suffer, due to overall complexity. A complete electrical power and microprocessor control system is required to drive the valves, in addition to high- and low-pressure gas reservoirs, regulators, plumbing and pressure sensors.

*Shape-memory alloys:*

Alloys such as Nitinol drawn into wire have been used as high-force, low-stroke actuators in a number of applications. They are simple, compact, and capable of extensive reuse (if yielding is avoided). Typically a Nitinol wire of 150 micron diameter is capable of .7 lbf maximum force and 5% maximum contraction in length. Thus, 19 such wires 25 inches in length could provide the necessary force and stroke for this application, in a very compact package.

The means of activation is heat, usually provided by current in the wire. Heating (therefore contraction) is easily controlled by a microprocessor, but rapid and accurate control of cooling for the reverse motion is problematical. The other principal drawback is response time. The quickest step response achievable is roughly .5 sec in contraction. These actuators are not suited to the accurate and rapid control of forces.

*Phase-Change actuators:*

Actuators have been designed for several applications which make use of energy storage in the phase change of a material such as paraffin. This results in a compact high-force low-stroke actuator, such as the linear motors marketed by Starsys Research. Unfortunately the same difficulties associated with shape-memory alloy actuators apply to these, since the means of activation is heating. Response times are typically 90 seconds, and forces are not well controllable.

*Voice Coil actuators:*

Direct electrical-to-mechanical transducers offer the simplest form of actuator, and promise the most rapid response. Voice coil actuators are one type. They are direct drive, limited linear motion devices that utilize a permanent magnet field and a coil winding to produce a force proportional to the current applied to the coil. They can provide high-force, low stroke motion with large accelerations and direct microprocessor control of forces.

For this application, however, they tend to have excessive acceleration capability, with insufficient stroke to use as a direct cable drive. An example from the BEI Kimco Magnetics Division illustrates this: their smallest voice coil actuator meeting the output power requirements is model #LA25-42-000, which can produce 60 lbf over a .5 inch stroke. It would require a 2:1 transmission to increase the stroke to 1 inch; force would still be available in excess of the requirements. Unfortunately, this unit weighs 2.2 lbs and is 2.75 inches in diameter and 4.17 inches long, which violates the packaging constraints by a large margin.

*DC servomotors:*

DC servomotors are similar in principle to voice coil actuators, but are designed for rotary motion. This requires the added complexity of commutation, but allows essentially unlimited stroke. As with voice coils, output force (in this case, torque) is proportional to current, which can easily be controlled by a microprocessor. Response is rapid, with electrical time constants typically less than a millisecond.

Brushed servomotors are simple to apply; commutation is done mechanically. Permanent magnets are attached to the stator, coils are attached to the rotor. Brush wear limits life to typically $10^7$ revolutions. Contamination of bearings and other sensitive components due to dust from the brushes must be prevented. Electromagnetic noise from arcing at the commutation points can be troublesome to sensitive electronics. Heat is dissipated in the rotor, which can be difficult to dispose of.

Brushless servomotors avoid the drawbacks of brushes at the expense of complexity in the drive electronics and the addition of rotor angle sensors. Commutation takes place electronically rather than mechanically. The permanent magnets are on the rotor, and a series of coils form the stator. These are excited in sequence by the drive electronics, according to the sensed rotor position. Heat is dissipated in the stator, and is easier to conduct away.

### 2.7.3 Selected Technology

After a survey of the available options, a brush-commutated DC servomotor was selected for the prototype glove actuation system. The drawbacks of a brushed vs. brushless motor were not considered significant for a prototype system, and simplicity is a definite advantage in a development process. The transition to a brushless design for production versions should be feasible with little impact on packaging.

The motor selected is model #QT-1106 from the Inland Motor Division of the Kollmorgen Company. It is 1.375 inches in diameter and .385 inches tall. With the required 2.5:1 transmission and an optical encoder for sensing glove position, the actuator system fits within the packaging constraints.

All performance requirements can be met with this system, assuming a transmission efficiency of 70%. A maximum supply voltage of 30 V is required, with a peak current of 2.5 amps.

### 2.7.4 Outstanding Issues

*Performance verification:*

Vendor specifications and transmission efficiency assumptions must be tested before performance is assured. Friction values are difficult to predict in advance; some experimentation will be required to optimize performance.

*Thermal Dissipation:*

Worst-case estimates of peak power dissipation in the motor are 75 watts, with average dissipation of 15 Watts. If these estimates are borne out in testing, a means of conveying the heat away from the actuator will be required. Possible options include conduction to a larger radiating surface on the pressure suit sleeve, or conduction to the internal suit cooling system.

## 3.0 Proposed Phase II Activities

Phase II activities will take the work and knowledge from Phase I and refine it to develop a functional system. Specifically, the best concept shall be prototyped, refined, thoroughly tested, and studied such that its operational characteristics are well documented. The following sections describe the proposed Phase II activities in detail. The information presented here is supplemental to ILC's initial proposal to NASA Research Announcement 95-OLMSA-01, entitled *Development of a Power-Assisted Space Suit Glove*.

### 3.1 Component Detailed Design

After testing and evaluation of the potential NRA configurations, one (or perhaps two) will be downselected and refined. A large portion of this activity will be to integrate the softgoods items with the hardware (i.e. actuation system, composite plates, etc.) Some of the items to be performed are as follows:

<u>Softgoods:</u>

1. Further reduce MCP joint torque to the greatest extent possible through iterative design modification and test.
2. Finalize restraint and bladder patterns.

<u>Actuation, Control, and Range of Motion Systems:</u>

1. Finalize load vs. deflection data and program into control system - based on Phase I test data and Phase I data obtained per paragraph 3.2 below.
2. Finalize integration method between actuator and composite plate on back surface of the restraint.

3. Finalize control system design and capabilities (i.e. size of motor, gear reduction, maximum load ability, response time, etc.).
4. Compare model predictions to tested results and alter model as required.

### 3.2 Prototype System Manufacture and Test

Once the desired system is defined, all components of it will be fabricated and assembled. To the greatest extent possible, the actual manufacturing techniques, materials, hardware used, etc. will be identical to that which would be proposed for a flight item.

The assembled system will be qualitatively and quantitatively evaluated to demonstrate the improvements over the space suit glove without the actuation system powered up. Additionally, a comparison to nude hand performance shall also be performed for the power assisted glove system.

Areas that will specifically be evaluated include the following:

- Torque of the MCP joint for each glove configuration
- range of motion
- Comfort and donning characteristics
- Continuity of MCP joint torque throughout its range of motion
- Stability of the system to maintain bend angles of the MCP joint
- Subjective measurement of fatigue
- Performance of normal, simulated EVA tasks
- Power requirements

## 4.0 Schedule and Deliverables

See attachment B which contains a top level schedule for Phase I and Phase II of this program. Included in the schedule are milestone dates and deliverables required under the program. In order to meet this schedule and the required program completion date, ILC will need a contract for Phase II of the program no later than January 1, 1997.

In summary, the following are the major deliverables that will be provided under Phase I and Phase II.

1. Phase I Interim Report - 10/31/96
2. Prototype definition and test data - 12/27/96
3. Phase II Report - 12/11/97
4. Working prototype - 11/3/97 (approximate date)

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**ATTACHMENT A**

Fig 1: Raw MCP angle data

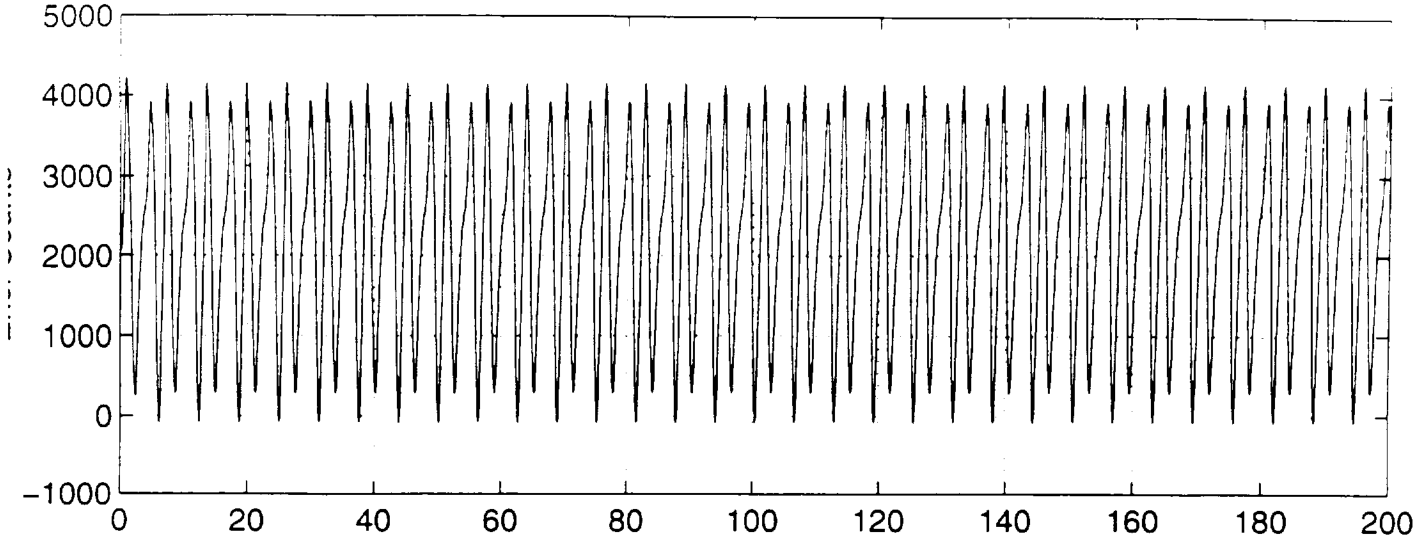



Fig 2: NARMA Prediction error

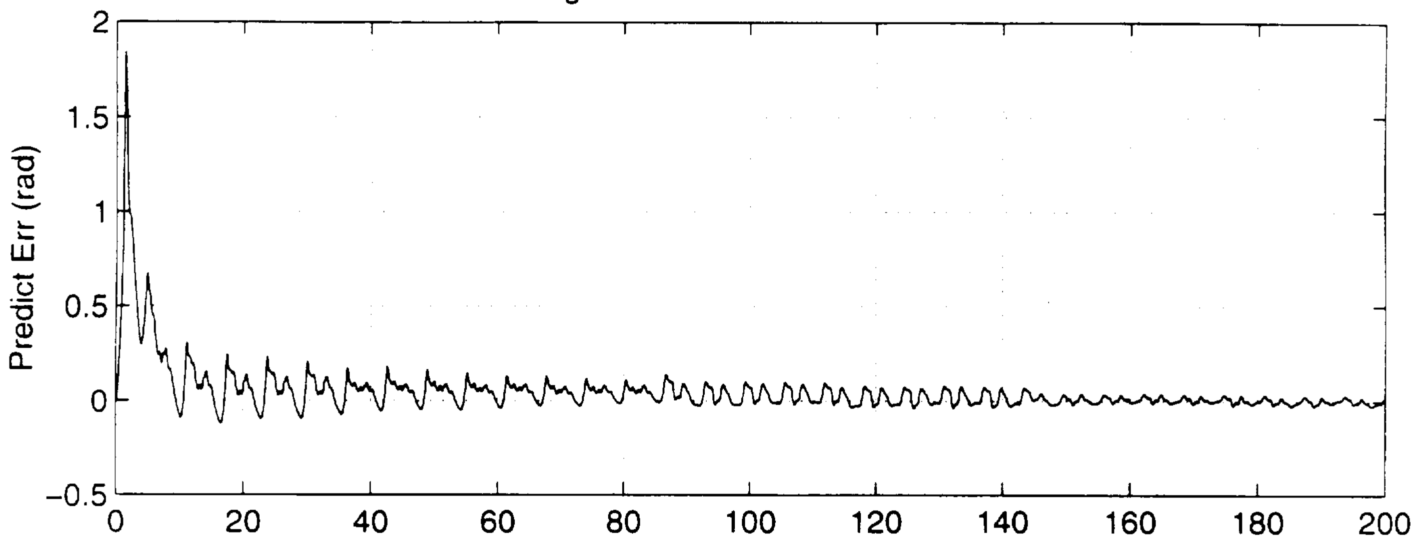
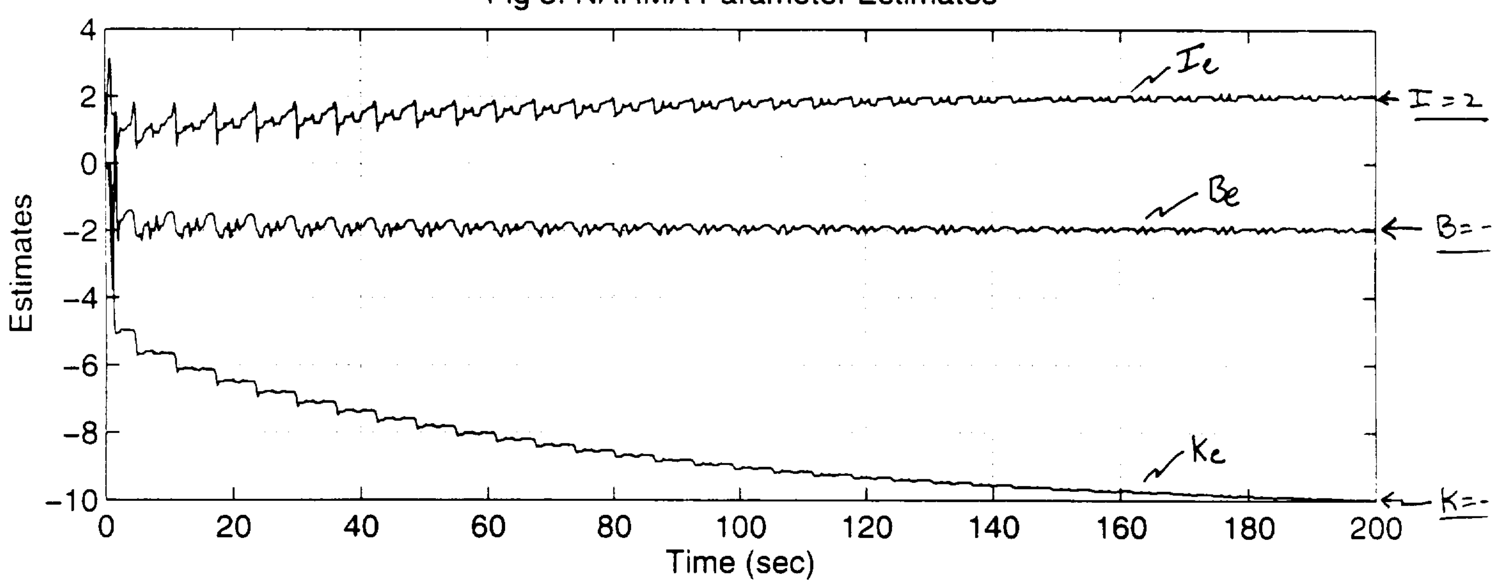


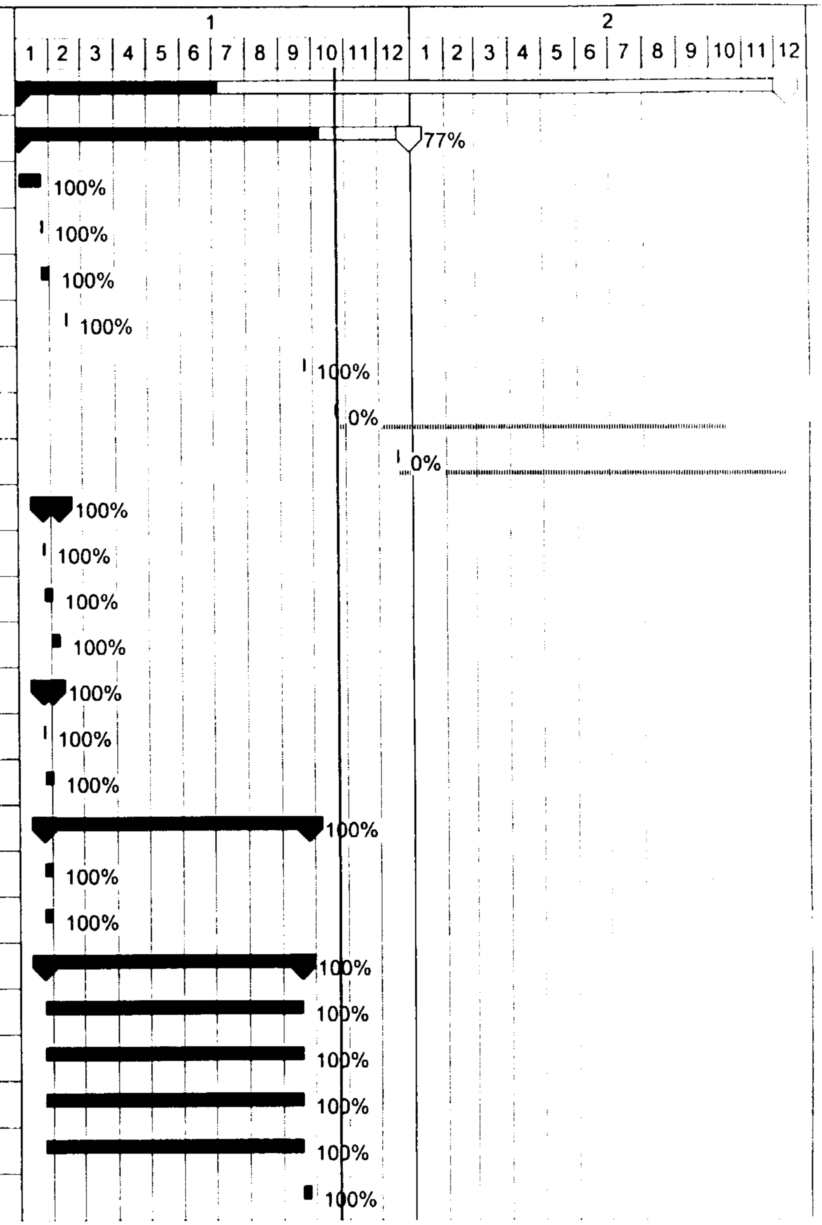

Fig 3: NARMA Parameter Estimates



**ATTACHMENT B**

Z:\DEPTMNT\PROGMGT\SCHDL\NASA\NASANRA.MPP    NASA NRA - POWER ASSIST SPACESUIT GLOVE PROGRAM    ILC Dover, Inc.    PI - Dave Cadogan

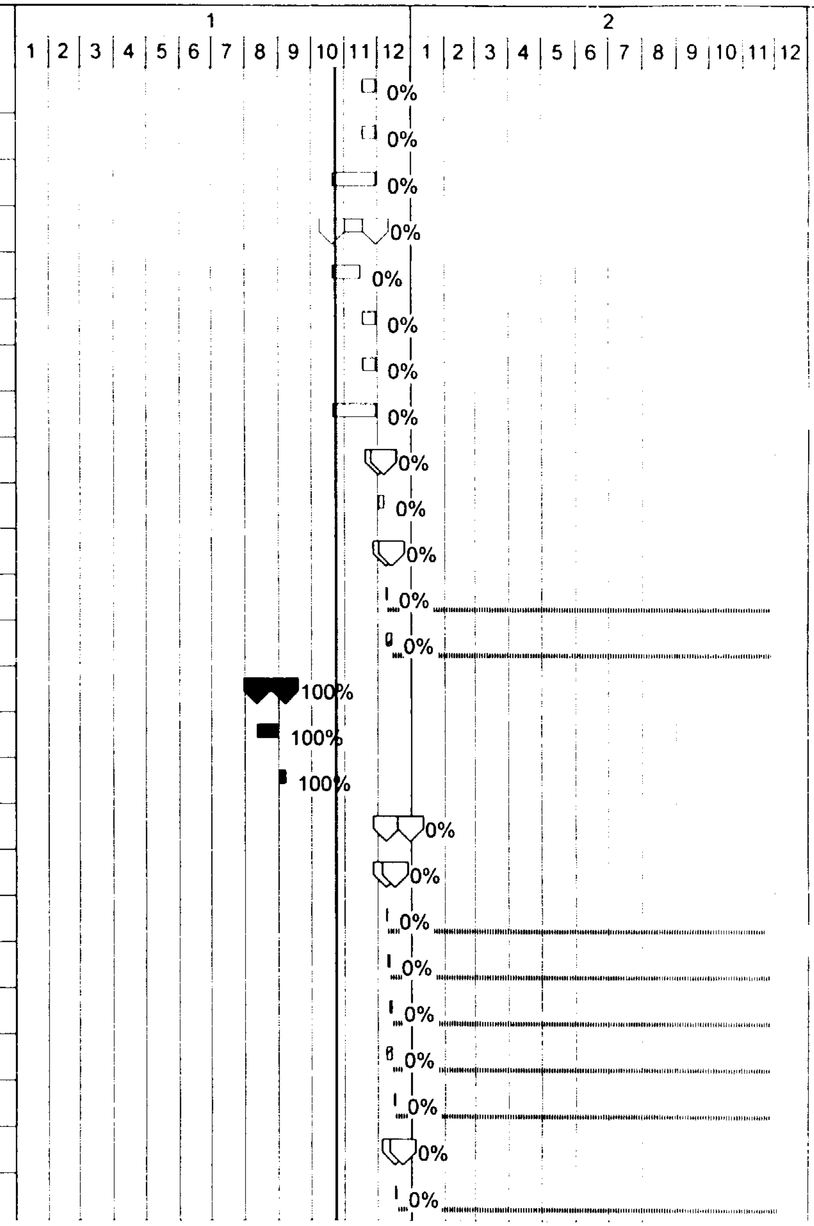
| ID | Task Name | Dur | Start | Finish | % Comp |
|---|---|---|---|---|---|
| 1 | **NASA NRA - POWER ASSIST GLOVE PRO** | **505d** | **1/5/96** | **12/11/97** | **26%** |
| 2 | **PHASE I - PRELIMINARY DESIGN & T** | **257d** | **1/5/96** | **12/30/96** | **77%** |
| 3 | Program Plan Development | 14d | 1/5/96 | 1/24/96 | 100% |
| 4 | Kick-off Meeting at ILC | 1d | 1/25/96 | 1/25/96 | 100% |
| 5 | On-Line Communication Plan / Test | 1w | 1/25/96 | 1/31/96 | 100% |
| 6 | Tech Interchange Meeting #1 (SSL) | 1d | 2/16/96 | 2/16/96 | 100% |
| 7 | Tech Interchange Meeting #2 (ILC) | 1d | 9/23/96 | 9/23/96 | 100% |
| 8 | Tech Interchange Meeting #3 | 1d | 10/22/96 | 10/22/96 | 0% |
| 9 | Tech Interchange Meeting #4 | 1d | 12/18/96 | 12/18/96 | 0% |
| 10 | **Requirements Development** | **11d** | **1/25/96** | **2/8/96** | **100%** |
| 11 | Develop Requirements | 1d | 1/25/96 | 1/25/96 | 100% |
| 12 | Write Document | 1w | 1/26/96 | 2/1/96 | 100% |
| 13 | Review and disseminate | 1w | 2/2/96 | 2/8/96 | 100% |
| 14 | **Baseline Design Development** | **6d** | **1/25/96** | **2/1/96** | **100%** |
| 15 | Brainstorm Concepts | 1d | 1/25/96 | 1/25/96 | 100% |
| 16 | Drawing | 1w | 1/26/96 | 2/1/96 | 100% |
| 17 | **Technology Review / Search** | **175d** | **1/25/96** | **9/25/96** | **100%** |
| 18 | Research Glove History | 1w | 1/25/96 | 1/31/96 | 100% |
| 19 | Research Robotic History | 1w | 1/25/96 | 1/31/96 | 100% |
| 20 | **Research New Technologies** | **170d** | **1/25/96** | **9/18/96** | **100%** |
| 21 | Sensors | 34w | 1/25/96 | 9/18/96 | 100% |
| 22 | Actuation Systems | 34w | 1/25/96 | 9/18/96 | 100% |
| 23 | Power Systems | 34w | 1/25/96 | 9/18/96 | 100% |
| 24 | Control Systems | 34w | 1/25/96 | 9/18/96 | 100% |
| 25 | Write Summary Report | 1w | 9/19/96 | 9/25/96 | 100% |




W/O# 1    Non-Critical    Critical    Milestone    Summary    Slack

**ILC - Innovation, Leadership and Commitment**

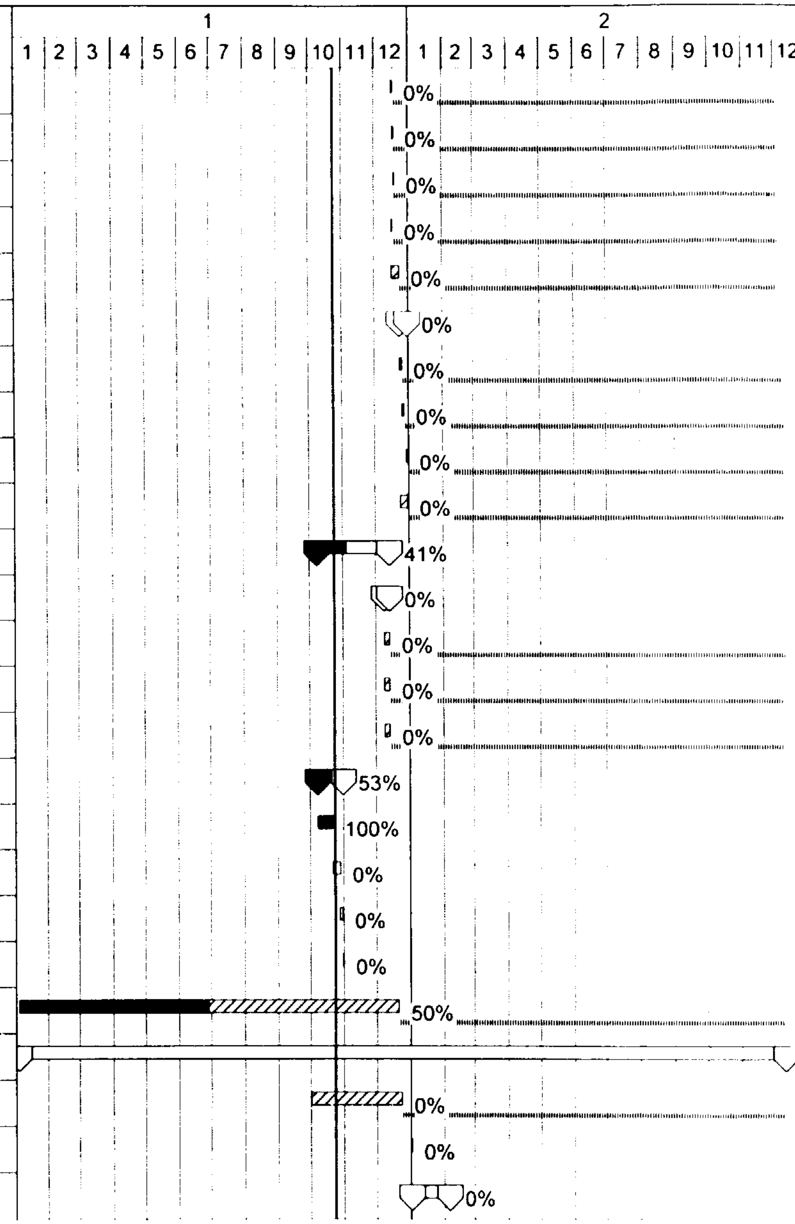
| ID | Task Name | Dur | Start | Finish | % Comp |
|---|---|---|---|---|---|
| 76 | PCB Assembly | 2w | 11/18/96 | 11/29/96 | 0% |
| 77 | Housing Fabrication | 2w | 11/18/96 | 11/29/96 | 0% |
| 78 | Cover / Mount Design & Fab | 6w | 10/21/96 | 11/29/96 | 0% |
| 79 | **Actuation System** | **30d** | **10/21/96** | **11/29/96** | **0%** |
| 80 | Materials Acquisition | 4w | 10/21/96 | 11/15/96 | 0% |
| 81 | Mount Fabrication | 2w | 11/18/96 | 11/29/96 | 0% |
| 82 | Tendon Fabrication | 2w | 11/18/96 | 11/29/96 | 0% |
| 83 | Cover Design & Fabrication | 6w | 10/21/96 | 11/29/96 | 0% |
| 84 | **System Integration** | **5d** | **12/2/96** | **12/6/96** | **0%** |
| 85 | Install on glove / suit | 1w | 12/2/96 | 12/6/96 | 0% |
| 86 | **System Check-out** | **5d** | **12/9/96** | **12/13/96** | **0%** |
| 87 | Qualitative Performance Test | 1d | 12/9/96 | 12/9/96 | 0% |
| 88 | Design Modifications | 1w | 12/9/96 | 12/13/96 | 0% |
| 89 | **Preliminary Testing (at ILC)** | **20d** | **8/12/96** | **9/6/96** | **100%** |
| 90 | Design & Build Test Fixture | 3w | 8/12/96 | 8/30/96 | 100% |
| 91 | Test Glove for Baseline Data | 1w | 9/2/96 | 9/6/96 | 100% |
| 92 | **Mock-up Testing (at ILC)** | **16d** | **12/9/96** | **12/30/96** | **0%** |
| 93 | **Testing Preparation** | **6d** | **12/9/96** | **12/16/96** | **0%** |
| 94 | Write Test Plan | 1d | 12/9/96 | 12/9/96 | 0% |
| 95 | TPS | 2d | 12/10/96 | 12/11/96 | 0% |
| 96 | Select 4000 Series Glove | 2d | 12/12/96 | 12/13/96 | 0% |
| 97 | Obtain 4000 Series Glove | 1w | 12/9/96 | 12/13/96 | 0% |
| 98 | Lab Set-up | 1d | 12/16/96 | 12/16/96 | 0% |
| 99 | **Glove Performance Testing** | **5d** | **12/17/96** | **12/23/96** | **0%** |
| 100 | Torque Testing (P off/on) | 1d | 12/17/96 | 12/17/96 | 0% |




W/O# 4

Non-Critical | Critical | Milestone | Summary | Slack

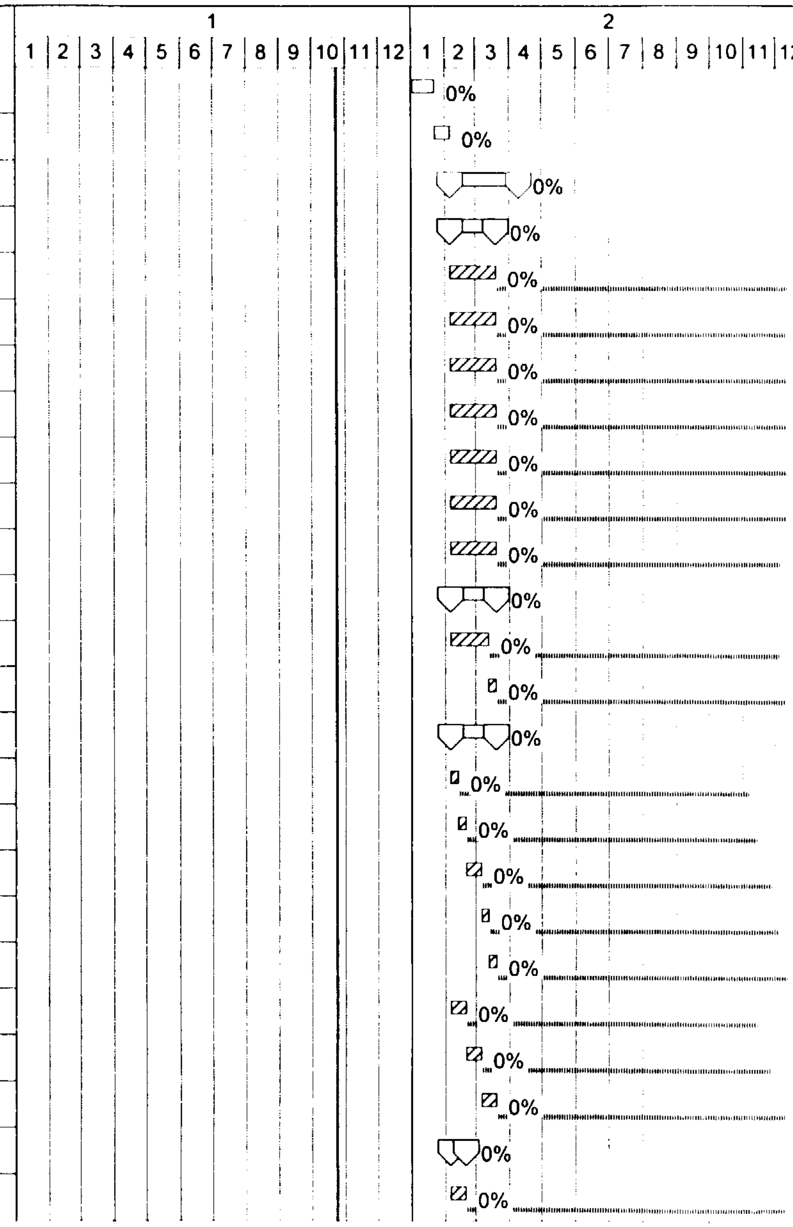
| ID | Task Name | Dur | Start | Finish | % Comp |
|---|---|---|---|---|---|
| 101 | Range of Motion Testing | 1d | 12/17/96 | 12/17/96 | 0% |
| 102 | Dexterity Testing | 1d | 12/18/96 | 12/18/96 | 0% |
| 103 | Fatigue Testing | 1d | 12/19/96 | 12/19/96 | 0% |
| 104 | Environmental Perf Analysis | 1d | 12/17/96 | 12/17/96 | 0% |
| 105 | Photo / Video Collection | 5d | 12/17/96 | 12/23/96 | 0% |
| 106 | **Preliminary Data Reduction** | **5d** | **12/24/96** | **12/30/96** | **0%** |
| 107 | Data Compilation | 2d | 12/24/96 | 12/25/96 | 0% |
| 108 | Data Reduction | 2d | 12/26/96 | 12/27/96 | 0% |
| 109 | Propose Design Modifications | 1d | 12/30/96 | 12/30/96 | 0% |
| 110 | Return GFE 4000 Glove | 1w | 12/24/96 | 12/30/96 | 0% |
| 111 | **Phase I Management & Del's** | **49d** | **10/8/96** | **12/13/96** | **41%** |
| 112 | **Follow-on Planning** | **5d** | **12/9/96** | **12/13/96** | **0%** |
| 113 | Phase II & III Planning | 1w | 12/9/96 | 12/13/96 | 0% |
| 114 | Phase II & III Costing | 1w | 12/9/96 | 12/13/96 | 0% |
| 115 | Phase II & III Proposal | 1w | 12/9/96 | 12/13/96 | 0% |
| 116 | **Phase I Report (Interim)** | **18d** | **10/8/96** | **10/31/96** | **53%** |
| 117 | Write Draft | 2w | 10/8/96 | 10/21/96 | 100% |
| 118 | Review | 1w | 10/22/96 | 10/28/96 | 0% |
| 119 | Final Copy | 3d | 10/28/96 | 10/30/96 | 0% |
| 120 | Present to NASA (by 10/31/96) | 1d | 10/31/96 | 10/31/96 | 0% |
| 121 | Program Management (PH I) | 251d | 1/5/96 | 12/20/96 | 50% |
| 122 | **PHASE II - WETF PROTOTYPE FAB &** | **505d** | **1/5/96** | **12/11/97** | **0%** |
| 123 | NASA Funding Review | 12w | 10/1/96 | 12/23/96 | 0% |
| 124 | Phase II Kick-off | 1d | 1/1/97 | 1/1/97 | 0% |
| 125 | **System Modeling** | **25d** | **1/2/97** | **2/5/97** | **0%** |




W/O# 5

Non-Critical Critical Milestone Summary Slack

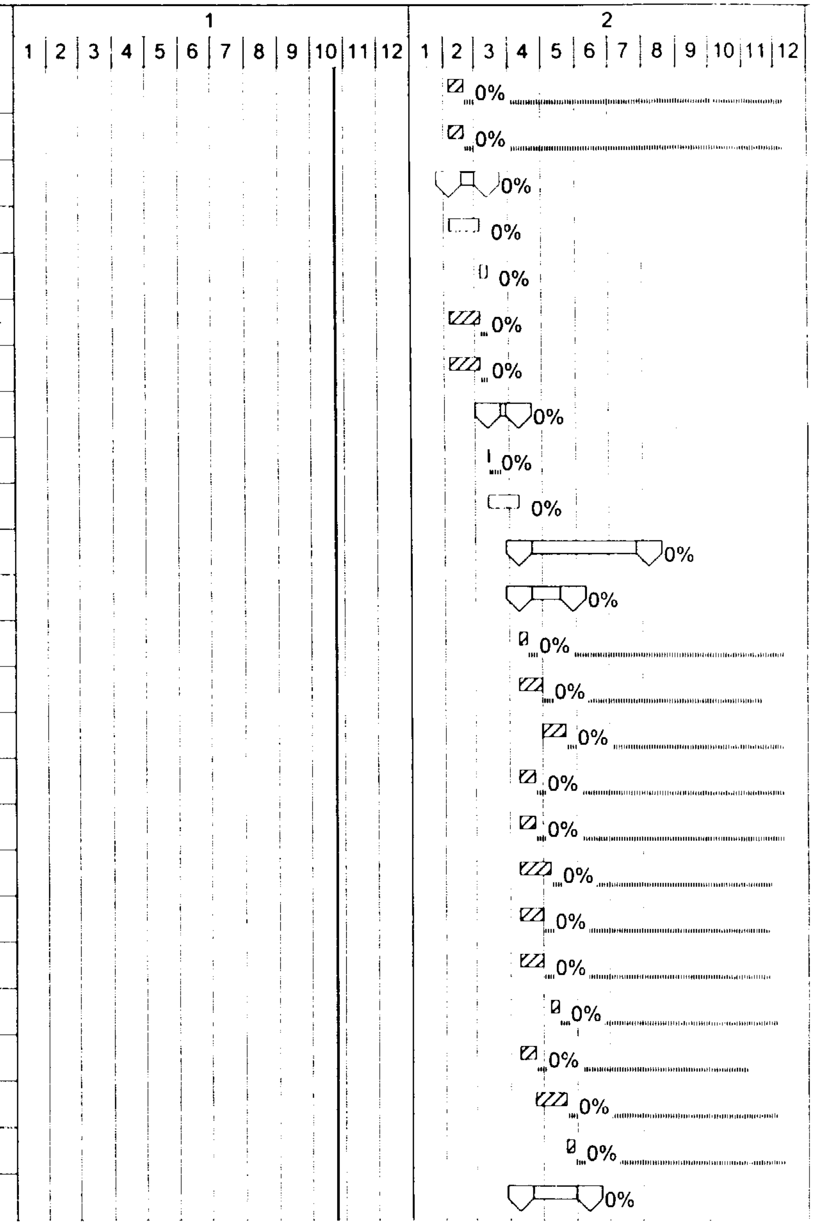
| ID | Task Name | Dur | Start | Finish | % Comp |
|---|---|---|---|---|---|
| 126 | Human Factors Analysis | 3w | 1/2/97 | 1/22/97 | 0% |
| 127 | Modeling | 2w | 1/23/97 | 2/5/97 | 0% |
| 128 | **Detailed Design** | **45d** | **2/6/97** | **4/9/97** | **0%** |
| 129 | **Spacesuit Glove** | **30d** | **2/6/97** | **3/19/97** | **0%** |
| 130 | MCP Joint | 6w | 2/6/97 | 3/19/97 | 0% |
| 131 | Restraint | 6w | 2/6/97 | 3/19/97 | 0% |
| 132 | Bladder | 6w | 2/6/97 | 3/19/97 | 0% |
| 133 | TMG | 6w | 2/6/97 | 3/19/97 | 0% |
| 134 | Indexing | 6w | 2/6/97 | 3/19/97 | 0% |
| 135 | Hardware Interface | 6w | 2/6/97 | 3/19/97 | 0% |
| 136 | Procure Glove Materials | 6w | 2/6/97 | 3/19/97 | 0% |
| 137 | **Position Sensing System** | **30d** | **2/6/97** | **3/19/97** | **0%** |
| 138 | Sensor design | 5w | 2/6/97 | 3/12/97 | 0% |
| 139 | Layout of sensors on glove | 1w | 3/13/97 | 3/19/97 | 0% |
| 140 | **Control System** | **30d** | **2/6/97** | **3/19/97** | **0%** |
| 141 | Control Algorithm & Programming | 1w | 2/6/97 | 2/12/97 | 0% |
| 142 | Power Source | 1w | 2/13/97 | 2/19/97 | 0% |
| 143 | Circuit Design | 2w | 2/20/97 | 3/5/97 | 0% |
| 144 | EMI Protection | 1w | 3/6/97 | 3/12/97 | 0% |
| 145 | PCB Layout | 1w | 3/13/97 | 3/19/97 | 0% |
| 146 | Mount Location Selection | 2w | 2/6/97 | 2/19/97 | 0% |
| 147 | Mount Design | 2w | 2/20/97 | 3/5/97 | 0% |
| 148 | Wiring & Pass-throughs | 2w | 3/6/97 | 3/19/97 | 0% |
| 149 | **Actuation System** | **10d** | **2/6/97** | **2/19/97** | **0%** |
| 150 | Drive Unit | 2w | 2/6/97 | 2/19/97 | 0% |




W/O# 6

Non-Critical Critical Milestone Summary Slack

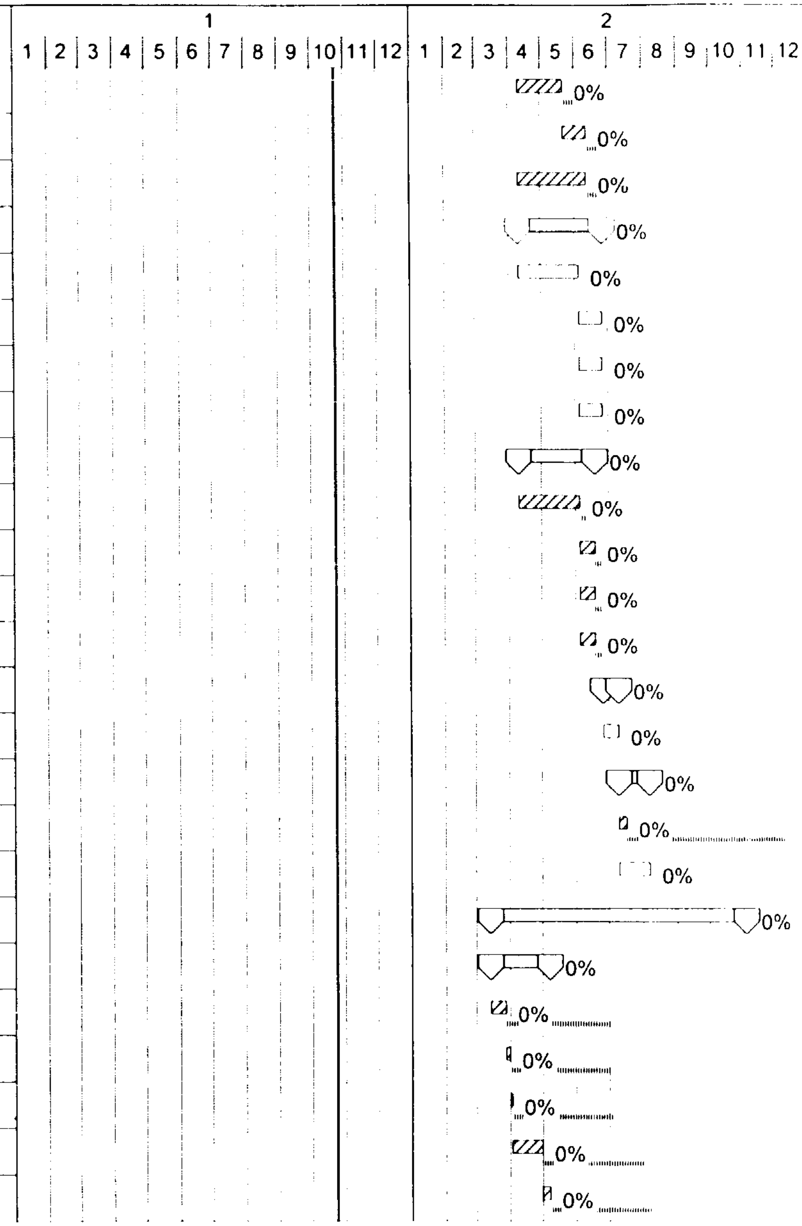
| ID | Task Name | Dur | Start | Finish | % Comp |
|---|---|---|---|---|---|
| 151 | Drive Mount | 2w | 2/6/97 | 2/19/97 | 0% |
| 152 | Cables / Tendons | 2w | 2/6/97 | 2/19/97 | 0% |
| 153 | **Systems Integration** | **25d** | **2/6/97** | **3/12/97** | **0%** |
| 154 | System Layout | 4w | 2/6/97 | 3/5/97 | 0% |
| 155 | Performance Estimation | 1w | 3/6/97 | 3/12/97 | 0% |
| 156 | Bill of Materials Dev't | 4w | 2/6/97 | 3/5/97 | 0% |
| 157 | Drawings (Level I) | 4w | 2/6/97 | 3/5/97 | 0% |
| 158 | **Detailed Design Review** | **20d** | **3/13/97** | **4/9/97** | **0%** |
| 159 | CDR | 1d | 3/13/97 | 3/13/97 | 0% |
| 160 | Modifications to design | 4w | 3/13/97 | 4/9/97 | 0% |
| 161 | **Mock-up Fabrication** | **85d** | **4/10/97** | **8/6/97** | **0%** |
| 162 | **Spacesuit Glove (size MS)** | **35d** | **4/10/97** | **5/28/97** | **0%** |
| 163 | Materials Acquisition | 1w | 4/10/97 | 4/16/97 | 0% |
| 164 | Bladder Dip Form Fabrication | 3w | 4/10/97 | 4/30/97 | 0% |
| 165 | Bladder Fabrication | 3w | 5/1/97 | 5/21/97 | 0% |
| 166 | Indexing Systems | 2w | 4/10/97 | 4/23/97 | 0% |
| 167 | Restraint Pattern Dev't (mods) | 2w | 4/10/97 | 4/23/97 | 0% |
| 168 | Restraint Fabrication | 4w | 4/10/97 | 5/7/97 | 0% |
| 169 | Palm Bar Mfg | 3w | 4/10/97 | 4/30/97 | 0% |
| 170 | Palm Plate Mfg | 3w | 4/10/97 | 4/30/97 | 0% |
| 171 | Glove Assembly | 1w | 5/8/97 | 5/14/97 | 0% |
| 172 | TMG (4750) Pattern Dev't (mods) | 2w | 4/10/97 | 4/23/97 | 0% |
| 173 | TMG Fabrication | 4w | 4/24/97 | 5/21/97 | 0% |
| 174 | TMG Integration | 1w | 5/22/97 | 5/28/97 | 0% |
| 175 | **Position Sensing System** | **45d** | **4/10/97** | **6/11/97** | **0%** |




W/O# 7

Non-Critical Critical Milestone Summary Slack

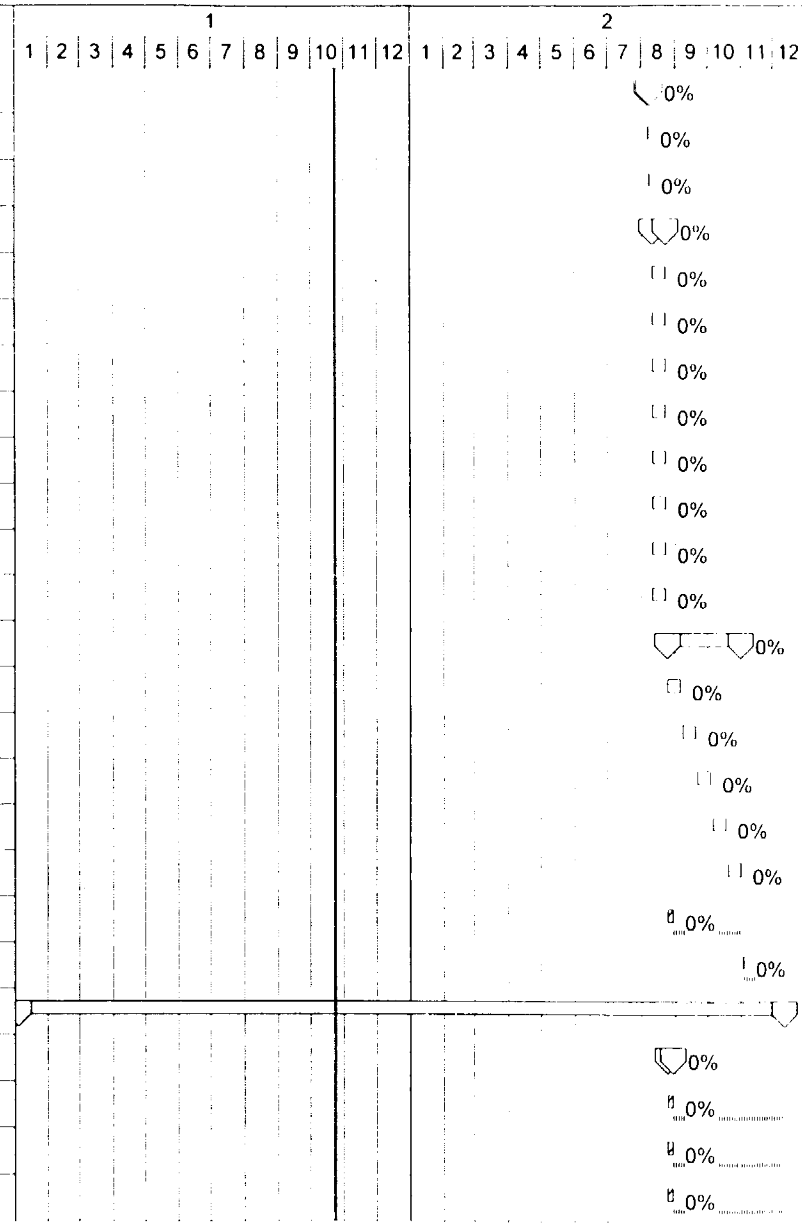
| ID | Task Name | Dur | Start | Finish | % Comp |
|---|---|---|---|---|---|
| 176 | Materials Acquisition | 6w | 4/10/97 | 5/21/97 | 0% |
| 177 | Sensor Fab | 3w | 5/22/97 | 6/11/97 | 0% |
| 178 | Cover Design & Fab | 9w | 4/10/97 | 6/11/97 | 0% |
| 179 | **Control System** | **55d** | **4/10/97** | **6/25/97** | **0%** |
| 180 | Materials Acquisition | 8w | 4/10/97 | 6/4/97 | 0% |
| 181 | PCB Assembly | 3w | 6/5/97 | 6/25/97 | 0% |
| 182 | Housing Fabrication | 3w | 6/5/97 | 6/25/97 | 0% |
| 183 | Cover / Mount Fabrication | 3w | 6/5/97 | 6/25/97 | 0% |
| 184 | **Actuation System** | **50d** | **4/10/97** | **6/18/97** | **0%** |
| 185 | Materials Acquisition | 8w | 4/10/97 | 6/4/97 | 0% |
| 186 | Mount Fabrication | 2w | 6/5/97 | 6/18/97 | 0% |
| 187 | Tendon Fabrication | 2w | 6/5/97 | 6/18/97 | 0% |
| 188 | Cover Fabrication | 2w | 6/5/97 | 6/18/97 | 0% |
| 189 | **System Integration** | **10d** | **6/26/97** | **7/9/97** | **0%** |
| 190 | Install on glove / suit | 2w | 6/26/97 | 7/9/97 | 0% |
| 191 | **System Check-out** | **20d** | **7/10/97** | **8/6/97** | **0%** |
| 192 | Qualitative Performance Test | 1w | 7/10/97 | 7/16/97 | 0% |
| 193 | Design Modifications | 4w | 7/10/97 | 8/6/97 | 0% |
| 194 | **Mock-up Testing (at ILC)** | **167d** | **3/14/97** | **11/3/97** | **0%** |
| 195 | **Testing Preparation** | **39d** | **3/14/97** | **5/7/97** | **0%** |
| 196 | Write Test Plan | 2w | 3/14/97 | 3/27/97 | 0% |
| 197 | TPS | 2d | 3/28/97 | 3/31/97 | 0% |
| 198 | Select 4000 Series Glove | 2d | 4/1/97 | 4/2/97 | 0% |
| 199 | Obtain 4000 Series Glove | 4w | 4/3/97 | 4/30/97 | 0% |
| 200 | Lab Set-up | 1w | 5/1/97 | 5/7/97 | 0% |




W/O# 8

Non-Critical | Critical | Milestone | Summary | Slack

| ID | Task Name | Dur | Start | Finish | % Comp |
|---|---|---|---|---|---|
| 201 | **Glove Integrity** | **2d** | **8/7/97** | **8/8/97** | **0%** |
| 202 | Leak/Proof/Leak | 1d | 8/7/97 | 8/7/97 | 0% |
| 203 | Break-in Cycles | 1d | 8/8/97 | 8/8/97 | 0% |
| 204 | **Glove Performance Testing** | **10d** | **8/11/97** | **8/22/97** | **0%** |
| 205 | Torque Testing (P off/on) | 2w | 8/11/97 | 8/22/97 | 0% |
| 206 | Range of Motion Testing | 2w | 8/11/97 | 8/22/97 | 0% |
| 207 | Mobility Testing | 2w | 8/11/97 | 8/22/97 | 0% |
| 208 | Fatigue Testing | 2w | 8/11/97 | 8/22/97 | 0% |
| 209 | Cycle Life Testing | 2w | 8/11/97 | 8/22/97 | 0% |
| 210 | Environmental Performance Analysi | 2w | 8/11/97 | 8/22/97 | 0% |
| 211 | WETF Simulation / Test | 2w | 8/11/97 | 8/22/97 | 0% |
| 212 | Photo / Video Collection | 2w | 8/11/97 | 8/22/97 | 0% |
| 213 | **Data Reduction** | **50d** | **8/25/97** | **10/31/97** | **0%** |
| 214 | Data Compilation | 2w | 8/25/97 | 9/5/97 | 0% |
| 215 | Data Reduction | 2w | 9/8/97 | 9/19/97 | 0% |
| 216 | Derivation of Results | 2w | 9/22/97 | 10/3/97 | 0% |
| 217 | Investigate Use on Other Joints | 2w | 10/6/97 | 10/17/97 | 0% |
| 218 | Propose Design Modifications | 2w | 10/20/97 | 10/31/97 | 0% |
| 219 | Return GFE 4000 Glove | 1w | 8/25/97 | 8/29/97 | 0% |
| 220 | Technical Interchange Meeting | 1d | 11/3/97 | 11/3/97 | 0% |
| 221 | **Phase I Management & Deliverable** | **505d** | **1/5/96** | **12/11/97** | **0%** |
| 222 | **Follow-on Planning** | **5d** | **8/25/97** | **8/29/97** | **0%** |
| 223 | Phase III Planning | 1w | 8/25/97 | 8/29/97 | 0% |
| 224 | Phase III Costing | 1w | 8/25/97 | 8/29/97 | 0% |
| 225 | Phase III Proposal | 1w | 8/25/97 | 8/29/97 | 0% |




W/O# 9

Non-Critical Critical Milestone Summary Slack

| ID | Task Name | Dur | Start | Finish | % Comp |
|---|---|---|---|---|---|
| 226 | **Phase II Report (Final)** | **29d** | **11/3/97** | **12/11/97** | **0%** |
| 227 | Write Draft | 3w | 11/3/97 | 11/21/97 | 0% |
| 228 | Review | 3d | 11/24/97 | 11/26/97 | 0% |
| 229 | Final Copy | 2w | 11/27/97 | 12/10/97 | 0% |
| 230 | Present to NASA | 1d | 12/11/97 | 12/11/97 | 0% |
| 231 | Program Management (PH II) | 361d | 1/5/96 | 5/23/97 | 0% |

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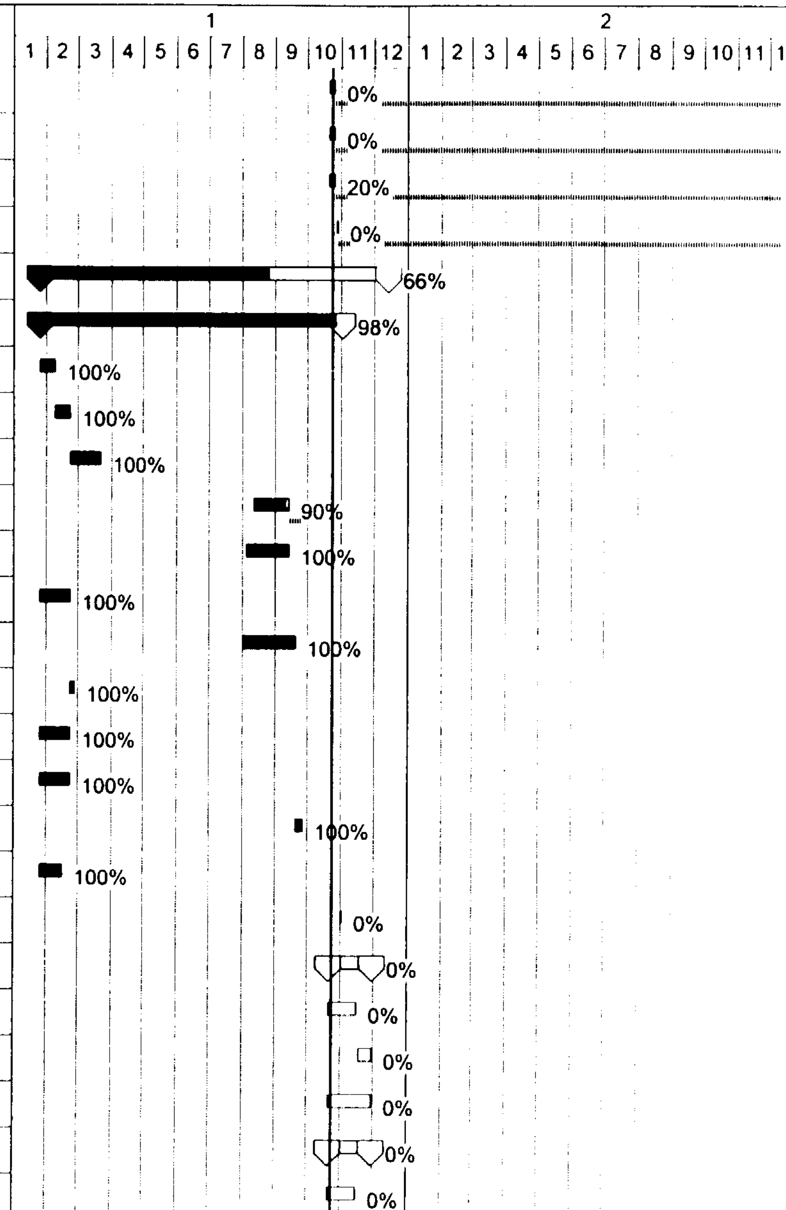
1 2 3 4 5 6 7 8 9 10 11 12 1 2 3 4 5 6 7 8 9 10 11 12

0%
0
0%

10
W/O#

Non-Critical Critical Milestone Summary Slack

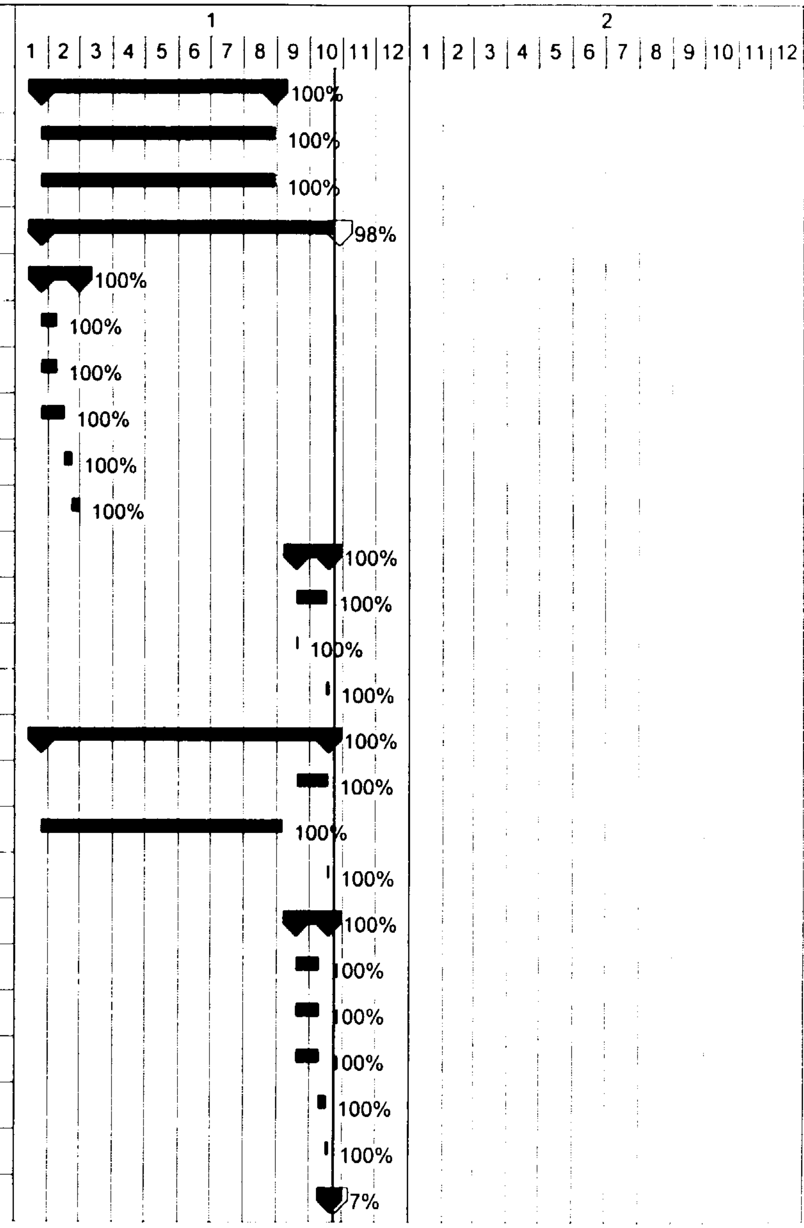
| ID | Task Name | Dur | Start | Finish | % Comp |
|---|---|---|---|---|---|
| 51 | Performance Estimation | 1w | 10/21/96 | 10/25/96 | 0% |
| 52 | Write Matl's List (Order L Lead) | 1w | 10/21/96 | 10/25/96 | 0% |
| 53 | Drawings (Level I) | 1w | 10/21/96 | 10/25/96 | 20% |
| 54 | Preliminary Design Review | 1d | 10/28/96 | 10/28/96 | 0% |
| 55 | **Mock-up Fabrication** | **231d** | **1/26/96** | **12/13/96** | **66%** |
| 56 | **Spacesuit Glove (size MS, RT)** | **201d** | **1/26/96** | **11/1/96** | **98%** |
| 57 | Procure Glove Materials | 2w | 1/26/96 | 2/8/96 | 100% |
| 58 | Bladder Dip Form Fabrication | 2w | 2/9/96 | 2/22/96 | 100% |
| 59 | Bladder Fab (RT) Concept #1 | 4w | 2/23/96 | 3/21/96 | 100% |
| 60 | Bladder Fab (RT) Concept #2 | 5w | 8/12/96 | 9/13/96 | 90% |
| 61 | Durney Restraint Mod | 6w | 8/5/96 | 9/13/96 | 100% |
| 62 | Restraint Fabrication (RT) | 4w | 1/26/96 | 2/22/96 | 100% |
| 63 | Restraint Fabrication (RT) | 7w | 8/2/96 | 9/19/96 | 100% |
| 64 | Disconnect Identification (temp) | 2d | 2/23/96 | 2/26/96 | 100% |
| 65 | Palm Bar Mfg (RT) | 4w | 1/26/96 | 2/22/96 | 100% |
| 66 | Palm Plate Mfg (RT) | 4w | 1/26/96 | 2/22/96 | 100% |
| 67 | Glove Assembly | 1w | 9/20/96 | 9/26/96 | 100% |
| 68 | TMG Identification (1 RT) | 3w | 1/26/96 | 2/15/96 | 100% |
| 69 | TMG Integration | 1d | 11/1/96 | 11/1/96 | 0% |
| 70 | **Position Sensing System** | **30d** | **10/21/96** | **11/29/96** | **0%** |
| 71 | Materials Acquisition | 4w | 10/21/96 | 11/15/96 | 0% |
| 72 | Sensor Fab | 2w | 11/18/96 | 11/29/96 | 0% |
| 73 | Cover Design & Fab | 6w | 10/21/96 | 11/29/96 | 0% |
| 74 | **Control System** | **30d** | **10/21/96** | **11/29/96** | **0%** |
| 75 | Materials Acquisition | 4w | 10/21/96 | 11/15/96 | 0% |




W/O# 3

Non-Critical Critical Milestone Summary Slack

| ID | Task Name | Dur | Start | Finish | % Comp |
|---|---|---|---|---|---|
| 26 | **System Modeling** | **155d** | **1/26/96** | **8/29/96** | **100%** |
| 27 | Human Factors Analysis | 31w | 1/26/96 | 8/29/96 | 100% |
| 28 | Modeling | 31w | 1/26/96 | 8/29/96 | 100% |
| 29 | **Preliminary Design** | **197d** | **1/26/96** | **10/28/96** | **98%** |
| 30 | **Spacesuit Glove** | **25d** | **1/26/96** | **2/29/96** | **100%** |
| 31 | MCP Joint | 2w | 1/26/96 | 2/8/96 | 100% |
| 32 | Restraint (draft Patterns) | 2w | 1/26/96 | 2/8/96 | 100% |
| 33 | Bladder | 3w | 1/26/96 | 2/15/96 | 100% |
| 34 | Indexing | 1w | 2/16/96 | 2/22/96 | 100% |
| 35 | Hardware Interface | 1w | 2/23/96 | 2/29/96 | 100% |
| 36 | **Position Sensing System** | **22d** | **9/19/96** | **10/18/96** | **100%** |
| 37 | Sensor design/ Bench Testing | 4w | 9/19/96 | 10/16/96 | 100% |
| 38 | System Ident for Control Dev't | 1d | 9/19/96 | 9/19/96 | 100% |
| 39 | System Selection for Mock-up | 2d | 10/17/96 | 10/18/96 | 100% |
| 40 | **Control System** | **191d** | **1/26/96** | **10/18/96** | **100%** |
| 41 | Circuit Design | 4w | 9/20/96 | 10/17/96 | 100% |
| 42 | Control Algorithm / Programming | 32w | 1/26/96 | 9/5/96 | 100% |
| 43 | System Selection for Mock-up | 1d | 10/18/96 | 10/18/96 | 100% |
| 44 | **Actuation System** | **22d** | **9/19/96** | **10/18/96** | **100%** |
| 45 | Drive Unit | 3w | 9/19/96 | 10/9/96 | 100% |
| 46 | Drive Mount | 3w | 9/19/96 | 10/9/96 | 100% |
| 47 | Cables / Tendons | 3w | 9/19/96 | 10/9/96 | 100% |
| 48 | Bench Test / Refinement | 1w | 10/10/96 | 10/16/96 | 100% |
| 49 | System Selection for Mock-up | 2d | 10/17/96 | 10/18/96 | 100% |
| 50 | **Systems Integration** | **5d** | **10/21/96** | **10/25/96** | **7%** |




2 W/O#

Non-Critical Critical Milestone Summary Slack