GLOVE CONTROLLER WITH FORCE AND TACTILE FEEDBACK FOR DEXTEROUS ROBOTIC HANDS

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PROJECT SUMMARY

The objective of this project was to establish the feasibility of developing a fully-sensorized master glove controller with force feedback at the joints and tactile feedback at the fingertips. The purpose of the master glove was to enable and enhance teleoperated control of dexterous slave hands.

Work began with an evaluation of a glove design utilizing pin-hinge joints. This was discovered to be unsatisfactory due to large displacements between the exoskeletal glove and operator's finger, causing unacceptably large shifting of the tactile display. Alternative joint designs were considered, and eventually two prototypes of an innovative "virtual hinge" joint were fabricated which permitted fixed registry between the glove and finger during all degrees of finger flexure. A 3-DOF glove finger was then fabricated based upon the virtual hinge joint, and the distal joint fitted with force and position sensors. Additionally, an advanced 37-element tactile telepresence system was fabricated to provide direct tactile feedback to the glove fingertip, and the glove finger was integrated with a motor control and sensor processing system to enable the eventual implementation of bi-lateral force control of a slave unit by the master glove.

An evaluation was performed of the fully-sensorized distal fingertip of the master glove controller with regard to range of motion, registry of tactile display, operation of the joint force and joint angle sensors, and functioning of the fingertip tactile display. As a multi-fingered master glove controller would simply be a duplication of these principal components, it was concluded that the development and construction of a full-scale glove was entirely feasible.

The anticipated applications of the master glove controller principally involve the control of dexterous teleoperated devices used for satellite servicing, structural assembly in space, unmanned experimentation and exploration, radioactive hot-cell or reactor maintenance, hazardous waste disposal, and underwater mining or salvage operations.

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GLOSSARY OF TERMS

System Terms:

Dexterous Teleoperator System:
Turnkey teleoperation system comprising a dexterous Master Glove Controller, dexterous Slave Hand, M/S Hand Control System (with joint force and position sensor feedback), and a Tactile Telepresence System for the fingers.

Sub-System Terms:

Master Glove Controller:
Exoskeletal "glove" which provides direct feedback to the operator with regard to the slave hand joint positions, joint forces, tactile sensations.

Slave Hand:
Dexterous hand used to remotely perform complex manipulative actions, and is equipped with joint position, force, and tactile sensors.

M/S Hand Control System:
System used to control the Slave Hand by the Master Glove Controller, and consisting of M/S Hand Interface, Motor Drivers, and joint force and position Sensor Signal Conditioners.

Tactile Telepresence System:
A sub-system of the Dexterous Teleoperator System which provides tactile feedback from the slave hand to the master glove controller.

Sub-System Component Terms:

LED Indicator:
An array of LEDs representing the distribution of tactile stimulator elements (tixels) in the tactile display, and which gives a visual interpretation of the tactile data being presented to the operator on his/her fingertips. (This is not the primary tactile data display mode, but is intended for diagnostic and system familiarization purposes only.)

M/S Hand Interface:
Supplies power for the joint actuators and force/position sensor data conditioning boards. Also controls the interaction between the slave hand and master glove controller, i.e., bi-lateral force control.

Motor Driver:
A generic board located near the master glove controller or slave hand, and designed to drive up to 9 actuators in a bi-polar DC or PWM mode.

Sensor Signal Conditioner:
A generic board located near the master glove controller or slave hand, and designed to power and condition the joint angle and joint force sensor signals. Each board can accommodate 18 sensors (9 position and 9 force), i.e., all the sensor pairs required on a 9-DOF master glove or slave hand.

Tactile Display:
Small thimble-like device attached to the Master Glove Controller which transmits tactile sensations (by means of a PWM vibratory pattern) generated by the fingertip tactile sensor on the slave hand to the fingertip of the operator. (The Tactile Display should not be confused with the LED Indicator.)

Tactile Display Driver:
An array of miniature pneumatic valves which control the gas flow to the tactile display. The drivers were located adjacent (2 m) to the tactile display.

Tactile Display Valve Drivers:
Circuit designed to convert the analog tactile sensor signal into a PWM signal, which subsequently is used to control solenoid driver ICs connected to the tactile display valve driver.

Tactile Sensor:
Fingertip-shaped device intended for mounting on the fingertip of a slave hand, and capable of generating analog signals representing the tactile pressure distribution pattern imparted to the sensor's surface.

Tactile Sensor Illuminator:
Fiberoptic illumination source used to energize the optical tactile sensor fabricated at Begej Corporation and used herein.

Tactile Sensor/Display Interface:
Power source and interface between the tactile sensor and tactile display.

Tactile Sensor Signal Conditioner:
Module located near the fingertip tactile sensor on the slave hand which converts the optical signal from the sensor into an analog electrical signal (0 to 10 V).

General Terms:

M/S:
Master/Slave.

PWM:
Pulse Width Modulation.

Taxels:
Tactile sensor elements (analogous to picture elements, or pixels).

Tixels:
Tactile display elements (tickle elements).

1. INTRODUCTION

The objective of this program was to demonstrate the feasibility of developing certain key elements of a Dexterous Teleoperator System. In particular, the elements that were addressed and developed were an exoskeletal Master Glove Controller, a Master/Slave Hand Control System, and a Tactile Telepresence System. These elements are defined in the Glossary of Terms, and the relationships between the elements are shown in Figure 1-1.

The primary thrust of this program was development of a dexterous master glove controller, with other elements being developed to enable proper evaluation of the glove. The initial glove design contemplated the use of simple pin-hinges in the finger and knuckle joints, with each fingertip of the glove controller provided with a fingertip-shaped tactile display containing from 37 to 44 elements. Furthermore, each joint segment would be provided with joint force and joint angle sensors for implementation of force and position control. The original goal was to design and build a simple controller and to evaluate it, and then to fabricate a second advanced unit for more refined testing. As part of the latter evaluation, the first glove prototype would have been used in conjunction with fingertip tactile sensors to function as a simple but effective slave hand.

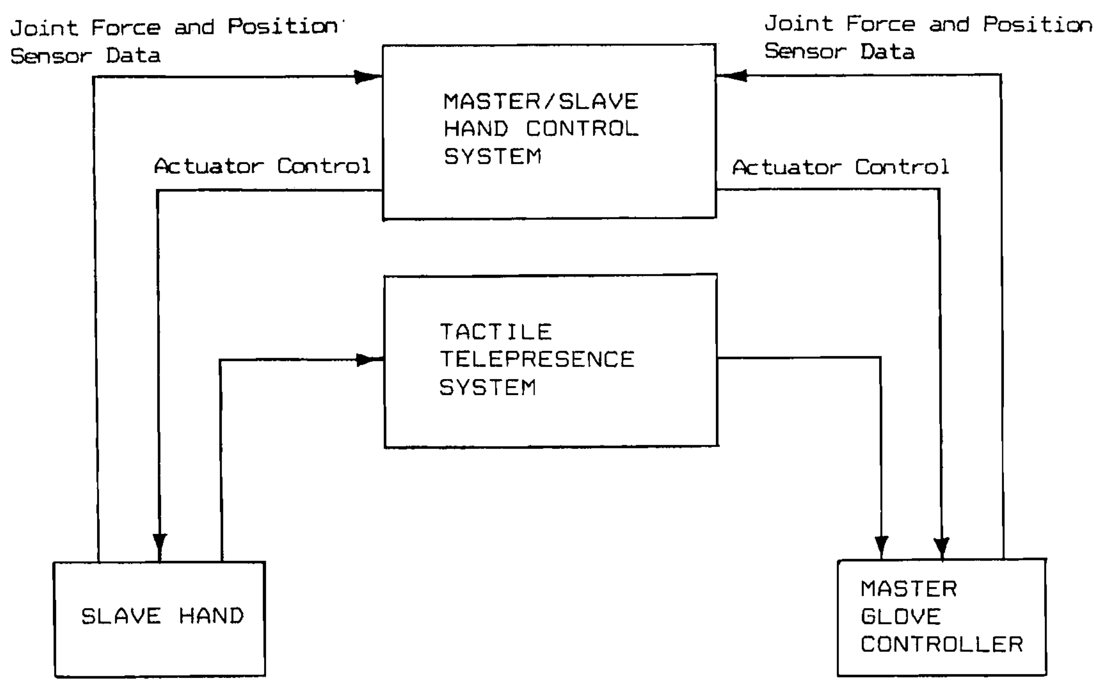


FIGURE 1-1: Block diagram showing the four principal elements of a Dexterous Teleoperator System.

Unfortunately, as the following sections will reveal in greater detail, the above plan was not followed because the pin-hinge joint was determined to be unsatisfactory, as it caused the tactile display to shift by as much as 25 mm with respect to the finger during joint flexure.

The development effort was therefore redirected into a search for a suitable joint design. This resulted in the selection of a joint design utilizing a "virtual hinge", as it behaved as though the exoskeleton were hinged through the same axes as the human hand. Two virtual hinge prototypes were fabricated and tested, and the second gear-driven, ball-bearing version selected for use in the design and fabrication of a single 3-DOF glove controller finger.

Due to significant and unanticipated drain that this joint development effort entailed, only the distal link of the glove finger prototype was fully instrumented with joint force and joint angle sensors. A further consequence of the virtual joint development effort was that the fabrication of the tactile telepresence system had to be abbreviated, with the result that only one finger system was designed and fabricated, though it incorporated the most important refinements, i.e., modularization and compact packaging of the tactile sensor and display units.

The result of this Phase I effort was the design and fabrication a single 3-DOF finger of an exoskeletal master glove controller with tactile, force, and joint angle sensing and display capability on the distal link. A Photograph of the Telerobotic Dexterous Hand System with associated Tactile Telepresence System is shown in Figure 1-2. This prototype incorporated all key elements of a Dexterous Teleoperator System except the slave hand, and was considered to be an adequate demonstration of the feasibility of the basic concepts involved.

A fuller description of the master glove controller, M/S hand controller system, and tactile telepresence system development efforts are presented in Sections 2, 3 and 4, respectively, and a evaluation of the single glove-finger performance is described in Section 5. Conclusions regarding technical feasibility and directions for future work are detailed in Section 6 and 7, respectively.

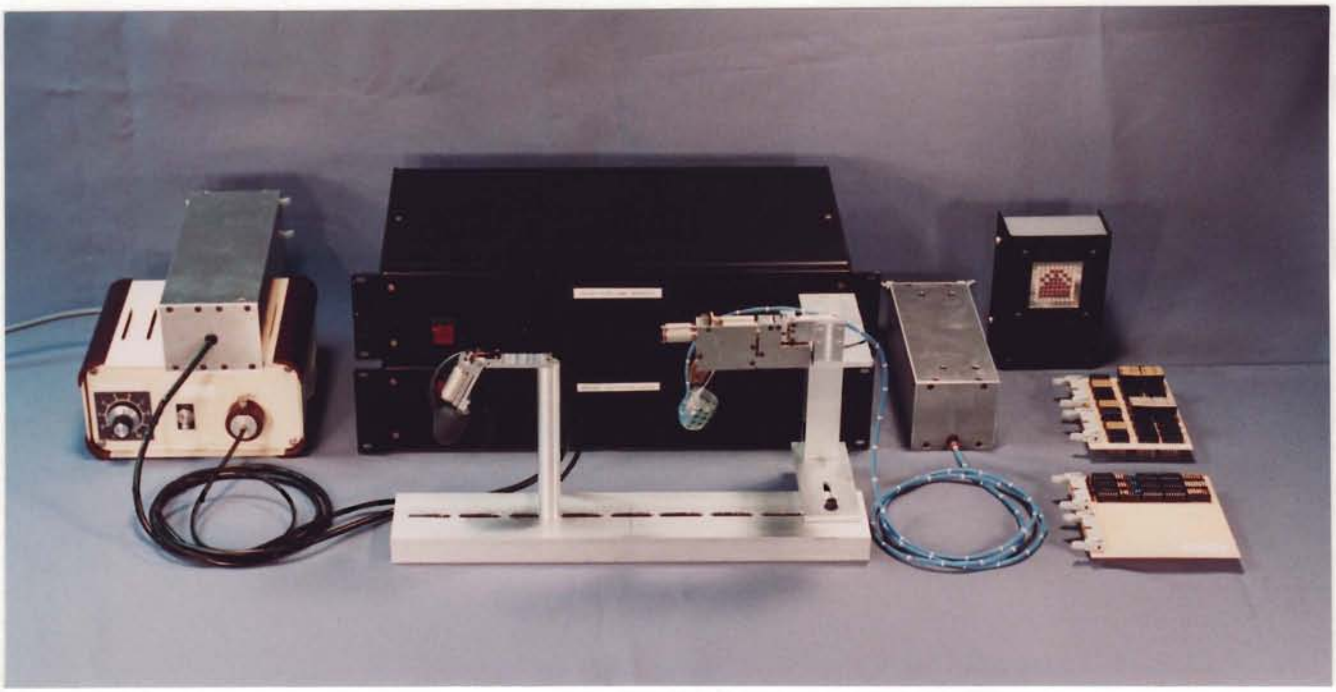


FIGURE 1-2: Photograph of the Dexterous Teleoperator System with a single-finger master glove controller developed under this Phase I program (cables omitted for clarity). Starting with the black tactile sensor in the left-center-foreground and moving CW:

- Fingertip-shaped tactile sensor with 37 channels (mounted on a non-operational slave finger),
- Illuminator for tactile sensor energization,
- Tactile sensor signal conditioner,
- Tactile sensor/display interface (lower box),
- Master/slave hand interface (upper box),
- Tactile display driver,
- LED indicator,
- Motor driver board for master glove finger,
- Joint force and joint angle sensor conditioning board for master glove,
- 3-DOF master glove finger (on testbed stand),
- Fingertip-shaped tactile display with 37 tactile display elements (tixels).

2. DEVELOPMENT of the MASTER GLOVE CONTROLLER

2.1. Glove Joint Development

2.1.1. Model I: Pin-Hinge Joints

The original glove controller concept is shown in Figure 2.1.1-1, and indicates a reliance upon an exoskeletal frame utilizing simple pin-hinge joints located above each finger joint. Each joint would be motor driven and be equipped with a force and joint angle sensor to enable the implementation of bi-lateral force control of the slave hand. Furthermore, each fingertip would be provided with a tactile display providing tactile feedback to the operator.

A prototype (termed Model I) of a pin-hinge joint was fabricated to assist in the design process regarding the joint actuation strength, angular swing, and selection of the joint force and angular position sensors. This prototype is shown in Figure 2.1.1-2. The motor was supplied by Micro Mo (St. Petersburg, FL), and operated on 12 VDC (SN 1516E012S). It was combined with a 76:1 gearhead and 36:1 worm drive, and was expected to provide approximately 20 N force at the tip of the finger.

The joint segments were designed to be a modular series of cantilevered elements, so that the force at each segment could be independently determined by measuring the deflection of the cantilevered portion of each segment with respect to a fixed portion of the joint. The specific force measurement means had not been decided at this point, though an optical displacement sensing method was favored. Joint angle sensors are not shown, as it was the purpose of this device to serve as a testbed for various sensor candidates such as resistive potentiometers and optical encoders. (Potentiometers were actually discarded rather early due to their relatively short lifetimes and high noise levels.)

After a fingertip tactile display was attached to the glove finger, a serious design flaw was uncovered. As shown in Figures 2.1.1-3 and 2.1.1-4, there was a significant relative displacement between the glove frame and the human hand during finger flexure. These displacements were more than 10 mm at both the main knuckle and the first finger joint, respectively, and would have resulted in a total shift of approximately 20 to 25 mm at the fingertip when displacements due to two joints in series are considered. This situation was clearly undesirable, as movements of the tactile display of this magnitude could never be tolerated.

It was at this point that the program emphasis changed from what appeared to be a straightforward task to that of inventing a glove joint design that would have no shifting but still enable force feedback (via joint actuators), force sensing, and joint angle sensing. The efforts to discover such a mechanism are summarized in the next section.

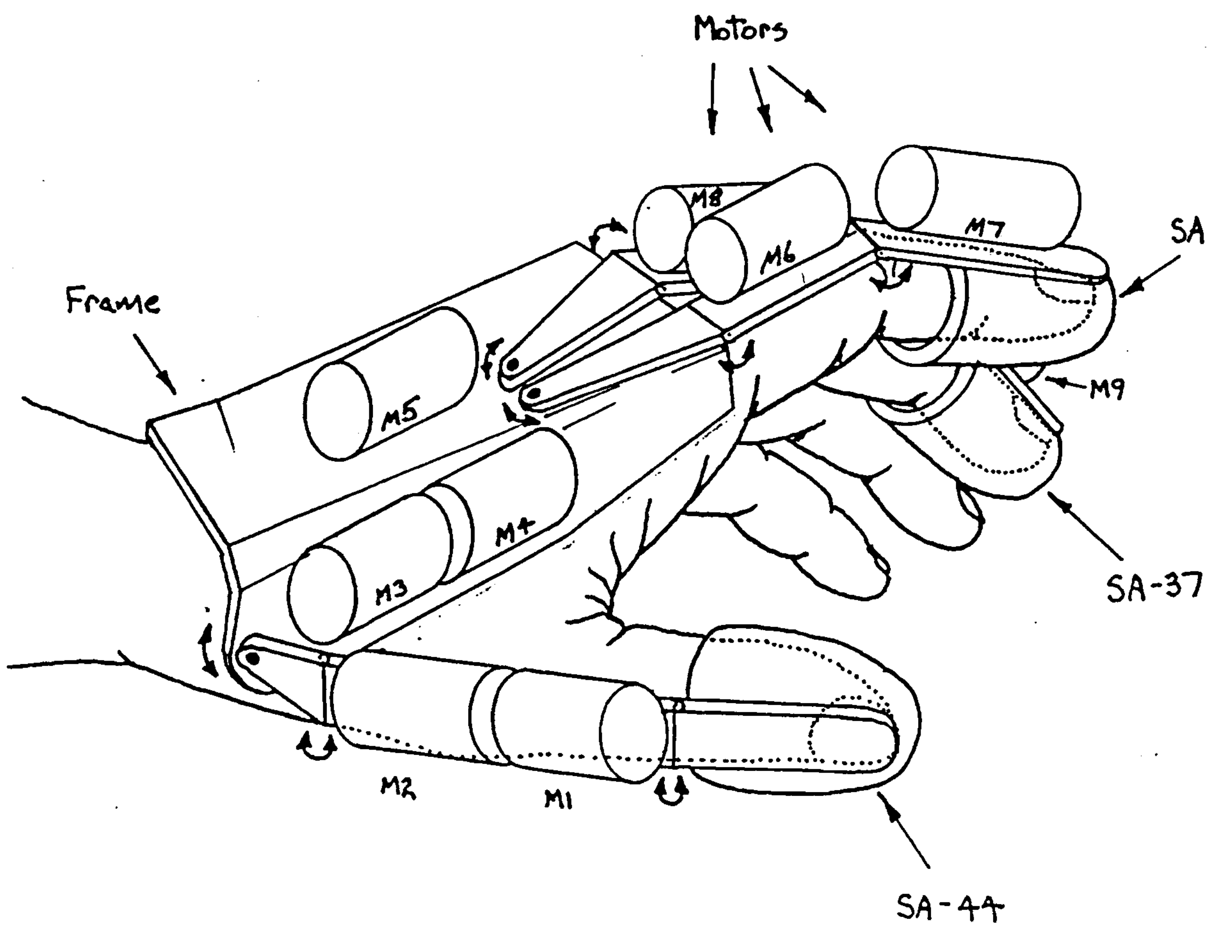
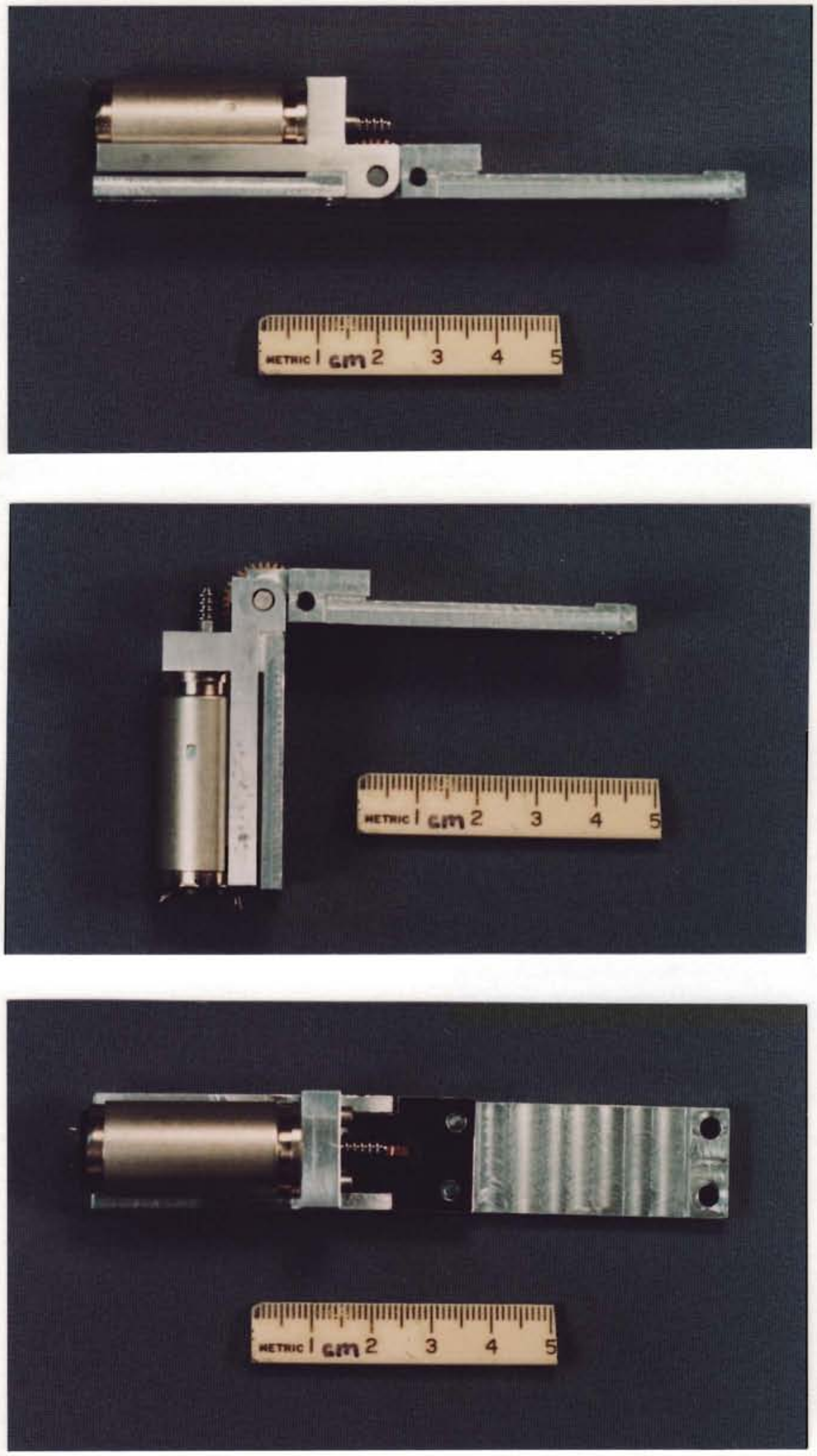


FIGURE 2.1.1-1: Schematic diagram of the original proposed concept for a three-fingered master glove controller. An exoskeletal frame with pin-hinge joints would be worn on the back of the hand, with each finger segment provided with an actuator (for force feedback), force sensor, joint angle sensor, and fingertip tactile display (distal segment only).



<u>FIGURE 2.1.1-2:</u> Model I prototype of an exoskeletal glove controller joint. A miniature motor acting through a 76:1 planetary and 36:1 worm gearing system was used to drive the joint. Each finger segment was attached to the end of a cantilever element protruding from the previous segment, with deflections of the cantilever being translated into the force at the joint (note gap between cantilever and motor mount).

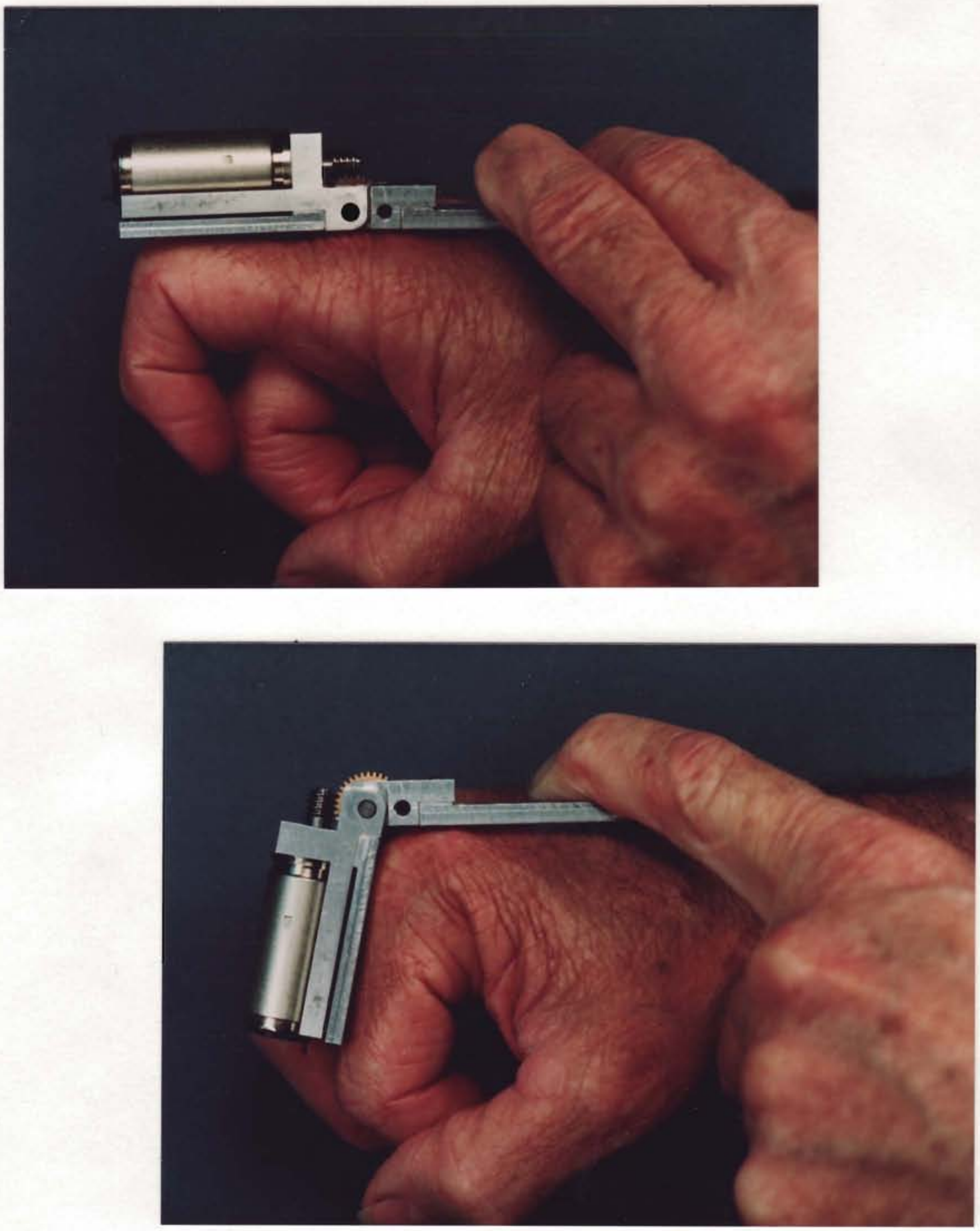
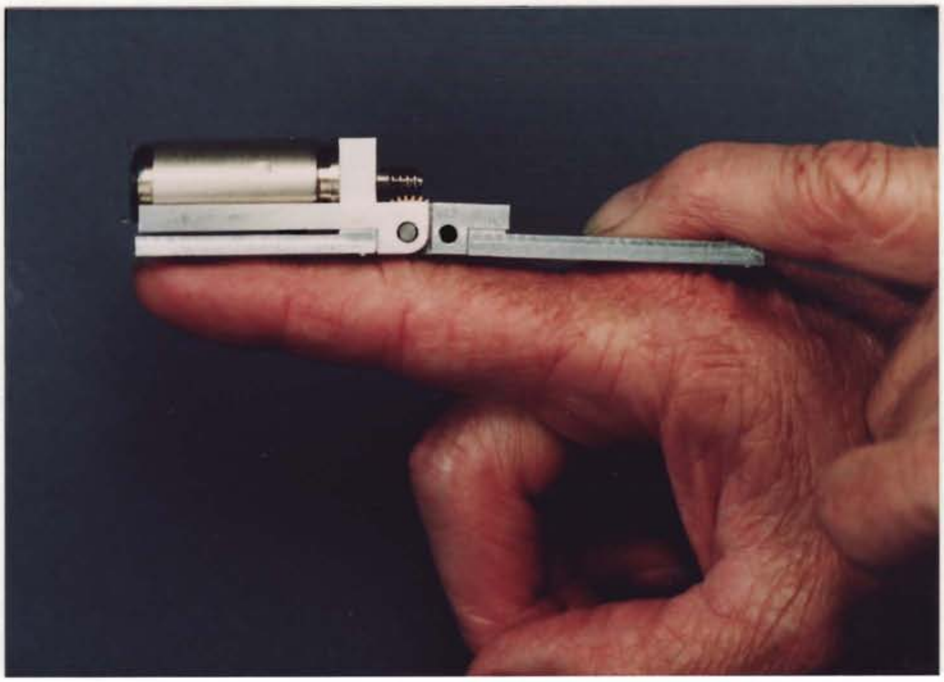


FIGURE 2.1.1-3: Flexure of the pin-hinge joint caused significant shifting between the exoskeletal frame and the finger at the main knuckle: compare distal portion of joint segment with finger before and after flexure.



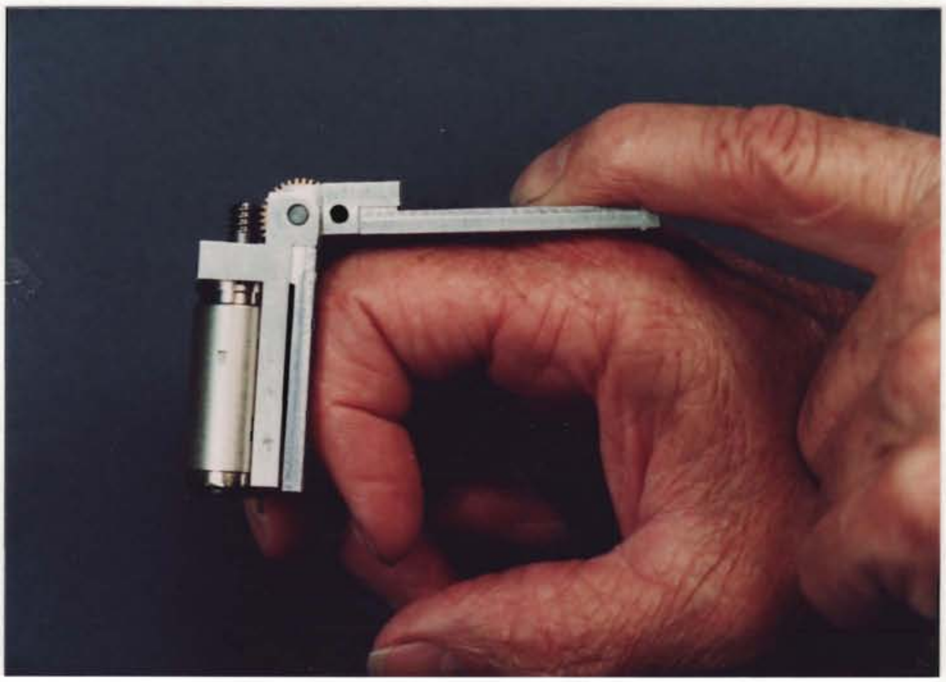


FIGURE 2.1.1-4: Shifting between the exoskeleton and finger is greater when the joint is positioned over the first finger knuckle than over the main knuckle (see Figure 2.1.1-3) due to the larger range of angular motion of the former.

2.1.2. Model II: Tendon-Drive Virtual Hinge

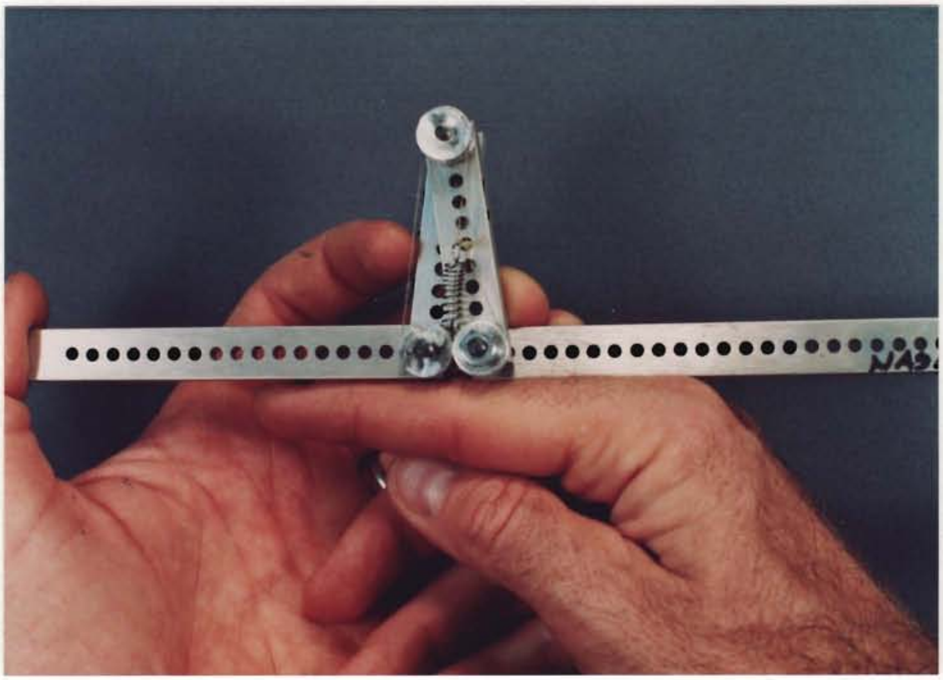
Several glove joint designs and concepts were explored in an attempt to address the tactile display displacement problem. The simplest approach was to place the exoskeleton hinges along the same line as the axes of rotation in the human finger joints. This approach is feasible for those joints allowing physical access to at least one side, e.g., the distal finger joints, and one side of the main knuckle. However, this approach fails to accommodate the "inner" main knuckles and spherical joint at the thumb, as no physical access is possible. (It may have been possible to straddle the entire knuckle with a rather cumbersome staggered hinge, but such an approach would severely restrict the range of joint motion.)

Another approach considered was to permit the finger segments to telescope in a manner related to the joint angle so as to maintain registry between the finger and exoskeleton. This was eventually abandoned as being overly complex and problematic, e.g., a telescoping/sliding mechanism would need to be added to each finger segment; a second actuator would be required at each segment to control the telescoping action (otherwise the finger of the operator would be required to carry axial loads); and the joint force sensor would have a response that was a function of the joint angle.

Also considered was a joint mechanism in which angular joint motions were coupled to longitudinal displacements. Figure 2.1.2-1 shows a prototype of one such device using pulleys and tendons to generate the desired motions (gears would be used in actual practice to reduce the physical size). However, this approach was abandoned as it offered insufficient longitudinal support for use in a force-feedback system (i.e., a system with actuators).

The last approach considered and finally pursued was that of a "virtual hinge". This is essentially an offset circular linear bearing in which one element is constrained to move as though it were pivoted at the virtual rotation axis of the bearing. This concept is illustrated in Figure 2.1.2-2.

(Late in the program after fabrication of a 3-DOF glove finger, it was discovered that several concepts related to the virtual hinge had been considered for other robotic applications. For example, Taylor and Ibbotson [1978] and Rosheim [1980, 1981, and 1989] discuss curved "linear" or "C" bearings and actuators in relation to flexible robotic wrists.)



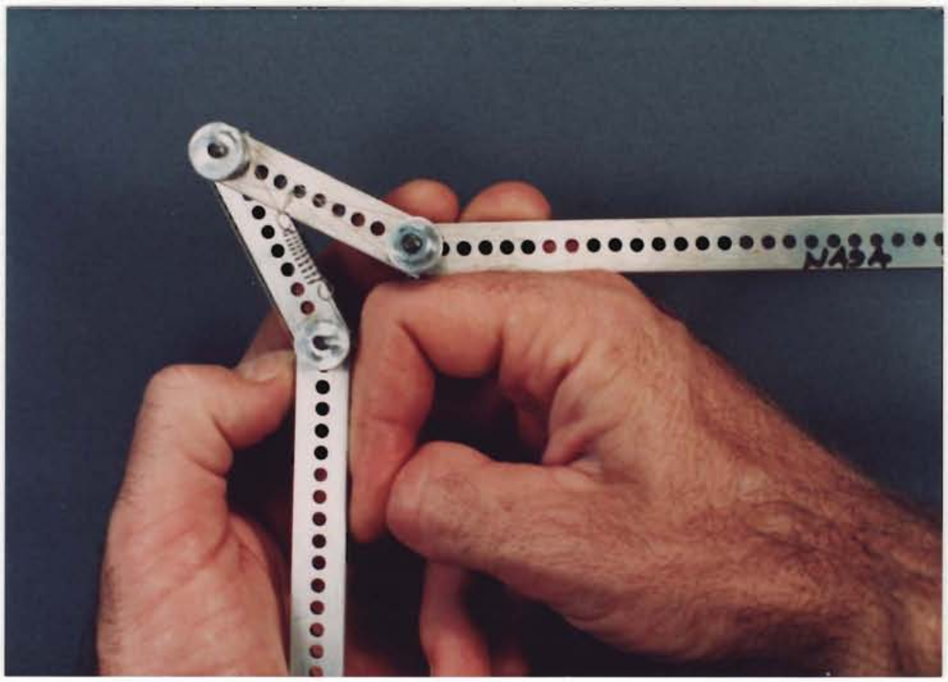


FIGURE 2.1.2-1: A special joint consisting of segments linked by means of pulleys and Kevlar tendons was fabricated in an attempt to address the displacement problem between the exoskeleton and finger. This approach did not prove to be successful, as it provided insufficient longitudinal support for use in a force-feedback system.

In addition to freedom from shifting between the hinge segments and the underlying finger, other important advantages of the virtual hinge were that the mechanism may be made quite narrow and located entirely above each hand joint, thereby avoiding lateral finger interference effects that may exist with alternative glove joint designs. However, concomitant disadvantages include: added mechanical complexity over pin-hinge joint; added difficulty of sensing joint moment and angle; limited joint angle range due to constraints on the slider length set by the finger joint separation distance; and routing of the sensor and motor power leads across the sliding joint sections.

To explore these issues in greater depth, a tendon-drive glove joint (termed Model II) was fabricated. This device is shown in Figure 2.1.2-3, and featured a relatively compact size, lack of side interference, and large angular range (71°). The three principal design concerns were the nature of the bearing used in the joint, the method of joint actuation, and location of the joint force sensor. (The problem of sensing the joint angle was not considered a top priority at this time, as numerous options were available once the above issues had been adequately addressed.)

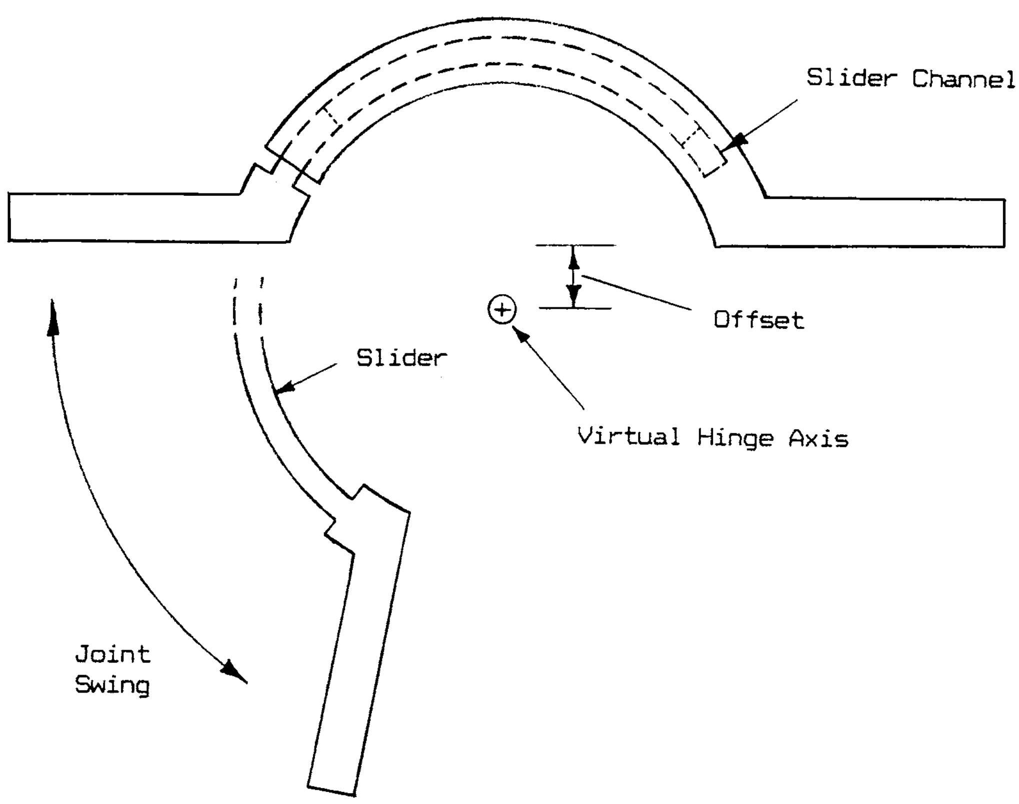
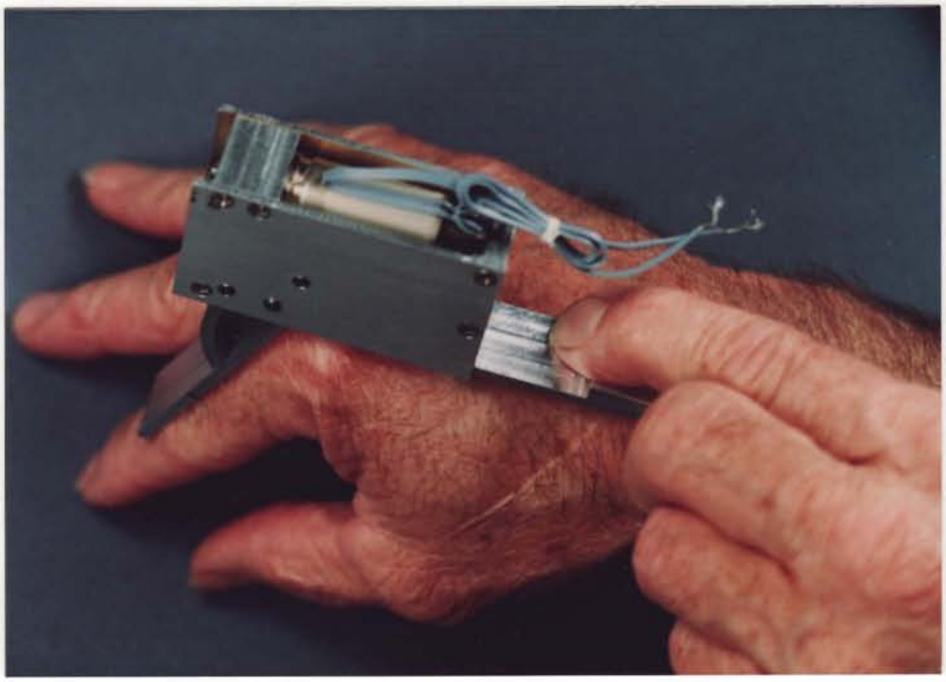


FIGURE 2.1.2-2: A "virtual hinge" consists of an offset circular "linear" (prismatic) bearing in which one element is constrained by channels or other means to move as though it were pivoted at the virtual axis of rotation.



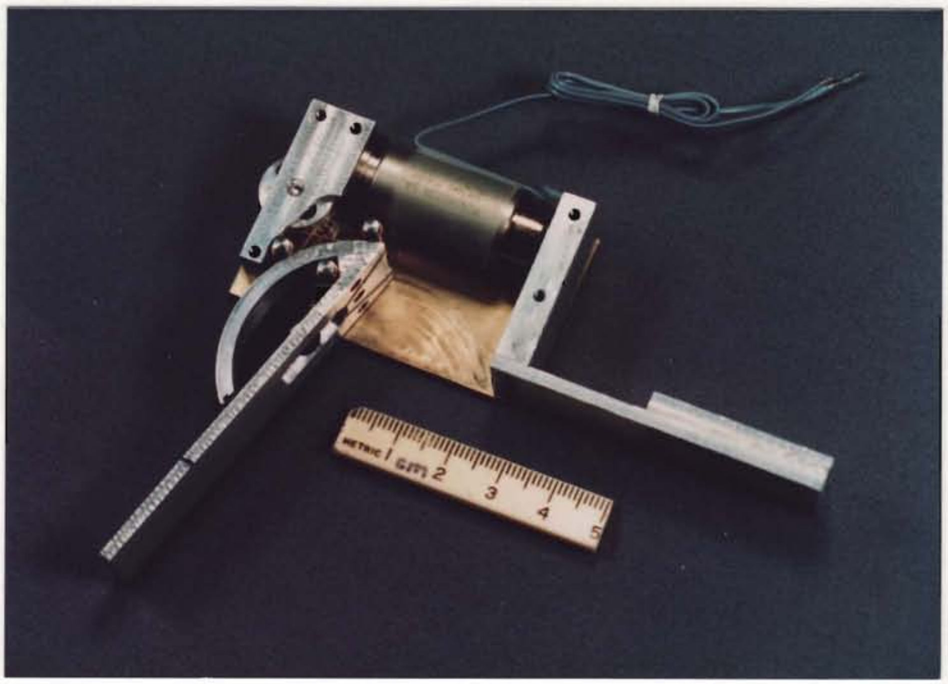


FIGURE 2.1.2-3: Tendon-drive glove controller joint utilizing the virtual hinge concept. Top photograph shows the joint placed over the finger knuckle, and bottom photograph is an internal view showing the electric motor, Kevlar tendon drive drum, and the virtual hinge (circular arc riding between three shafts). The virtual axis of rotation coincides approximately with the top-left corner of the metric scale. The angular range of joint motion was 71°.

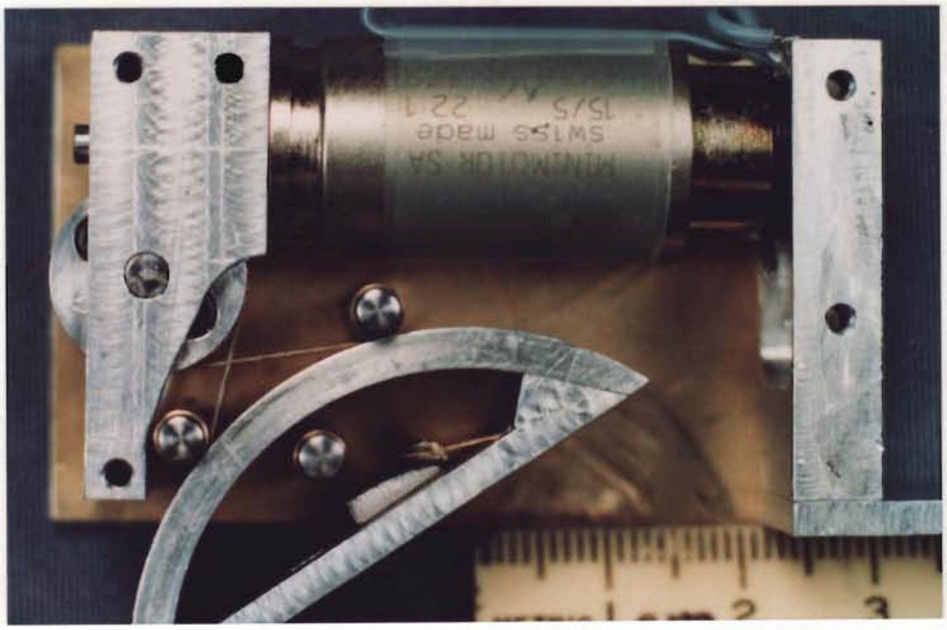
Experiments were performed with various linear bearings utilizing purely sliding surfaces, and led to the recognition that minimization of friction effects was an important goal. Designs utilizing ball bearings were then explored, though the interests of minimizing development time dictated selection of simple brass-bushing bearings supporting a circular arc segment. A cantilever was attached to the base of the arc segment to enable measurement of forces acting on the joint. An optical sensor was to have been mounted in the space between the arc and cantilever, and the joint force inferred by measuring the displacement between the latter two members. It was reasoned that the force measurements would be sufficiently independent of joint angle if the stiffness of the arc segment was much higher than the cantilever.

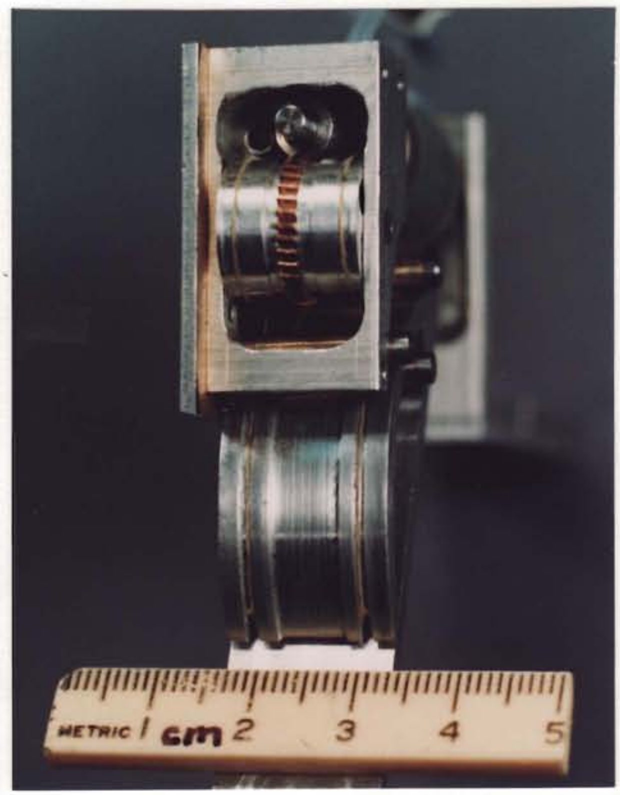
A positive-action gear-drive mechanism was the preferred mechanism of actuation, but fabrication was considered to be too time consuming. Therefore, a tendon-drive design was utilized instead, as it was relatively easy to implement and could tolerate lower levels of machining accuracy. Details of the tendon drive system are shown in Figure 2.1.2-4, especially the worm-driven drum and tendon routing paths.

The results of the evaluation performed on the Model II joint were mixed. The results were encouraging because they confirmed the validity of the virtual hinge concept. Figure 2.1.2-5 and 2.1.2-6 show that the virtual hinge mechanism eliminated the problem of exoskeleton/finger displacements during joint flexure, thereby making this approach suitable for use with glove controllers utilizing tactile displays.

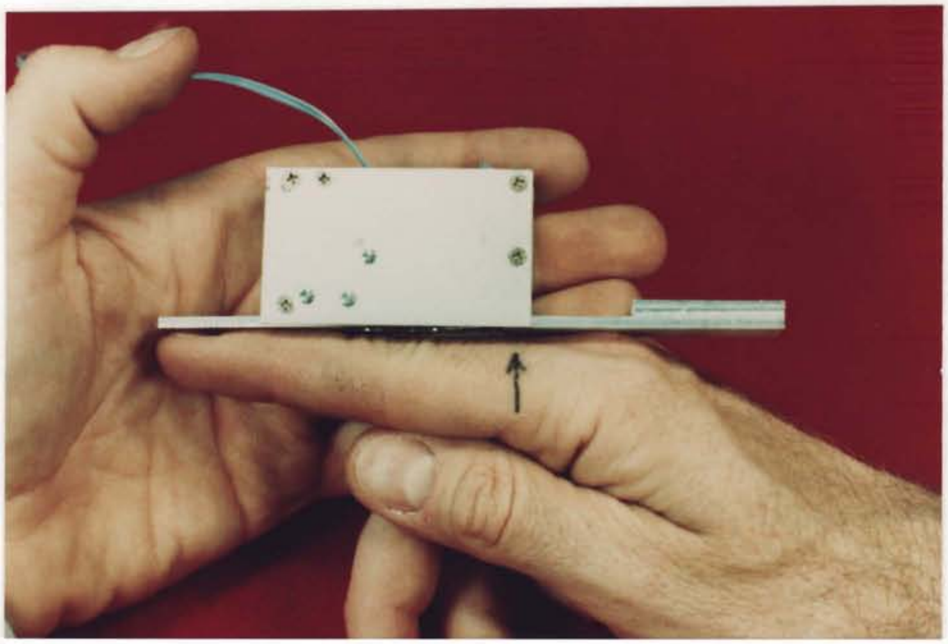
However, the evaluations also revealed severe design problems, most notably the presence of severe stiction in the rollers (which caused jamming of the slide mechanism at both extremes of motion) and stiction between the hinge slider and the sideplates. Attempts were made to alleviate the latter difficulty with brass shims and lubricants (lithium grease, molybdenum sulfide, graphite, and teflon powder), but relief was only short-lived. Furthermore, the use of such lubricants contaminated the Kevlar drive tendons and caused slippage, eventually diminishing the joint actuation forces to inadequate values. Lastly, it was recognized that an optical joint angle encoder could be attached to the tendon drum, but too much space was consumed by the center bearing and tendon tensioning post to permit placement of an optical displacement/force sensor on the cantilever.

For the above reasons, work on the tendon-drive virtual-hinge was abandoned, and a new gear-drive and ball-bearing design undertaken to address the previous difficulties. These efforts resulted in a new version (Model III) of the glove controller joint, which is described in the following section.





<u>FIGURE 2.1.2-4:</u> Details of the tendon-drive virtual-hinge joint. An electric micro-motor and worm gear was used to drive the dual-sided tendon drum. The Kevlar tendon tension adjustment post is seen lying inside the space between the hinge slider and force cantilever (top photograph).



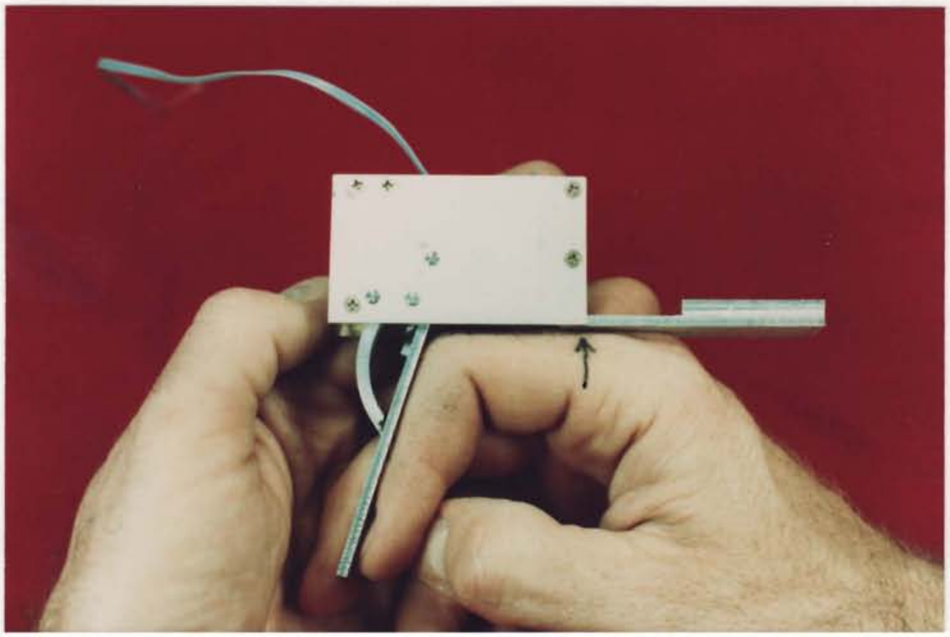
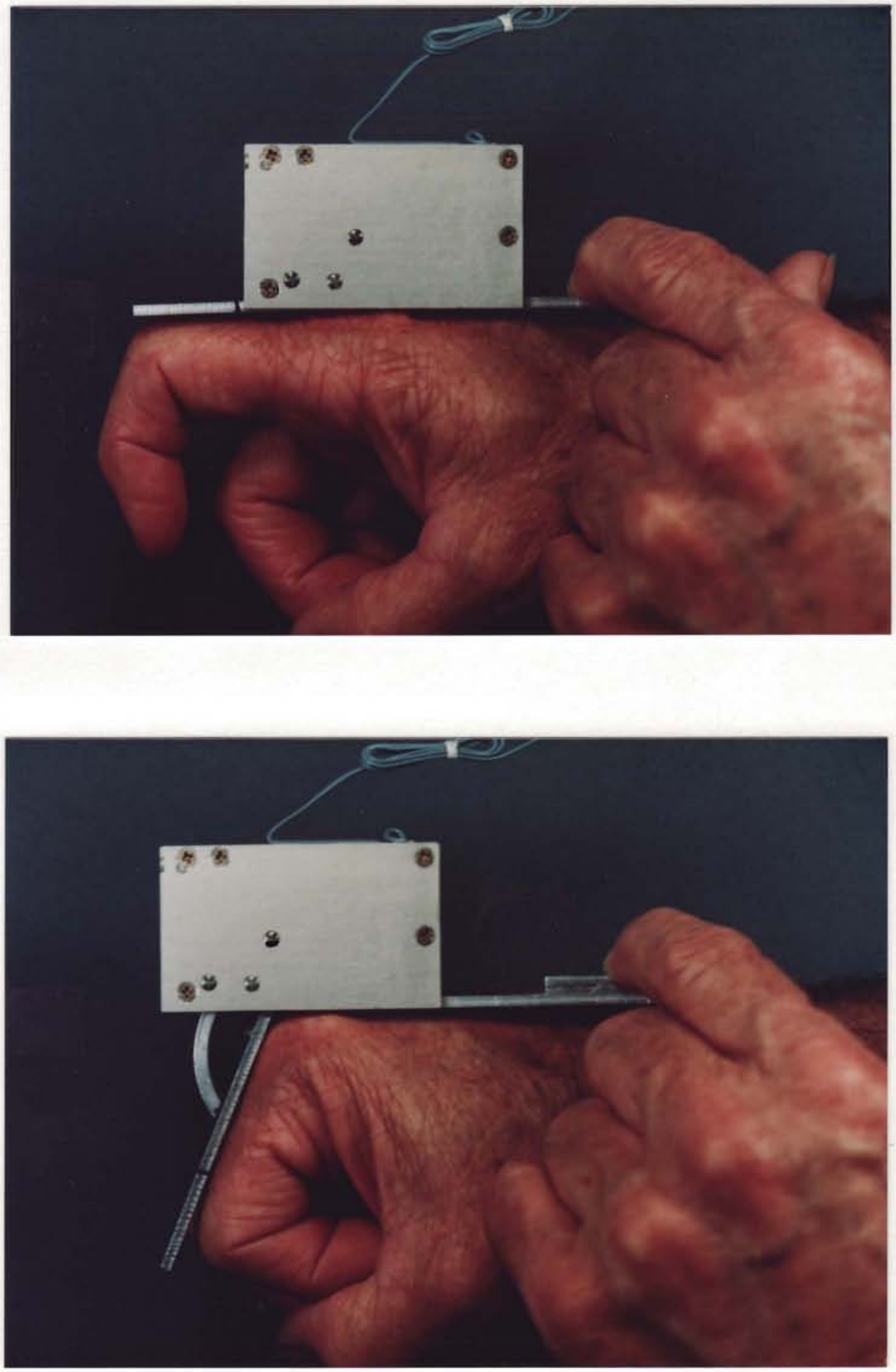


FIGURE 2.1.2-5: Model II of the virtual hinge joint showed that displacements between the joint segments and finger were greatly reduced or eliminated during joint flexure, thereby rendering the concept suitable for use on master glove controllers with tactile displays. Using arrow on hand as a stationary reference, note the minor fingertip displacement in comparison to that seen with a pin-hinge joint (Figure 2.1.1-4).



<u>FIGURE 2.1.2-6:</u> Minimal shifting is seen between the Model II glove joint and the finger when the joint is placed at the main knuckle. Compare to shift seen with pin-hinge joint shown in Figure 2.1.1-3.

2.1.3. Model III: Gear-Drive Virtual Joint

Jamming of the bushing rollers, stiction between the sideplate and slider, and loss of tendon traction prompted development of a new virtual hinge design incorporating ball bearings and a positive-traction gear drive. Photographs of the Model III glove joint are shown in Figure 2.1.3-1. The new joint had a angular motion range of 62°, compared to 71° for Model II.

Bearing jamming and sideplate stiction were eliminated by the use of miniature flange bearings (W.F. Berg, Inc) attached to the sideplates. These bearings rode in channels machined into the slider body: see Figure 2.1.3-2. A sliding clearance was provided between the bearings and the channel walls, so that under no-load conditions the bearings simply moved through the channels without rotation or binding. However, once a bending force was applied to the joint, the bearing pairs would be pressed against opposite channel walls, and would rotate in opposite directions (without scrubbing the opposite wall) while carrying the imposed load. This arrangement resulted in less than 1° play in the hinge mechanism.

Figure 2.1.3-1 illustrates how coupling was achieved with an idler worm gear between the motor shaft worm and integral gear rack machined into the slider. A longer motor shaft would have permitted direct worm drive of the slider and thereby significantly reduced the vertical dimension of the joint, though would have made sensing of the joint angle more difficult. The idler gear was sized so that it rotated approximately three-quarters of a turn during full slider travel, thereby permitting the convenient direct attachment of an absolute single-turn optical encoder to the idler. This encoder is discussed in a later section. (The encoder was developed under IRAD at Begej Corporation as a pre-production prototype.)

During evaluation of the Model III joint it was observed that frictional effects were markedly reduced over the previous design, and that much higher forces could be imparted to the joint without jamming. Therefore, with these encouraging results, the design and fabrication of the spherical joint of the main knuckle joint was undertaken based on the Model III virtual hinge joint design.

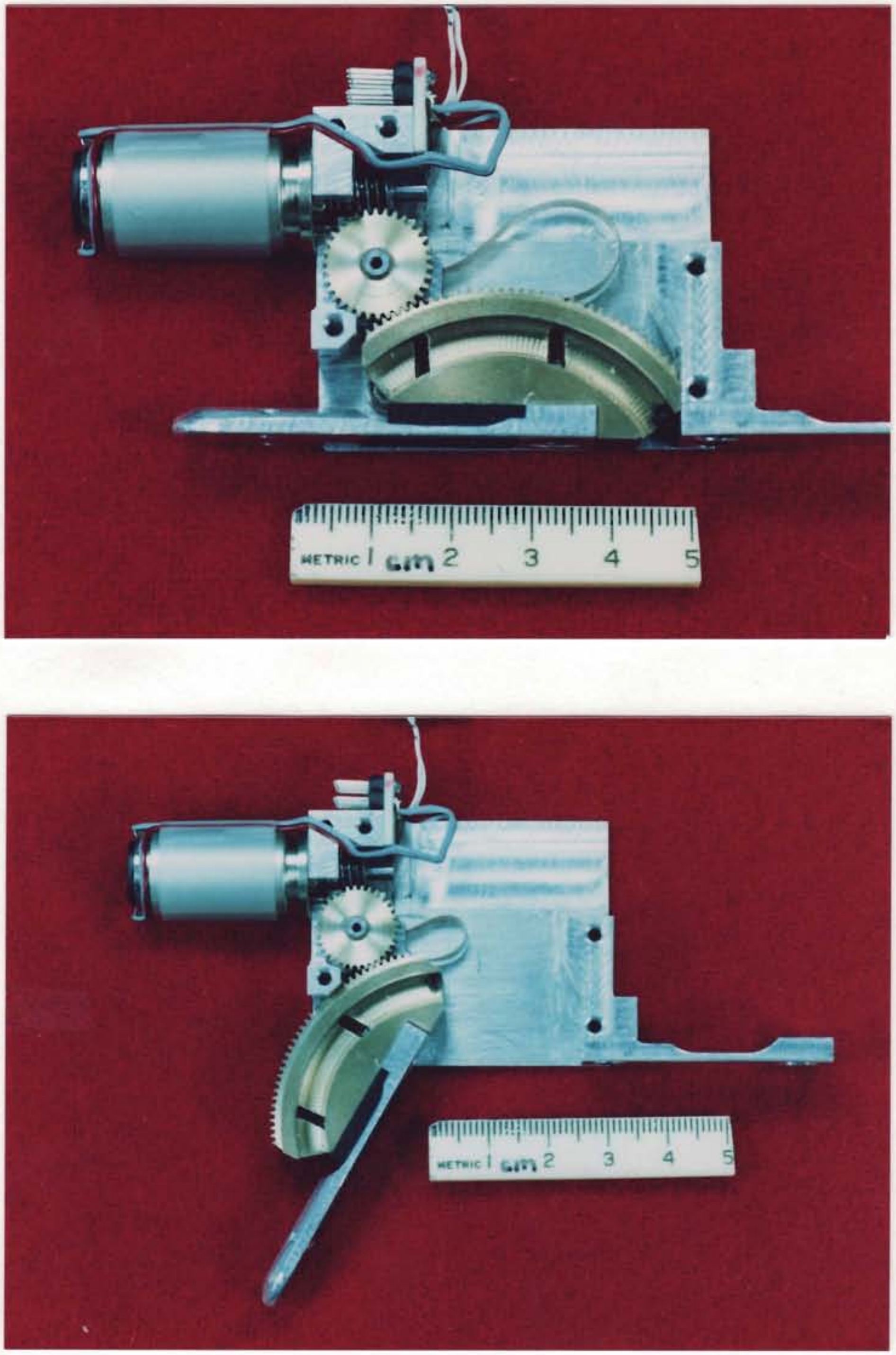
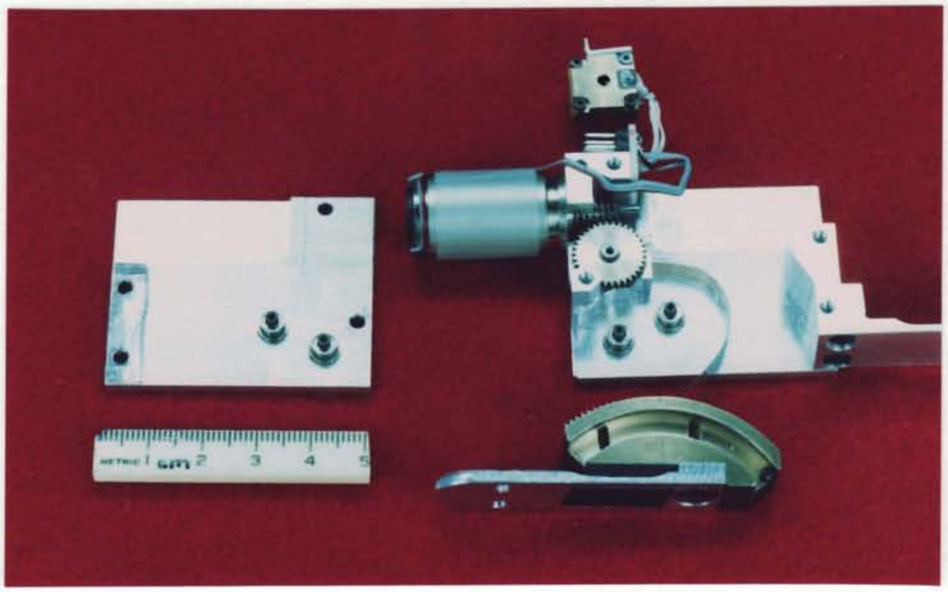
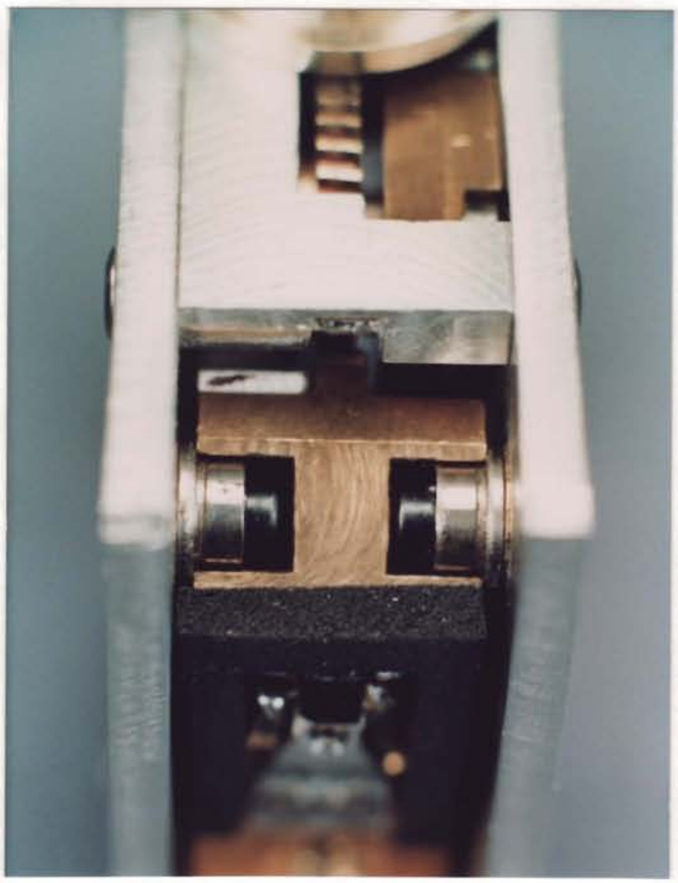


FIGURE 2.1.3-1: The Model III glove controller joint utilized a virtual hinge design in which miniature flange ball-bearings rode in channels machined into a curved slider, thereby eliminating slider jamming and sideplate friction. Additionally, positive slider motion was achieved with a gear drive mechanism which overcame the tendon slipping problem of the previous design. The angular rotation achieved by this joint was 62°.





<u>FIGURE 2.1.3-2:</u> Details of the bearing mechanism used in the Model III virtual hinge. Two miniature ball bearings were attached to each sideplate with 0-80 UNF socket head cap screws (top), and rode in sliding-fit channels machined into the hinge slider (bottom).

2.4 Glove Finger Prototype

Figures 2.4-1 and 2.4-2 show several views of the finger prototype, and illustrate the range of motion of the virtual hinges (62° each) and placement of the actuators for each joint. A spherical virtual joint was created at the hand knuckle by causing the (vertical) axis of a lateral-motion pin-hinge to intersect the (horizontal) axis of the virtual hinge. Figure 2.4-3 presents details of the pin-hinge joint actuator, and Figure 2.4-4 shows the range of lateral motions (35° and 15° to the left and right, respectively) permitted by this hinge.

An important safety feature built into the glove controller was the incorporation of failsafe joint-travel limits which prevented any possibility of injury to the operator. The virtual hinges are inherently safe as all motion stops once the idler gear disengages from the slider gear rack: see Figure 2.1.3-1. Such self-disassembly would be inconvenient, and was prevented by the incorporation of the hard and semi-hard mechanical stops shown in Figure 2.4-5. The pin-hinge of the spherical joint at the main knuckle was also capable of automatic disengagement, though not in sufficient time or distance to prevent injury. Thus, hard mechanical stops incorporating the finger structure have been used to enforce lateral motion constraints.

The following sections will discuss "sensorization" of the distal finger joint, and, in particular, the addition of force and joint angle sensing and tactile display capabilities to the distal joint of the glove controller.

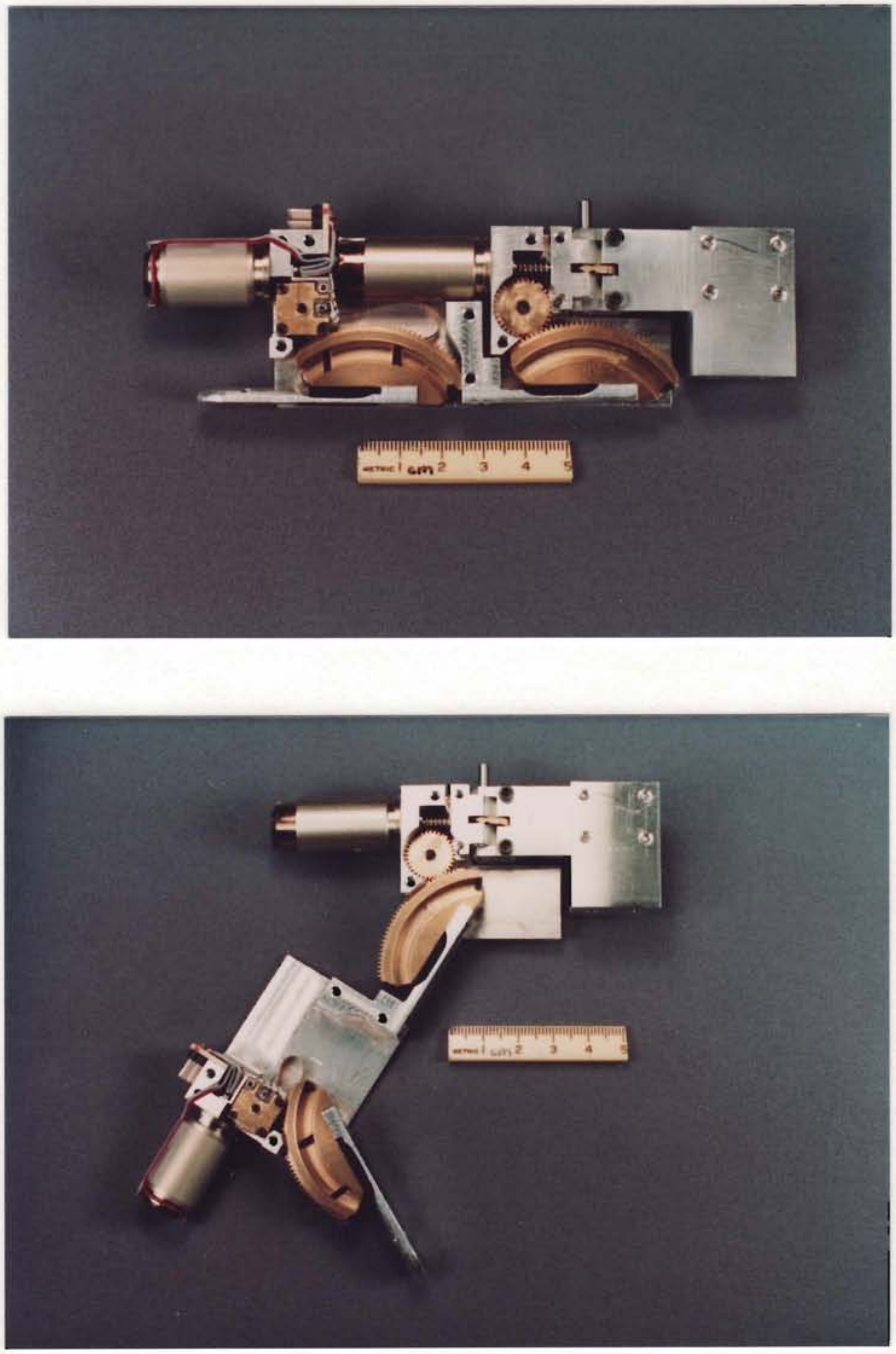


FIGURE 2.4-1: Internal view of the glove controller finger. The joints consisted of a 1-DOF virtual joint at the first finger knuckle and a 2-DOF spherical virtual/pin joint at the hand knuckle. The angular swing of each virtual joint was 62°.

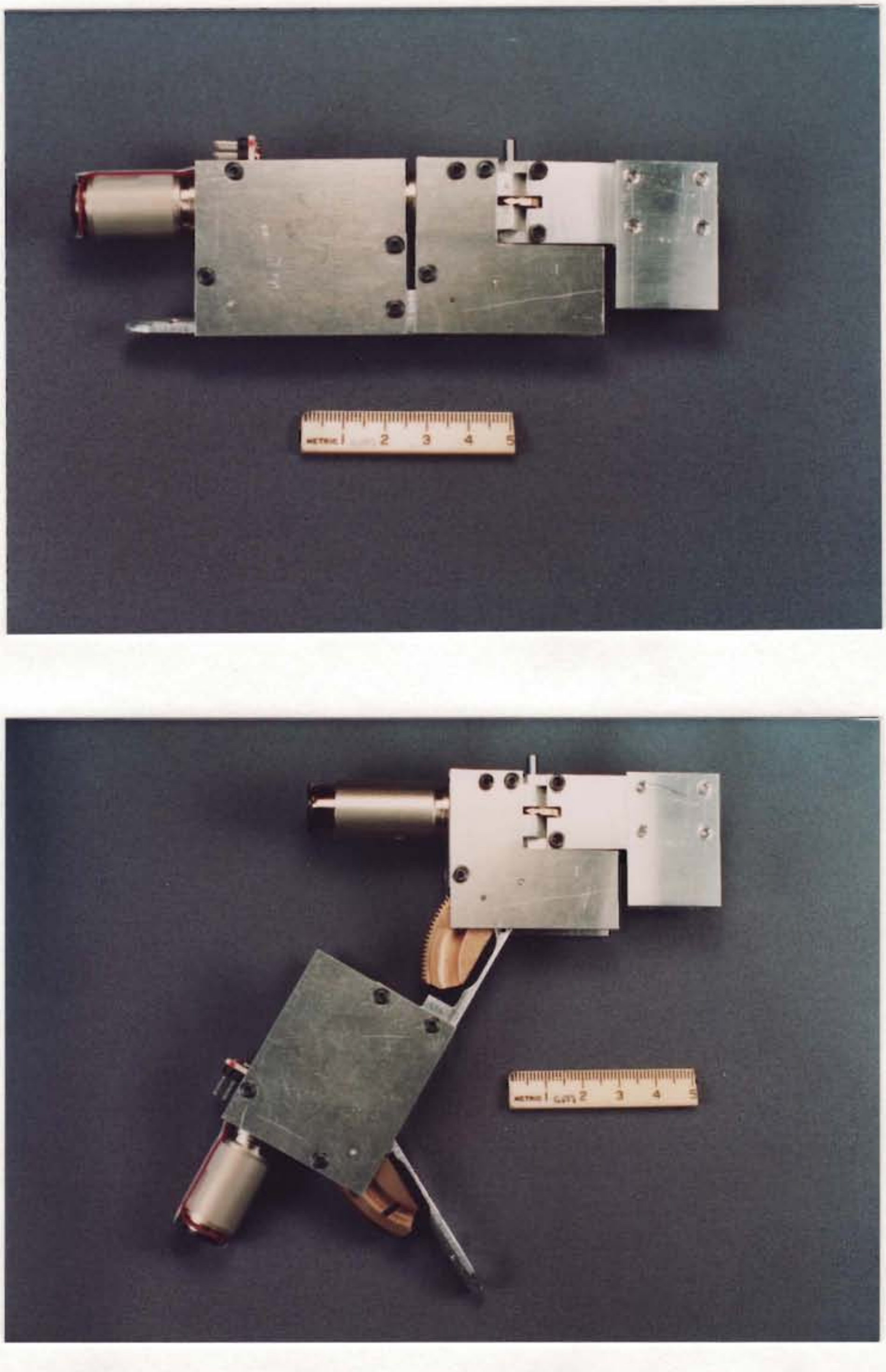
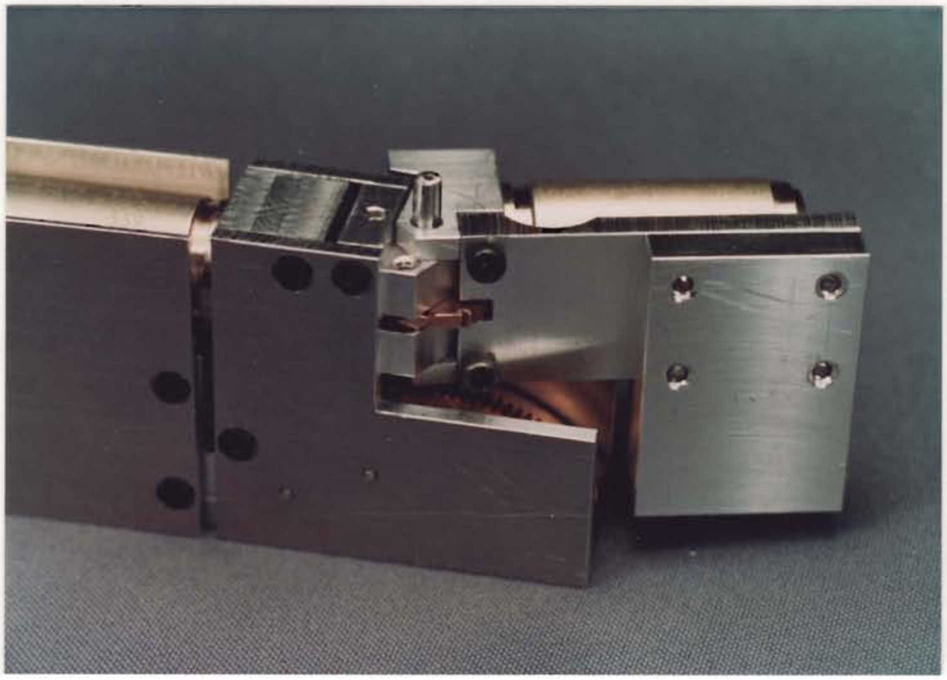


FIGURE 2.4-2: Glove-controller finger prototype with side-plates attached (see Figure 2.4-1).



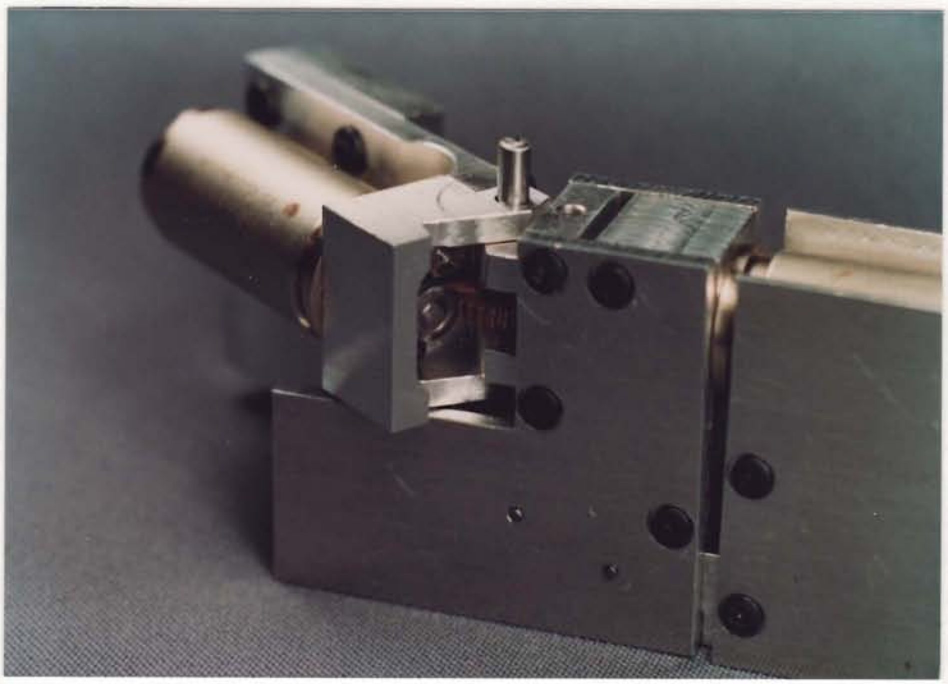
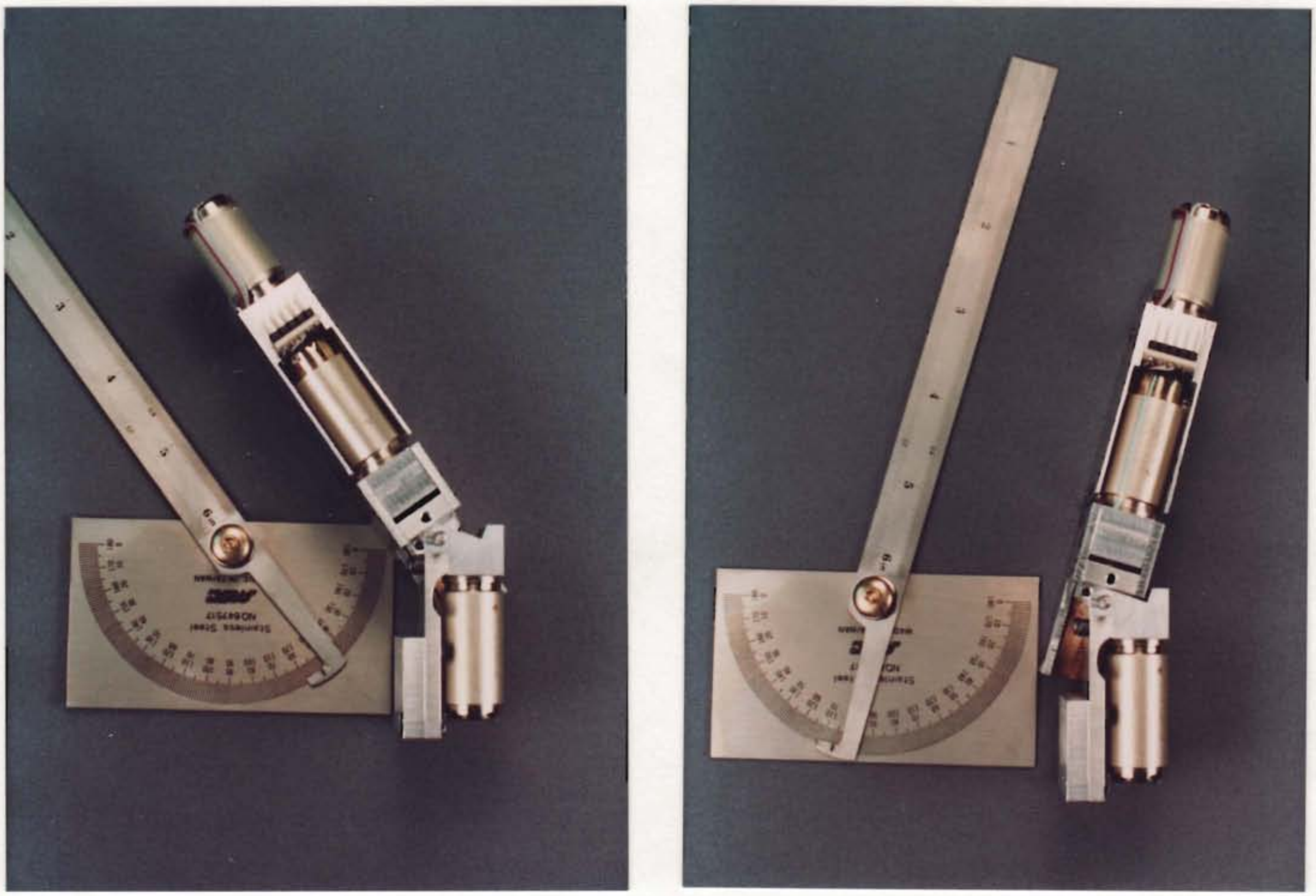


FIGURE 2.4-3: Front and back views of the pin-hinge joint and actuator. Lateral motion at the hand knuckle was provided by this pin-hinge whose (vertical) axis coincided with the (horizontal) axis of the virtual joint, thereby effectively creating a virtual spherical joint at this location.



<u>FIGURE 2.4-4:</u> The lateral limits of finger motion were 35° and 15° to the left and right, respectively.

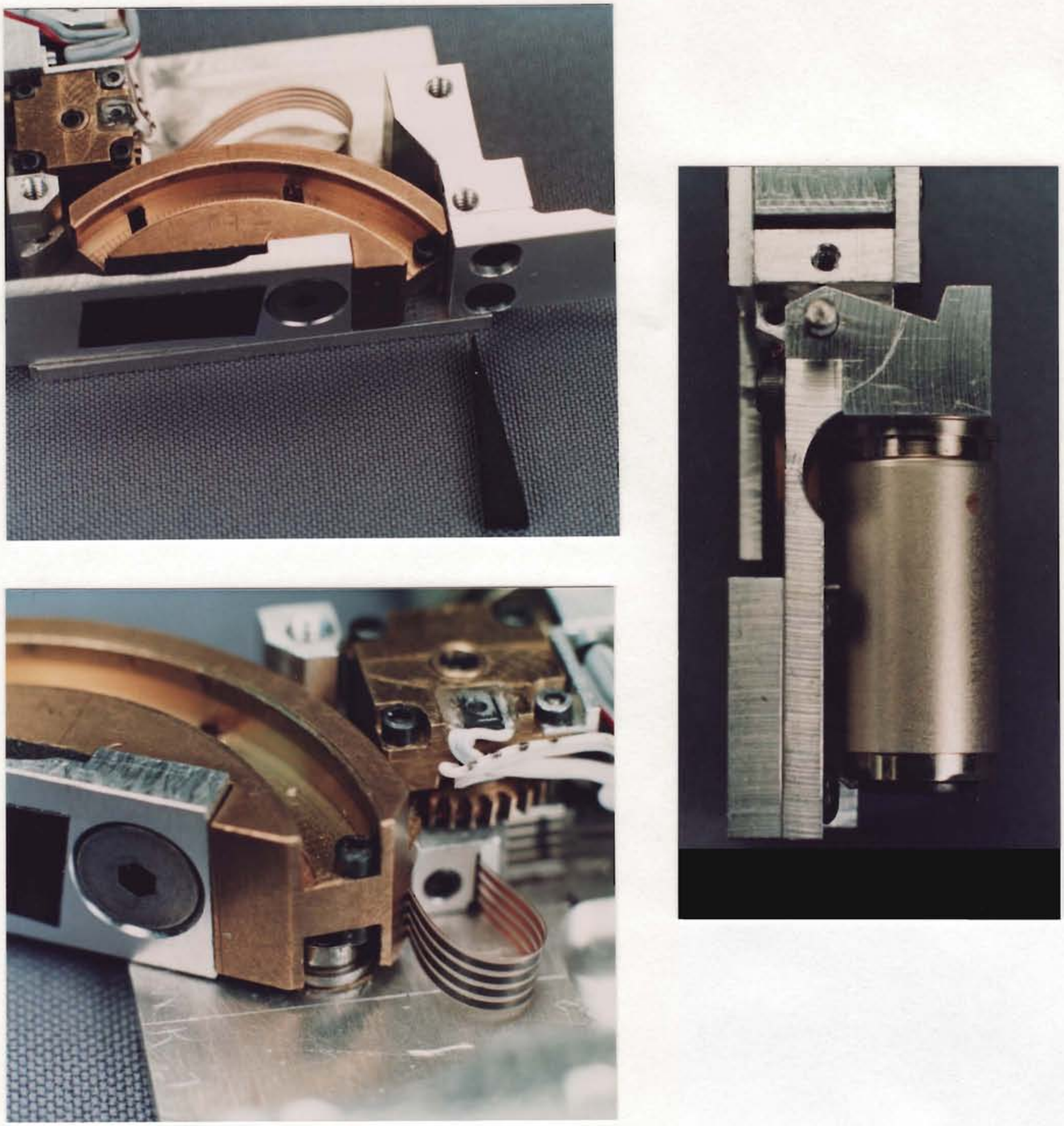


FIGURE 2.4-5: The safety of the glove controller was ensured by the presence of hard mechanical stops to limit joint motion. Failure-proof structural body stops were used to limit the extension motion of the virtual-hinge joints (top-right) and the lateral motion range of the pin-hinge (center-left), whereas semi-hard stops to block the bearing channels in the slider were used to limit finger flexure motions (note screw heads in bottom right photograph). Failure of the latter stops was considered tolerable, as self-disassembly of the hinge would quickly follow.

2.5. Joint Angle Sensor

Various methods were considered for sensing the virtual joint angle, e.g., motor encoder, actuator output shaft encoder, various absolute encoders on the slider, and encoding of the idler gear position. Major emphasis was placed on simplicity, ruggedness, and compactness of the joint angle sensing system, rather than high accuracy. This tended to argue against approaches measuring relative position (such as the first two sensor candidates), as extra circuitry must be used to count the sensor pulses, and complete loss of absolute position was possible during power losses. Absolute optical and resistive encoders were considered for placement on the slider, but were abandoned due to the difficulty of shielding the sensor from ambient light and electrical slider longevity problems, respectively.

Eventually, an absolute encoder was chosen as the joint angle sensing means, and was to be placed on the idler gear between the actuator and slider. The size of the idler was chosen so that it rotated only three-quarters of a turn during the full excursion of the slider, thereby permitting the use of a single-turn encoder device. Potentiometers and magnetic encoders were initially considered for this function, but were not selected due to the short lifetime (200 -50,000 rotations) and susceptibility to noise from external magnetic fields and materials, respectively.

Instead, a single-turn optical encoder (concurrently under IRAD development at Begej Corporation for robotic applications) was selected due to its small size (12 mm square x 5 mm thick) and absolute analog output. The encoder was of the transmissive type, and utilized a circular variable-density filter positioned between an IR emitter and detector pair: a view of the disassembled sensor is shown in Figure 2.5-1. The sensor rotor was attached to the idler gear with a 0-80 UNF cap screw, and anchored to the actuator body with a compliant spring-like clip, as shown in Figure 2.5-2.

A circuit diagram of the sensor energization and signal conditioner is shown in Figure 2.5-3, and illustrates the provisions made for adjusting the drive signal (LED intensity), signal gain, and signal offset. The unprocessed signal from the detector ranged from 0.3 V (zero degrees) to 2 V (330°), which was then amplified and offset into the range 0 - 10 V, corresponding to full extension and full flexure of the finger joint. (However, further development work must be done on the circular encoder filter, as the output is non-linear and is not corrected by the signal processing circuitry. Alternatively, as suggested in the Future Work Section, a microcontroller could be use to linearize the signal by the use of a look-up table.)

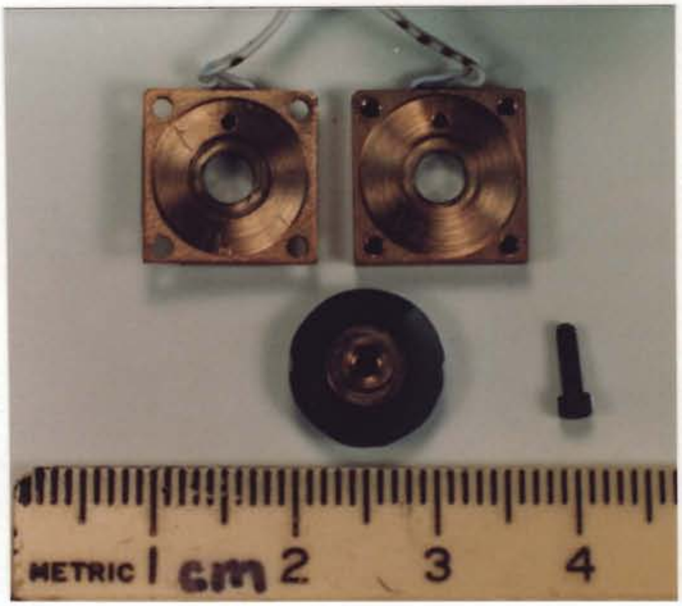


FIGURE 2.5-1: View of disassembled optical shaft encoder used to sense the finger joint angles of the glove controller. The sensor is of the transmissive type in which a circular variable-density filter (center) modulated the transmitted light intensity between an IR emitter/detector pair (holes at top in brass body). Screw (right) attaches filter rotor to shaft of the worm idler gear.

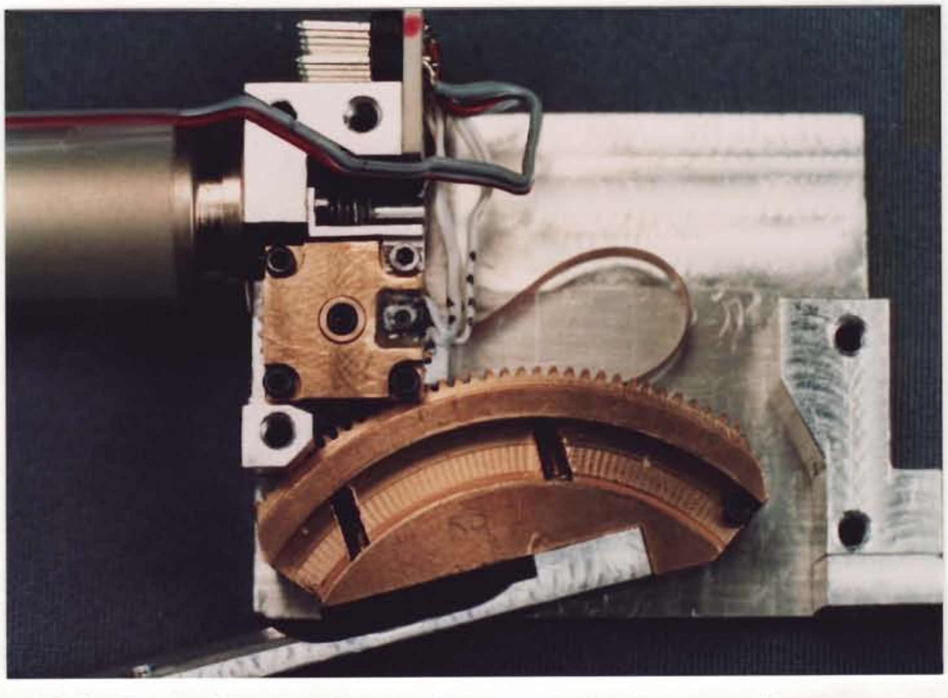


FIGURE 2.5-2: The rotor of an optical encoder was attached to the idler gear shaft by a 0-80 UNF cap screw, and the encoder body compliantly anchored to the actuator mount with a spring-like clip (just beneath the drive worm). Note back of one detector element on the right side of the encoder.

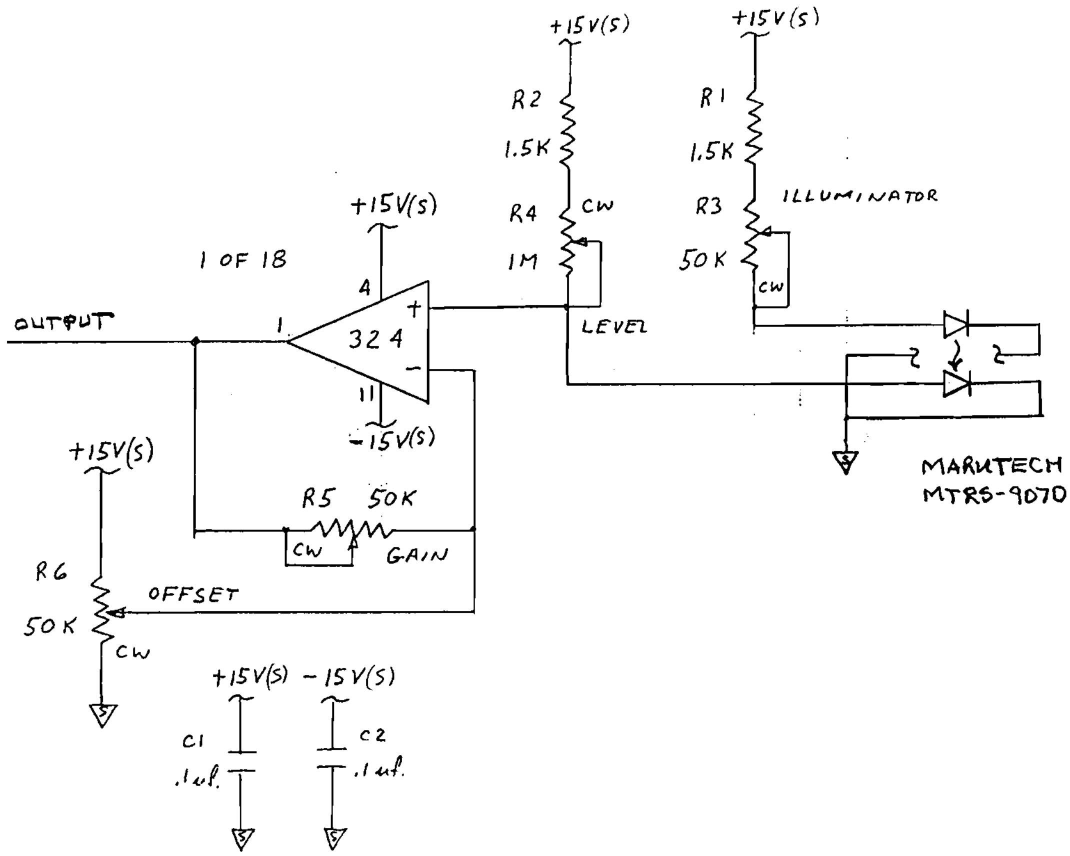


FIGURE 2.5.3: Signal conditioner for optical joint angle sensor. Signal range was adjustable via the LED intensity, amplifier gain, and amplifier offset potentiometers, and was set for 0 - 10 V corresponding to full extension and full flexure of the finger joint. Sensor linearity, however, is not adjustable by this circuit.

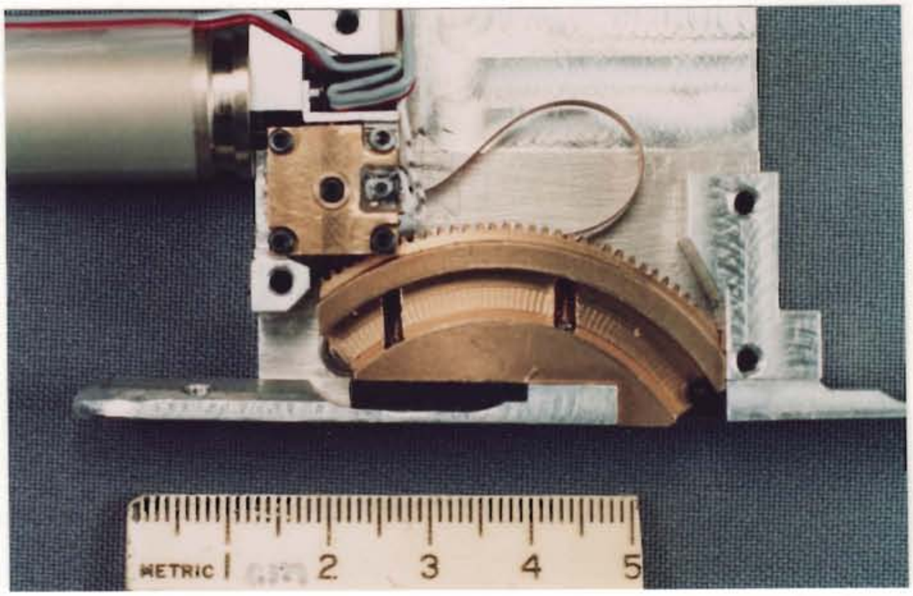
2.6. Joint Force Sensor

Force-sensing at each joint was accomplished by using an miniature optical sensor (Marktech MTRS-9080) to measure the displacement of a cantilever from its equilibrium position with respect to a "fixed" portion of the finger structure. A photograph of the cantilever attached to the virtual hinge slider is shown in Figure 2.6-1, and an internal view of the displacement sensor shown in Figure 2.6-2.

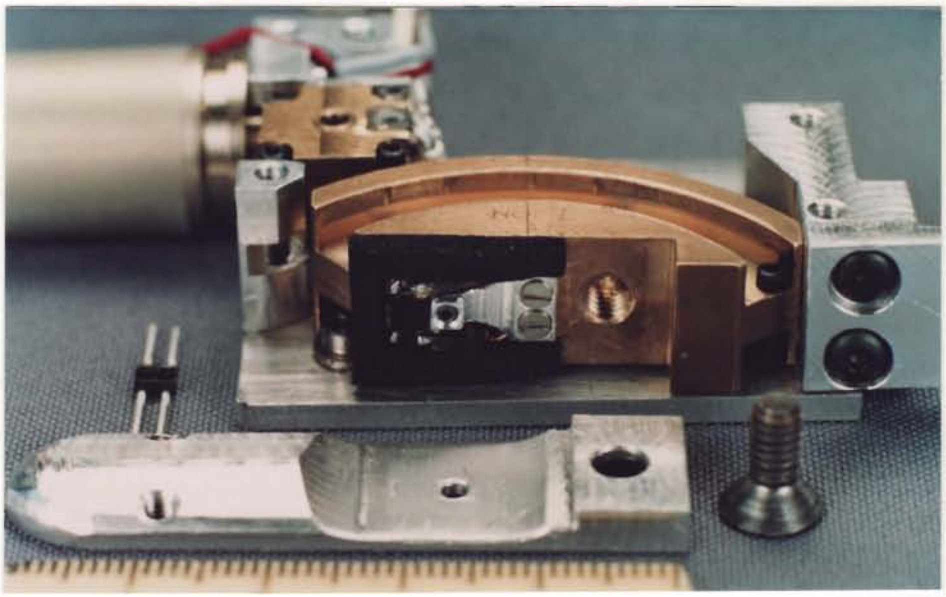
Cantilever bending was detected by a miniature optical displacement sensor mounted on a smaller cantilever structure placed inside a trench within the virtual joint slider. Adjustment of the sensor location for maximum sensitivity and linearity by accomplished by means of an screw on the detector cantilever mount which was accessed through a hole in the finger cantilever arm. Black foam was placed around the detector chamber to shield it from ambient light.

Routing of the sensor leads from the detector to the external connector on the finger structure proved to be somewhat challenging due to the mechanical and structural complexity of the virtual hinge joint. The routing problem was solved by using a flexible ribbon cable to form a bridge from the finger structure to the slider, and then burrowing through the slider body to reach the optical detector chamber. The details of routing the force sensor leads are shown in Figures 2.6-3 and 2.6-4.

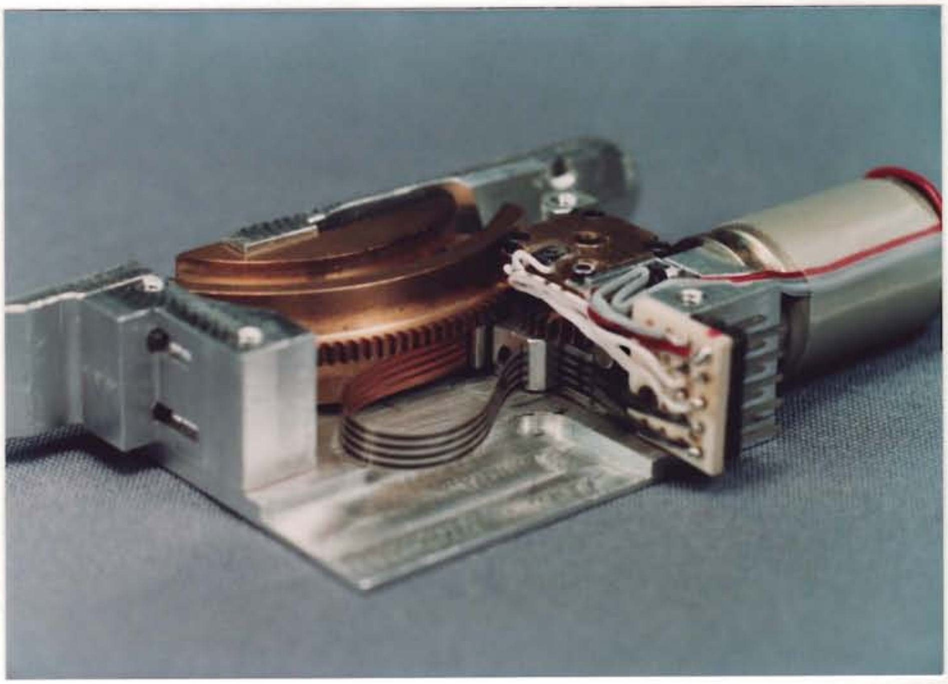
The signal conditioner for the force sensor was identical to that developed for the optical joint angle encoder, as the optical elements were identical for both sensor systems: see Figure 2.5-3. The output signal was adjusted to range from -10 to +10 V to correspond to fingertip joint opening and closing forces of 20 N, respectively.



<u>FIGURE 2.6-1:</u> Force sensing at the finger joint was accomplished by measuring the displacement of a cantilever arm (silver bar at bottom) with respect to the virtual hinge slider ("C" shaped brass member).



<u>FIGURE 2.6-2:</u> Bending of the force-sensing cantilever was detected by a miniature optical displacement sensor. The sensor itself was mounted on a small cantilever structure and placed inside a trench within the virtual joint slider. The access hole for adjusting the operating point of the detector is seen in the center of the finger cantilever arm (bottom), with the detector being located just to the left of this screw. (An unmounted detector is shown on the far left.) Black foam around the chamber was used to shield the detector from ambient light noise.



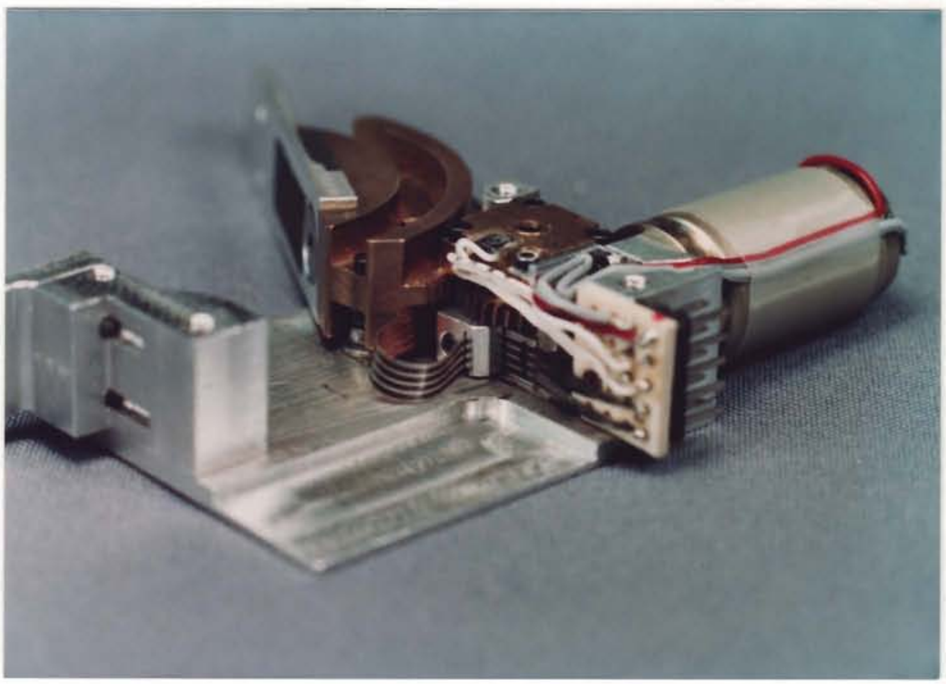


FIGURE 2.6-3: A four-lead flexible ribbon cable was used to bridge the gap from the virtual hinge slider (containing the force sensor) and the finger body. Top and bottom photographs show the behavior of cable when the finger was fully extended and fully flexed, respectively.

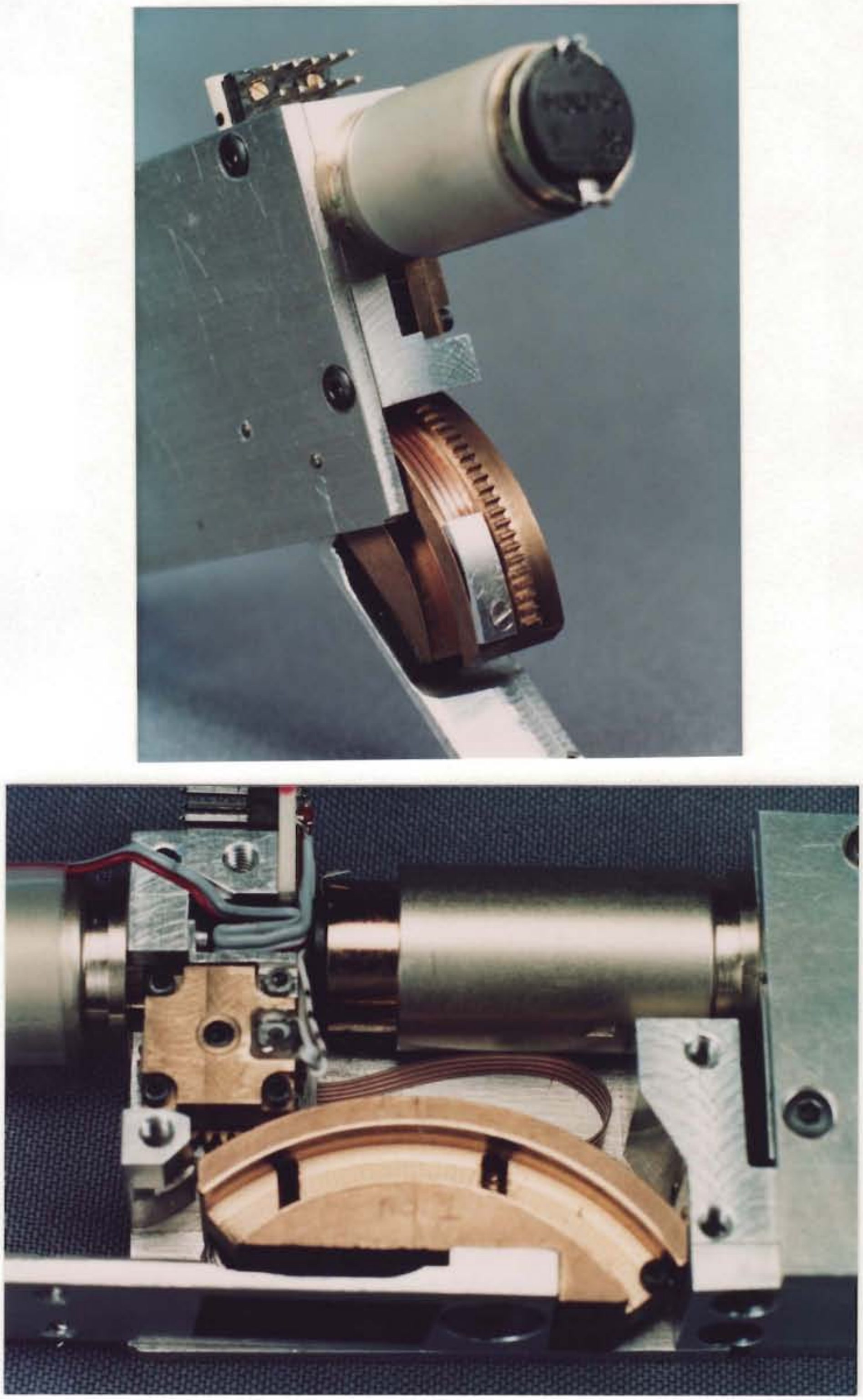


FIGURE 2.6-4: The ribbon cable for the force sensor was anchored to the virtual hinge slider by means of a small spring clip on the side of the gear rack (top photograph). The cable was then segmented into individual leads and routed through an offset hole down into the detector chamber (bottom photograph: leftmost vertical hole is for the force sensor leads). Also shown is the ribbon behavior in the presence of the adjacent joint actuator (bottom).

3. DEVELOPMENT of a M/S HAND CONTROL SYSTEM

3.1. Introduction

The original scope of this program contemplated the creation of a simple slave hand in addition to a complete master glove controller, but, as detailed in Section 2, unexpected turns in the glove-joint development process prevented the full implementation of this plan. However, in deference to the original intention of this program, a Master/Slave Hand Control System was designed and implemented to the degree permitted by available developments.

The function of this system was to act as an interface between the master glove controller and slave hand, and permit bi-lateral force control of the slave by the glove master. A photograph of a partial system is shown in Figure 3.1-1, and a block diagram of the M/S Hand Control System is illustrated in Figure 3.1-2 (note that the Tactile Telepresence System is not shown, as it is an independent sub-system of the Dexterous Teleoperator System: see Figure 1-1.) Only the master side was implemented, leaving implementation of the slave side for a later date.

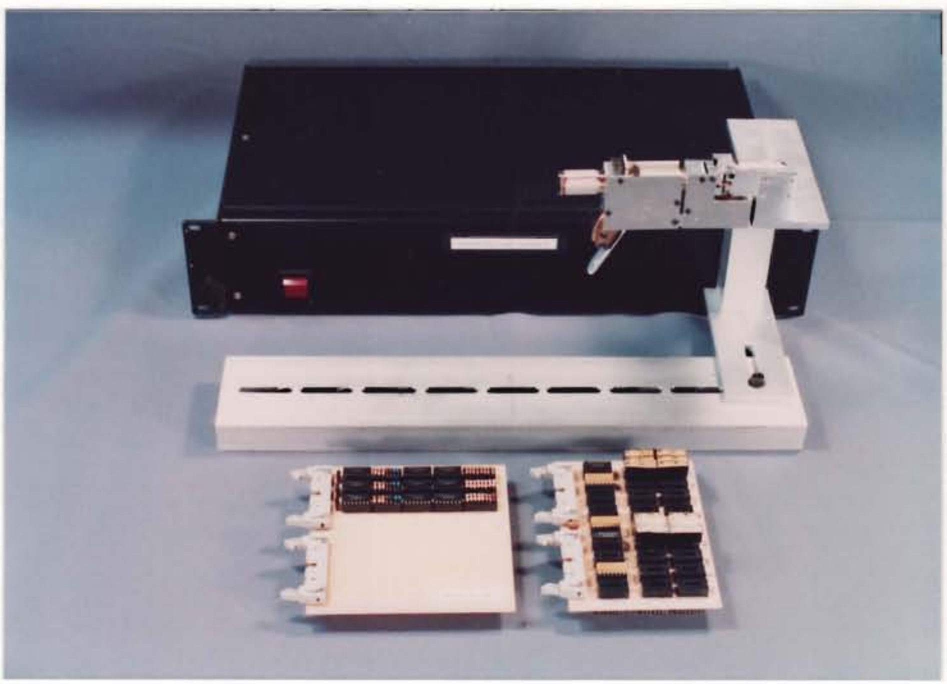


FIGURE 3.1-1: Master/Slave Hand Controller System implemented for one finger of the Master Glove Controller. Starting with the black box and moving CW: M/S Hand Interface; one finger of the Master Glove Controller mounted on a test stand; Motor Driver board (only three of nine channels active); and Sensor Signal Conditioner board for joint force and joint angle sensors in glove finger (only 4 of 18 channels active). Cables omitted for clarity.

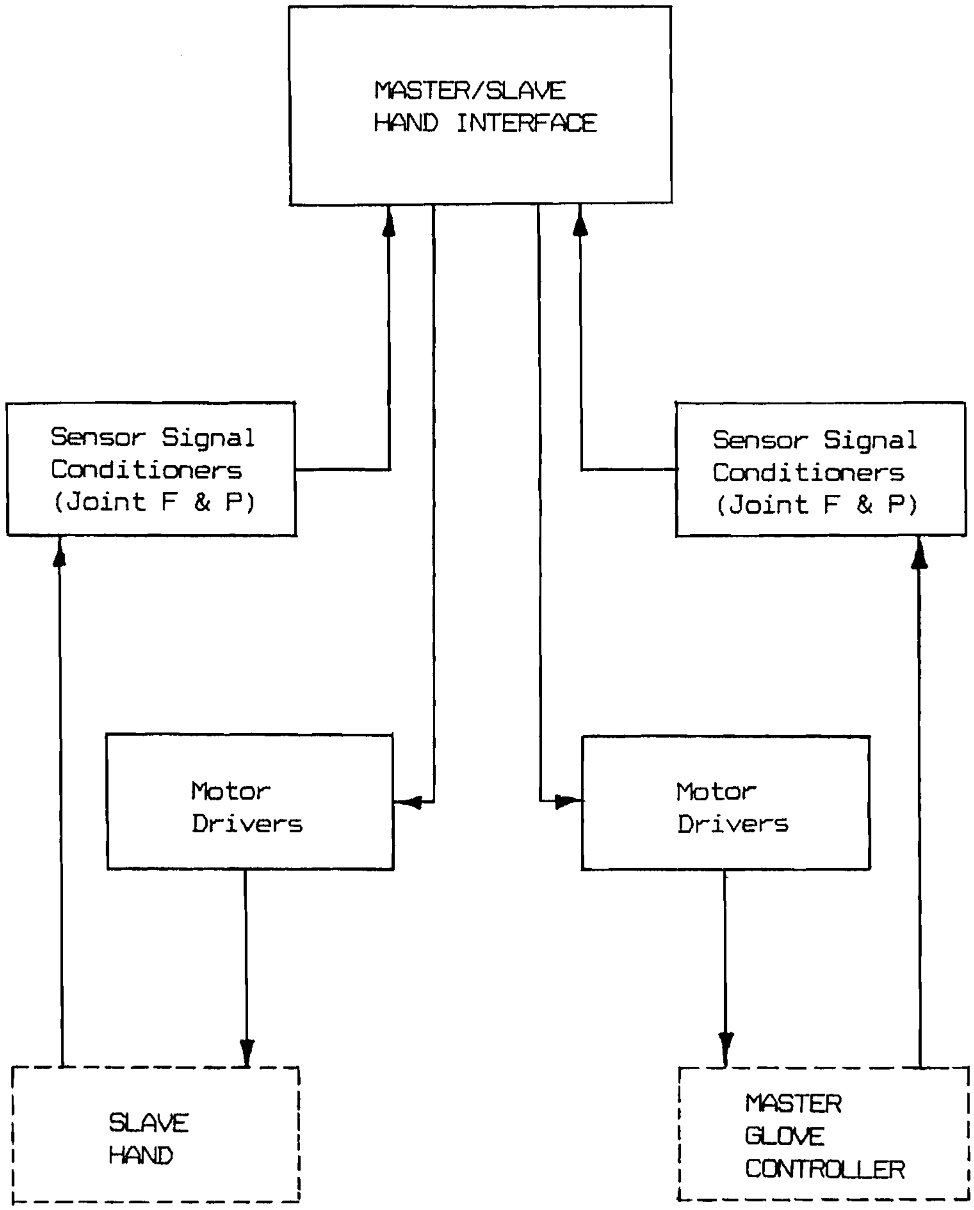


FIGURE 3.1-2: Block diagram of the Master/Slave Hand Control System. See Figure 1-1 for relationship of this system to the Dexterous Teleoperator System.

3.2. M/S Hand Interface

The purpose of the Master/Slave Hand Interface was to provide power to the dexterous hands and Sensor Signal Conditioner boards, and to permit control of the slave hand with the master glove by means of appropriate algorithms implemented in hardware and/or software. An internal view of the Interface developed for this program is shown in Figure 3.2-1.

The power supplies provided 2.4 A at +/- 15 V to the external motor drivers and sensor signal conditioner boards, and to the internal PWM oscillator (located beneath the prototype boards). The circuit diagram for the oscillator is shown in Figure 3.2-2, which generated a triangle-wave with amplitude 0 to +10 V at a frequency of 500 Hz.

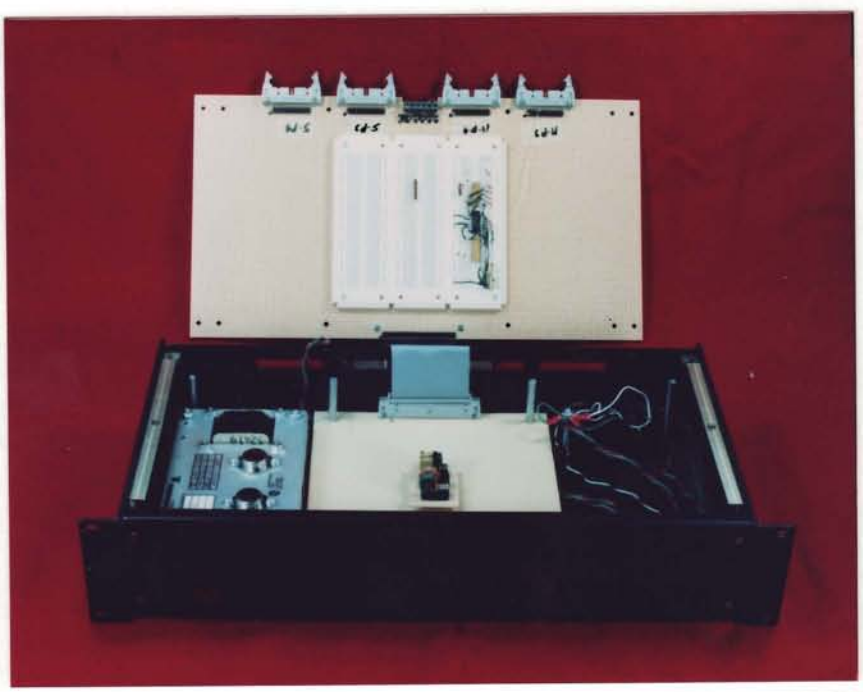


FIGURE 3.2-1: Internal view of the M/S Hand Interface. On the bottom level are the power supply (left) and a hard prototyping area for circuits implementing a shared functionality, e.g., a PWM oscillator for the motors (center). The top level was configured as a soft prototyping area for control hardware development. Top connectors lead to the master and slave sensors and actuators.

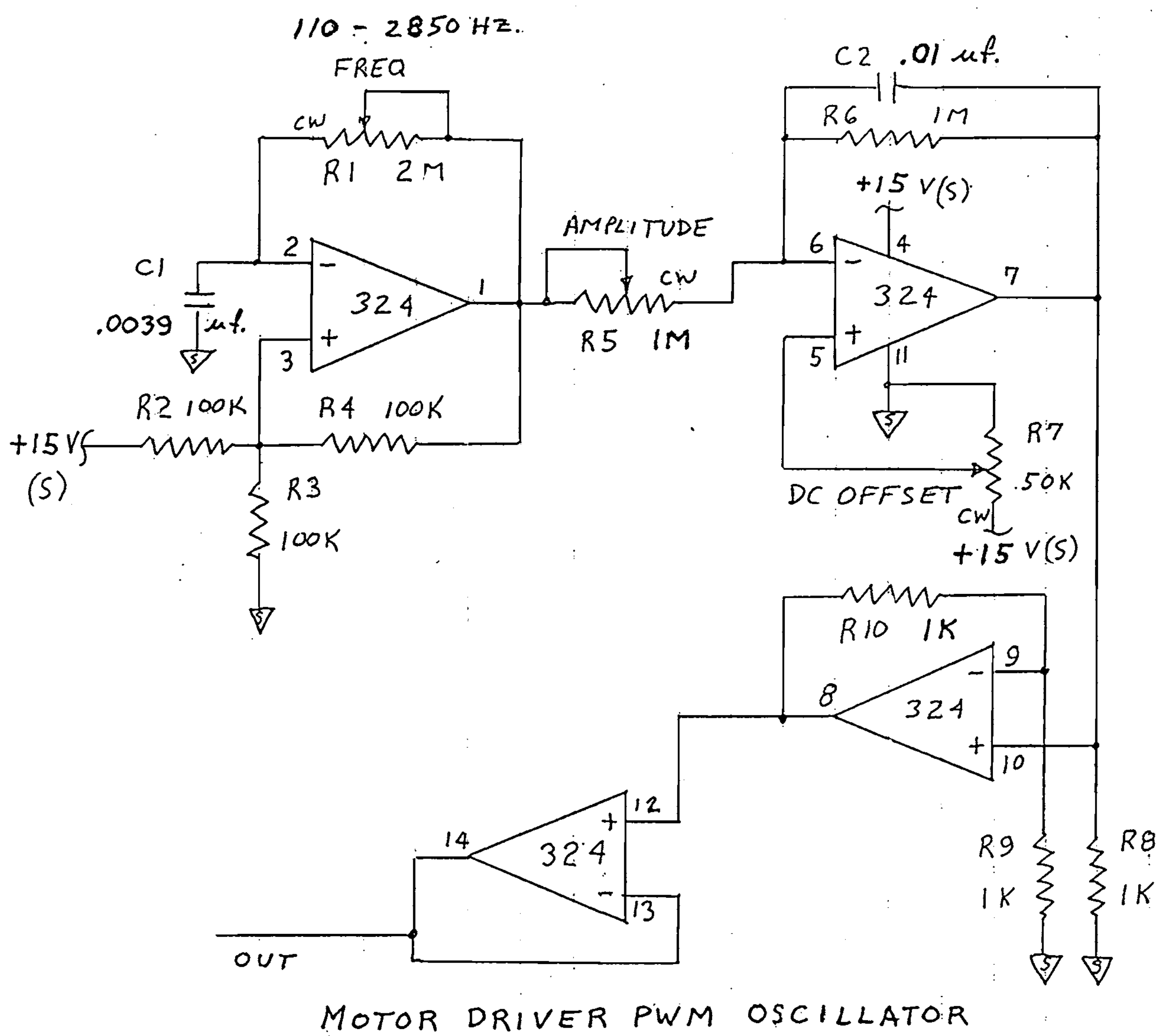


FIGURE 3.2-2: Oscillator circuit used to generate a triangle-wave for the PWM motor control circuit. The amplitude ranged from 0 to +10 V at a frequency of 500 Hz.

3.3. Sensor Signal Conditioners

The joint force and joint angle sensor signal conditioning circuits were placed external to the M/S Hand Interface to minimize the distance that unamplified sensor signals had to travel. As the joint angle and force sensors were of the same type (e.g., optical displacement sensor), a significant simplification in circuit development and fabrication could be achieved. Each sensor signal conditioner board was designed to accommodate up to 18 signals, so that two identical boards would be sufficient for a 9-DOF master glove controller and a corresponding 9-DOF slave hand.

However, a slave hand or finger was not available, and the glove controller was completed only to the point of developing a master glove finger partially-sensorized at the distal joint. Therefore, only one board was fabricated, and only four of the sensor conditioner channels were populated. The resulting board is shown in Figure 3.3-1.

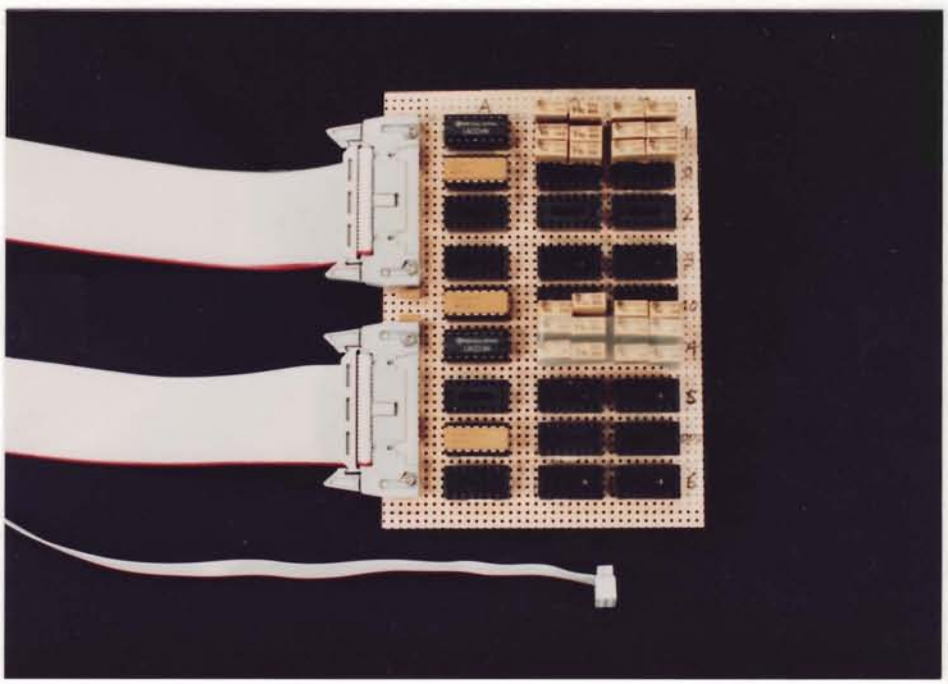


FIGURE 3.3-1: Joint angle and force Sensor Signal Conditioner board for the master glove controller. The bottom and top cables represent input from the glove controller sensors and output to the M/S Hand Interface, respectively.

3.4. Motor Drivers

A motor driver board with nine driver modules was designed, though only three drivers were activated to correspond with the three actuators on the single-finger master glove prototype: see Figure 3.4-1. Figure 3.4-2 shows the circuit diagram of the bi-polar PWM motor driver. The power output was +/- 15 V with a duty cycle proportional to the analog control signal (range: -10v to +10 V) from the M/S Hand Interface.

The board was designed to be placed near the glove controller so as to minimize the amount of RF noise radiated by the PWM driver. Additionally, a jumper was provided at each driver to disable the PWM portion of the circuit and to permit conversion of the device into a simple power op amp driver.

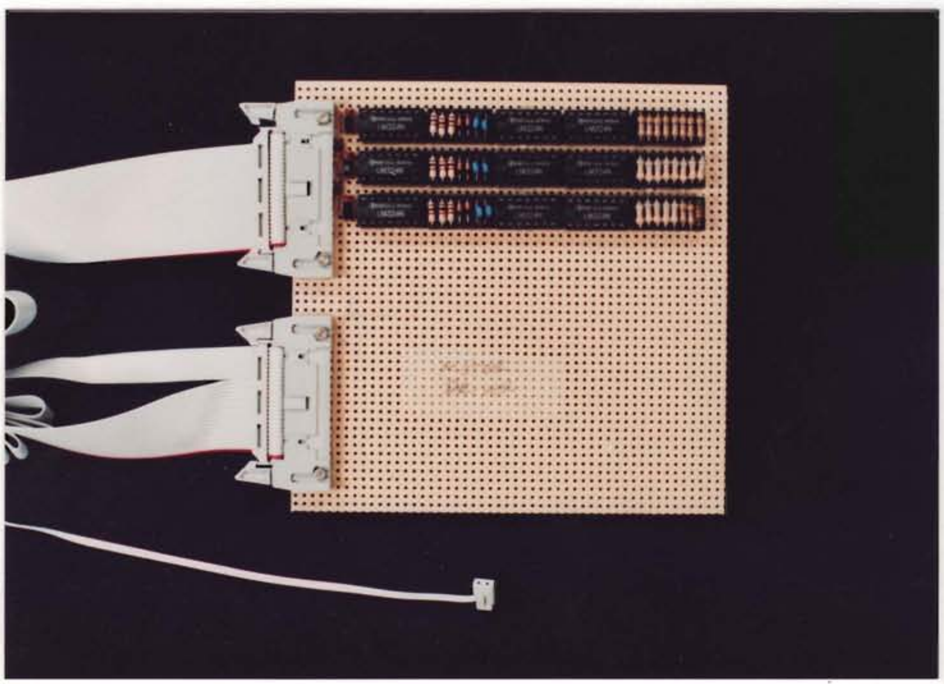


FIGURE 3.4-1: Motor driver board capable of driving up to nine motors, though only three drivers were activated for the master glove controller prototype. Each driver channel was configurable either as a bi-polar power op amp or as a bi-polar PWM driver. The upper cable carried the power bus and the analog control signals from the M/S Hand Interface, and the lower cable connected to the individual actuators on the master glove controller (or slave hand).

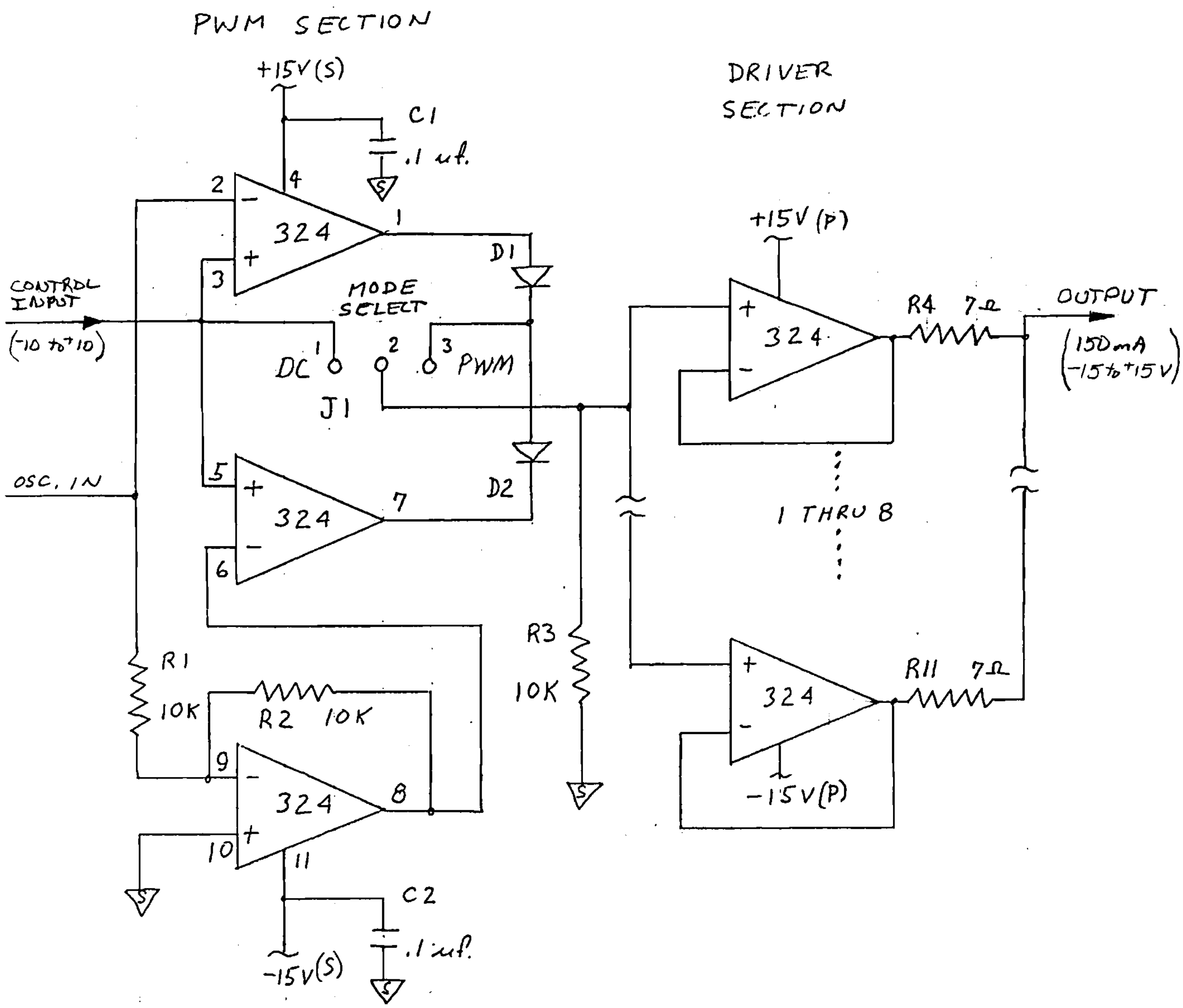


FIGURE 3.4-2: Bi-polar PWM motor drive circuit for the master glove controller or slave hand actuators. For convenience, the drivers were simply eight op amps (two LM324 chips) configured with parallel outputs.

4. DEVELOPMENT of a TACTILE TELEPRESENCE SYSTEM

4.1. Introduction

A sensory mode which is considered of significant importance for dexterous control by teleoperation is that of touch, particulary at the fingertips. One task of this program was to fabricate several fingertip tactile telepresence systems each containing approximately 50 tactile channels. However, little time was actually available for this due to the emphasis and effort place in the development of a suitable glove joint.

The tactile telepresence task was therefor modified to concentrate on the most important elements, i.e., reducing the system size and weight, particulary the tactile sensor signal conditioner and display driver modules. To save time, an existing 37-channel tactile telepresence system was upgraded in this regard, and the only parts of the old system retained were the tactile sensor head and the tactile display head.

The old and the new Tactile Telepresence Systems are shown in Figures 4.1-1 and 4.1-2, respectively. A block diagram showing the relation of the main elements of this system - the tactile sensor, tactile display, and the sensor/display interface - is shown in Figure 4.1-3. These elements are discussed separately in the following sections.

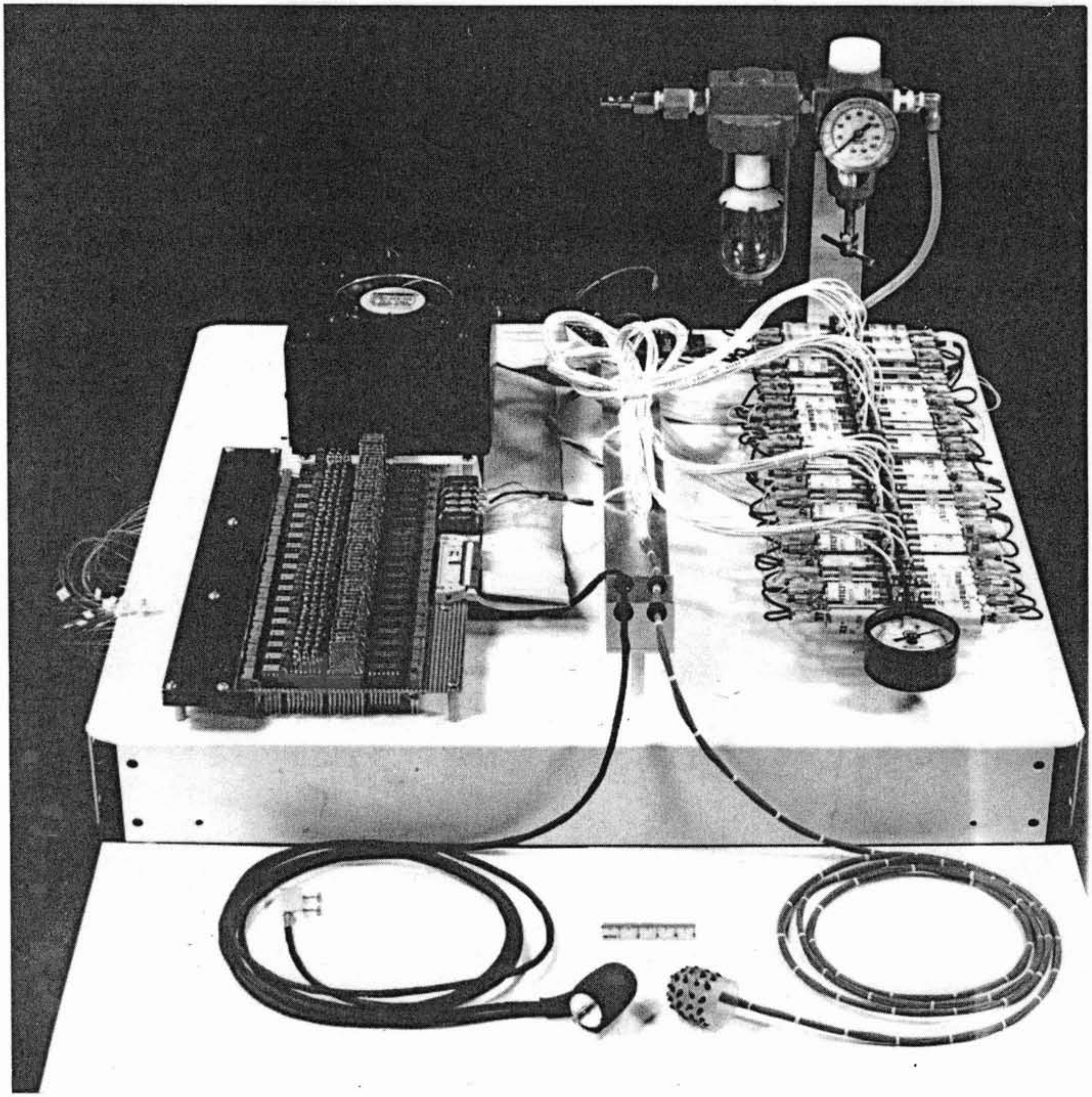


FIGURE 4.1-1: Thirty-seven channel opto-pneumatic Tactile Telepresence System previously developed by Begej [1988b]. Moving CW from left-bottom-center: optical fingertip-shaped tactile sensor with 37 taxels; board for optical-to-electrical conversion and PWM circuits; valve drivers (covered with fan); electro-pneumatic valve manifold; pneumatic micro-diaphragm tactile display with 37 tixels. Not shown is a 150 W illuminator and power supplies (+/- 15 V, and +24 V). The maximum separation distance between the tactile sensor and tactile display was approximately 4 m.

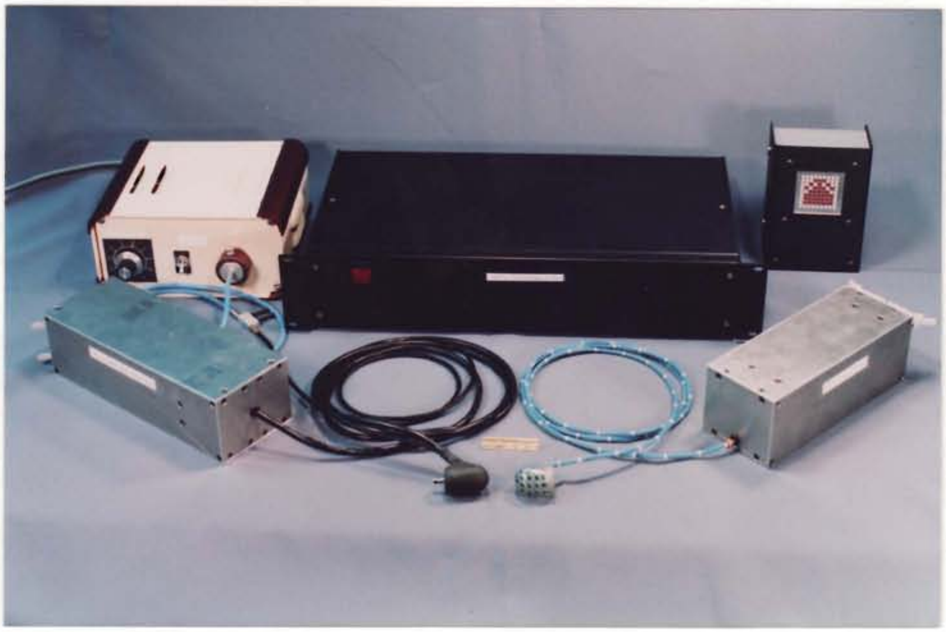


FIGURE 4.1-2: Tactile Telepresence System for the fingertip (some cables omitted for clarity). Starting with the tactile sensor at left-center-foreground and moving CW:

- 37-element fingertip-shaped tactile sensor,
- 48-channel tactile signal conditioner,
- 150 W illuminator for sensor energization,
- sensor/display interface (large black box containing power supply, pneumatic pressure regulator, and electric valve drivers),
- LED indicator (connected in parallel with the tactile display),
- 48-channel tactile display driver (valve manifold),
- 37-element fingertip-shaped tactile display.

The system was configured to permit a sensor/display separation distance of approximately 30 m, but this distance could be increased by simply adding extension cables.

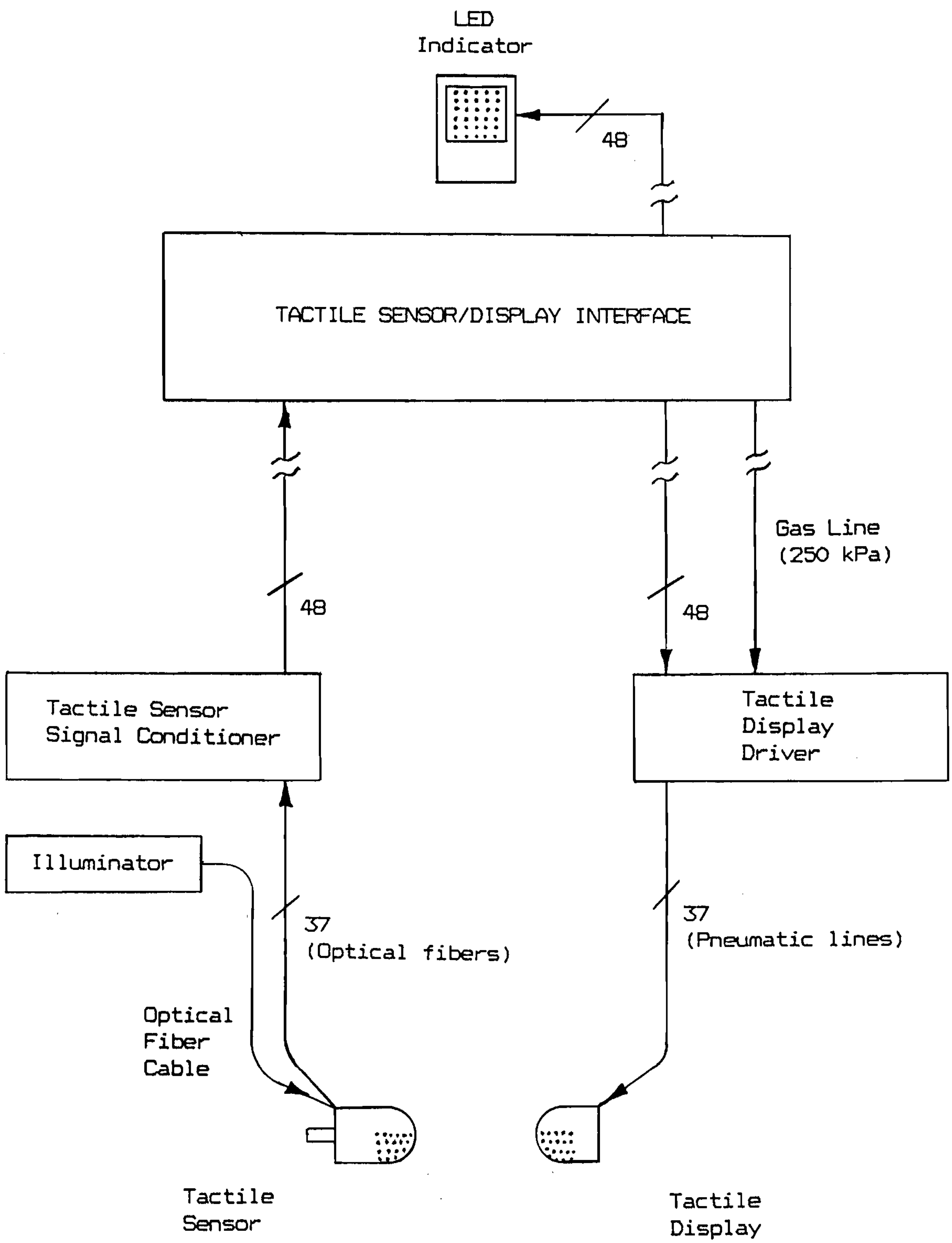


FIGURE 4.1-3: Block diagram showing the relationship between the main elements of the Tactile Telepresence System developed for this program.

4.2. Tactile Sensor

The optical tactile sensor utilized in this program relied on frustration of total internal reflection at an optical waveguide interface, and has been described in greater detail elsewhere by Begej [1984, 1985, 1986, 1988a, and 1988c]. The output of the sensor is an analog optical signal appearing at the end of an optical fiber, the number of fibers corresponding to the number of taxels (tactile elements) on the sensor. Prior to processing and analysis, these optical signals must be converted to electrical form, e.g., by imaging the end of the fiber bundle onto a CCD camera (Begej [1985] and [1986]), or by terminating each fiber into a discrete photodetector (Begej [1988b]). For a "small" number of channels (e.g., less than 100), the latter method has been preferred because of a lower cost per channel.

The principal deficiencies of previous tactile sensors incorporated into tactile telepresence systems (Begej [1988b]) were: large size of the optical-to-electrical converter; lack of sufficient signal amplification; lack of sufficient shielding from ambient lighting; and lack of modularity with regard to the sensor head and processing electronics. These issues were addressed in this program and resulted in the fabrication of the compact 48-channel tactile signal conditioner shown in Figure 4.2-1. However, only 37 of the available channels were utilized, corresponding to the number of channels present on the available tactile sensor. The spatial distribution of these tactile sensing elements is shown in Figure 4.2-2.

The tactile sensor signal conditioning circuit is shown in Figure 4.2-3. New photodarlington detector elements (Motorolla MFOD-73) were utilized that adequately addressed the pre-amplification function and provided a convenient method whereby the sensor fibers may be detachably terminated: see Figure 4.2-4. Additionally, previously unsheathed fiber ends were covered with black 28-gage Kynar tubing to provide better shielding from ambient light.

High attenuation of the optical signal along the plastic optical fibers requires that the optical-to-electrical converter be located close to the tactile sensor head. To minimize mounting problems, the signal conditioning electronics were packaged more densely: see Figure 4.2-5. This was accomplished by fabricating two 24-channel modules and placing them back-to-back in such a manner that removal of the case side-plates provided ready access to the signal gain and offset adjustment controls.

FIGURE 4.2-1: Compact 48-channel tactile signal conditioner fabricated for this program (top) coupled to a 37-channel optical tactile sensor (center). The unit weighed 0.9 kg, and measured 90 mm x 70 mm x 250 mm.

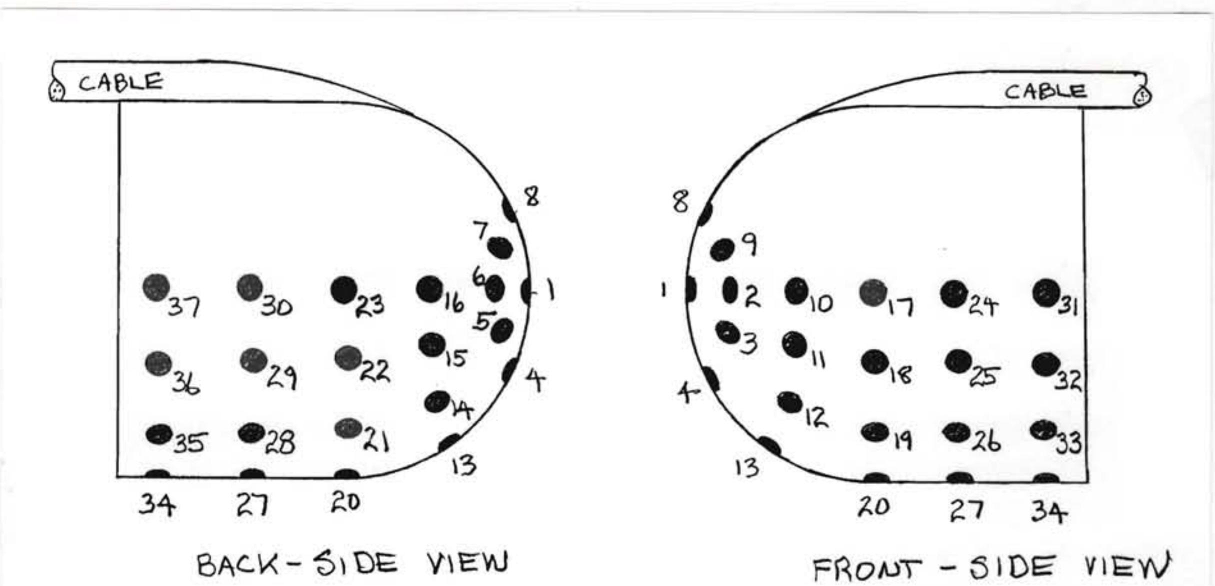


FIGURE 4.2-2: Taxel distribution on the 37-channel fingertip-shaped tactile sensor (which is identical to the tixel distribution on the tactile display). Begej [1988b].

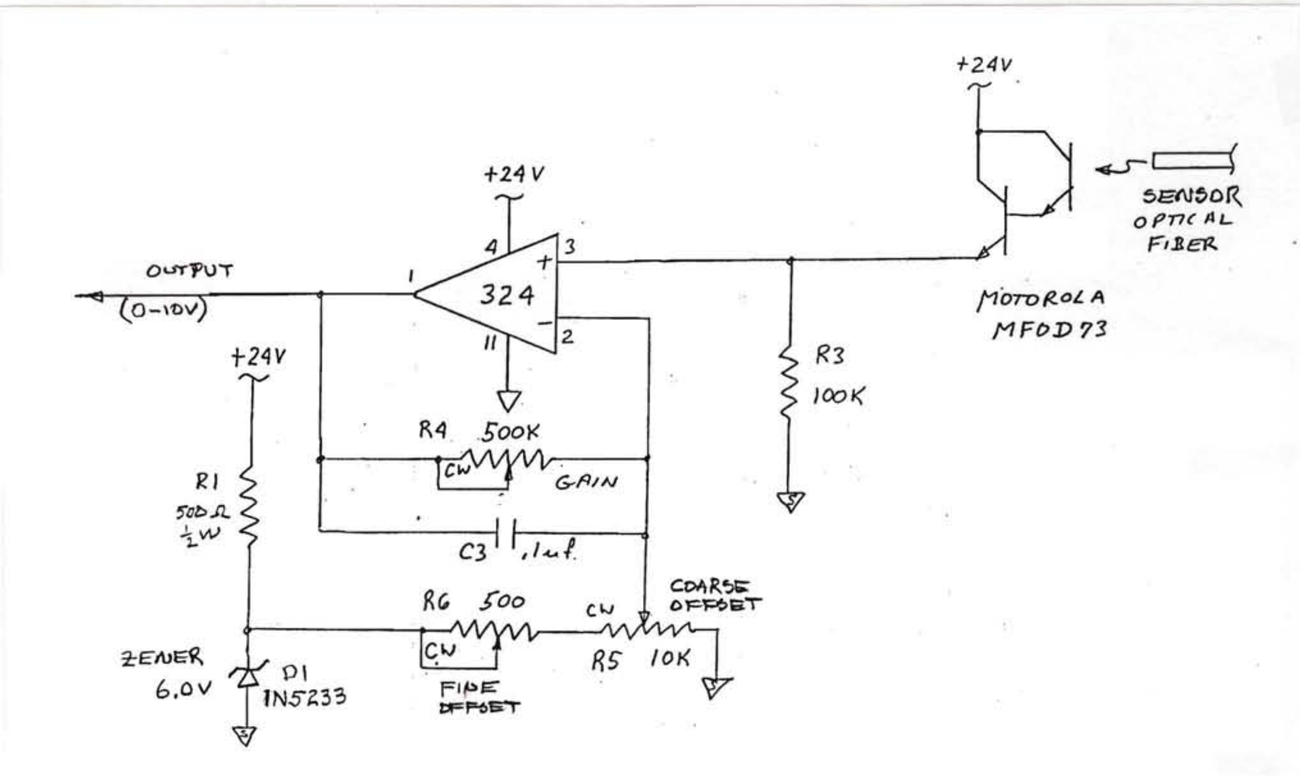


FIGURE 4.2-3: Optical-to-electrical converter circuit used in the tactile sensor signal conditioning module. A single Zener diode was used to provide a stable offset reference voltage for all channels.

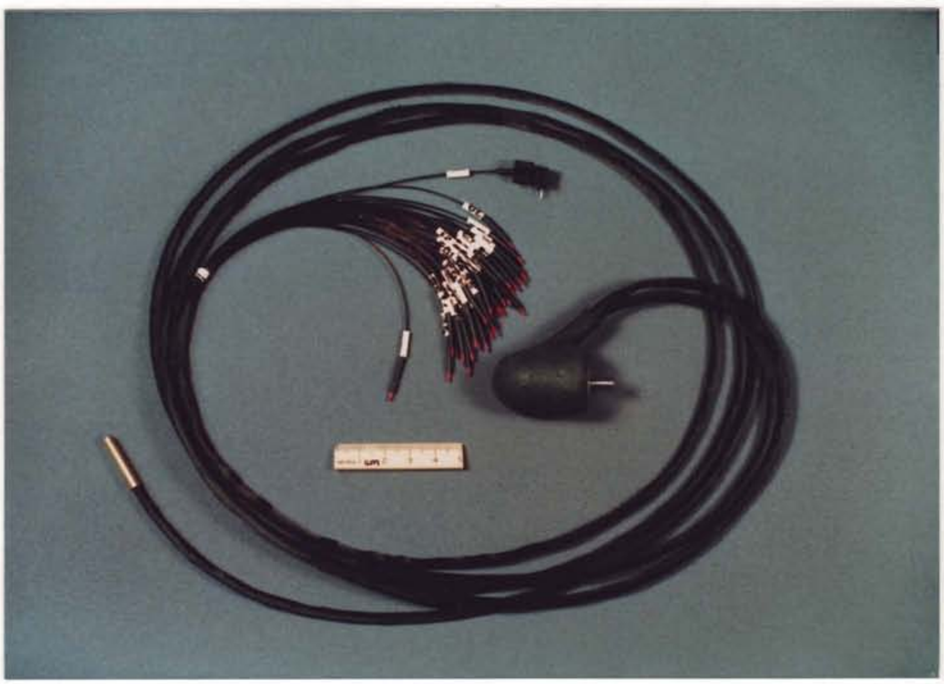
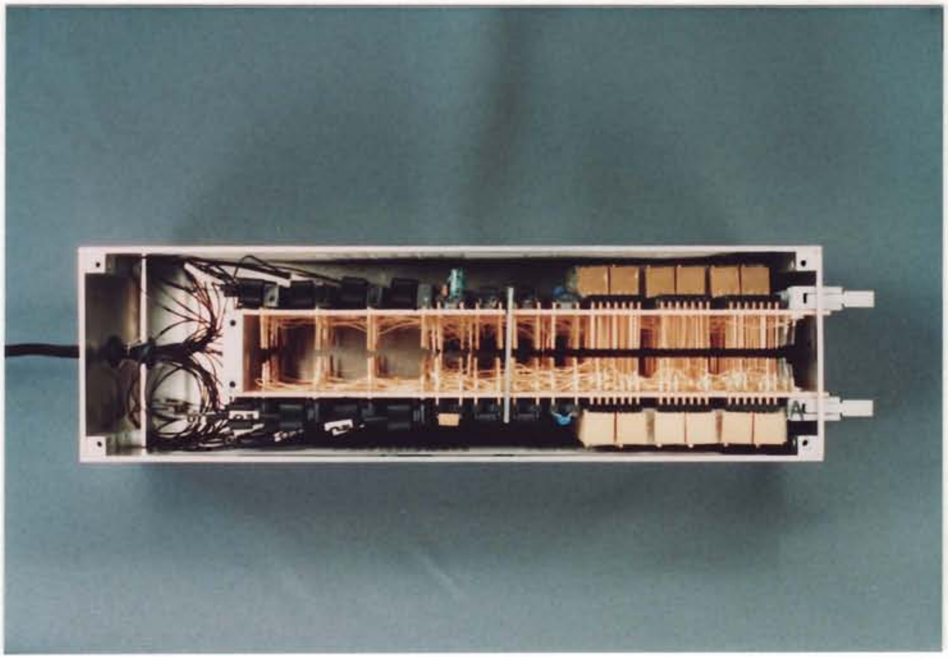


FIGURE 4.2-4: The 37-element tactile sensor head was made into a modular unit by connectorizing the optical fibers to fit Motorolla-type MFOD-73 photodarlington detectors (see top of bundle for example). Fiberoptic cable at left is for sensor illumination.



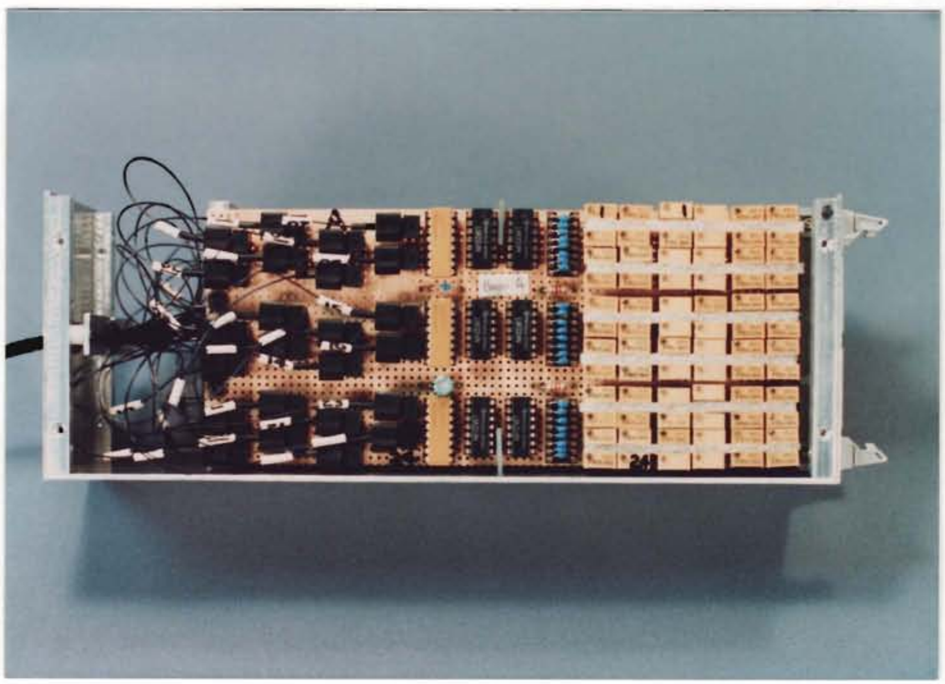


FIGURE 4.2-5: Internal view of the 48-channel tactile signal conditioner. Three banks of potentiometers adjusted the gain (L), coarse offset (C), and fine offset (R) for each channel. Only 37 of the available 48 channels were populated.

4.3. Tactile Display

Previously (see Figure 4.1-1), Begej [1988b] developed a fingertip-shaped tactile display containing 37 miniature pneumatic stimulator elements (tixels) utilizing the design shown in Figure 4.3-1. The major deficiencies of this system were the large size and weight of the display driver valves, and lack of modularity with regard to the tactile display and driver (i.e., valve manifold). These issues were addresses in this Phase I program, resulting in the new 48-channel display driver package shown in Figures 4.1-2 and 4.3-2.

Tactile display modularity was accomplished by connectorizing each pneumatic tube, as shown in Figure 4.3-3. Furthermore, a new miniature pneumatic valve (Angar Scientific Co., model 407-M-3-040-24-50-N) was selected which offered a two- to four-fold improvement in volumetric size in comparison to other valves that were previously used. Manifolds for these new valves were not available off-the-shelf from the manufacturer, so a special 48-valve unit was fabricated and loaned for use on this program by Begej Corporation. The manifold, pneumatic tube connections, and mounted valves are shown in Figure 4.3-4. The drivers of the solenoid valves were mounted in the sensor/display interface to minimize the size of the display driver package, and are discussed in the next section.

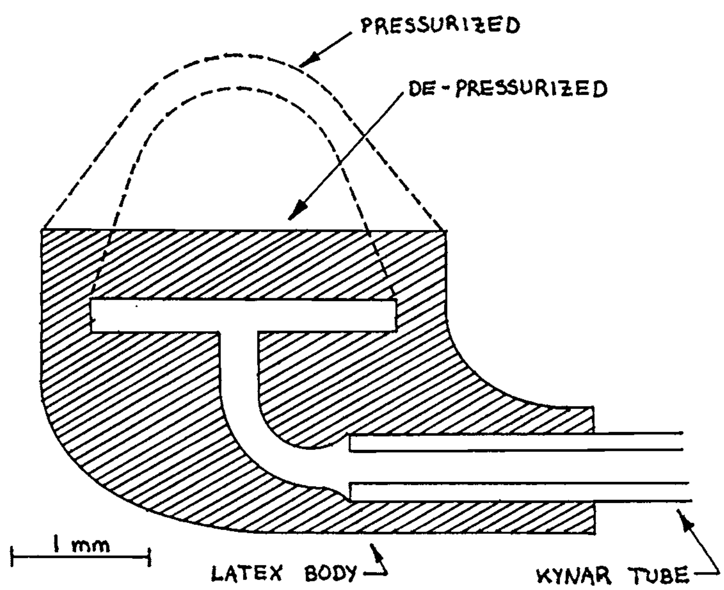


FIGURE 4.3-1: Pneumatic micro-diaphragm tactile display tixels developed by Begej [1988b]. The entire device was fabricated from latex, and connected to the display driver by 0.5 mm diameter Kynar tubing.

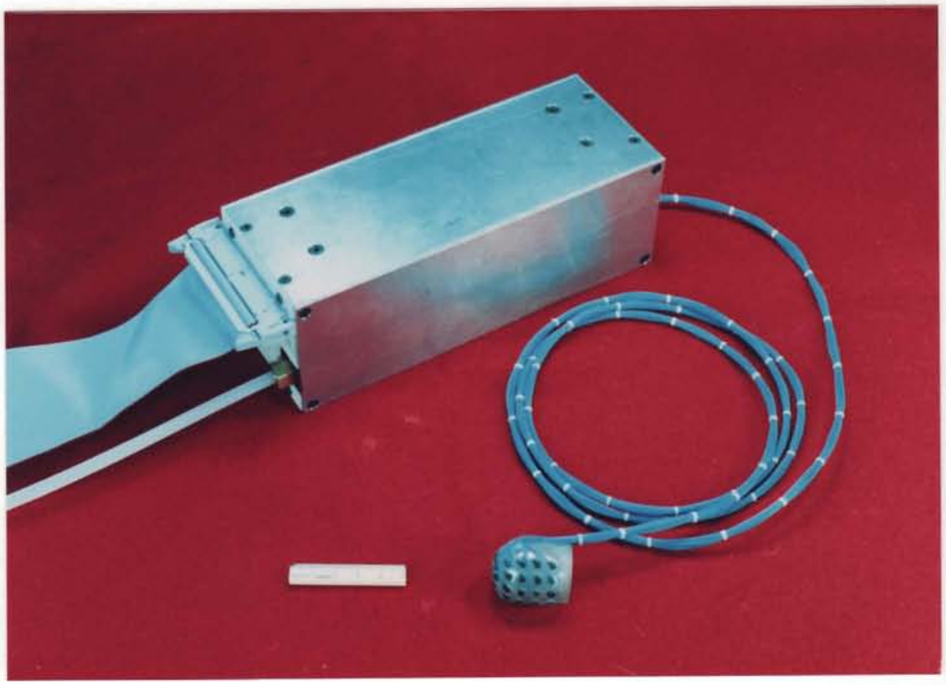


FIGURE 4.3-2: 48-channel tactile display driver attached to a 37-element fingertip-shaped tactile display. The driver package weighed 1.9 kg, and measured 80 mm x 70 mm x 210 mm.

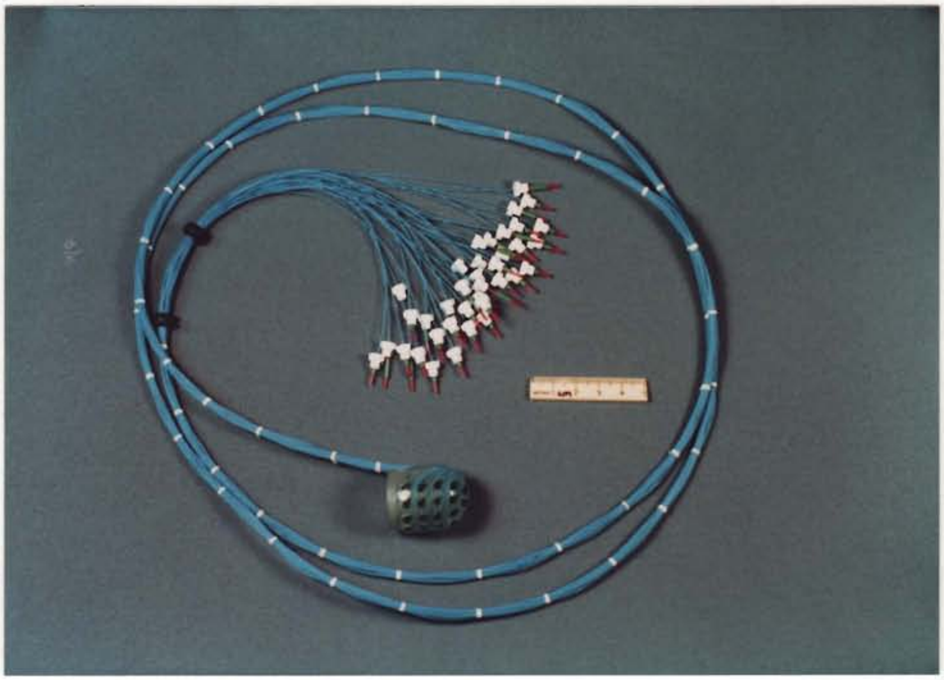
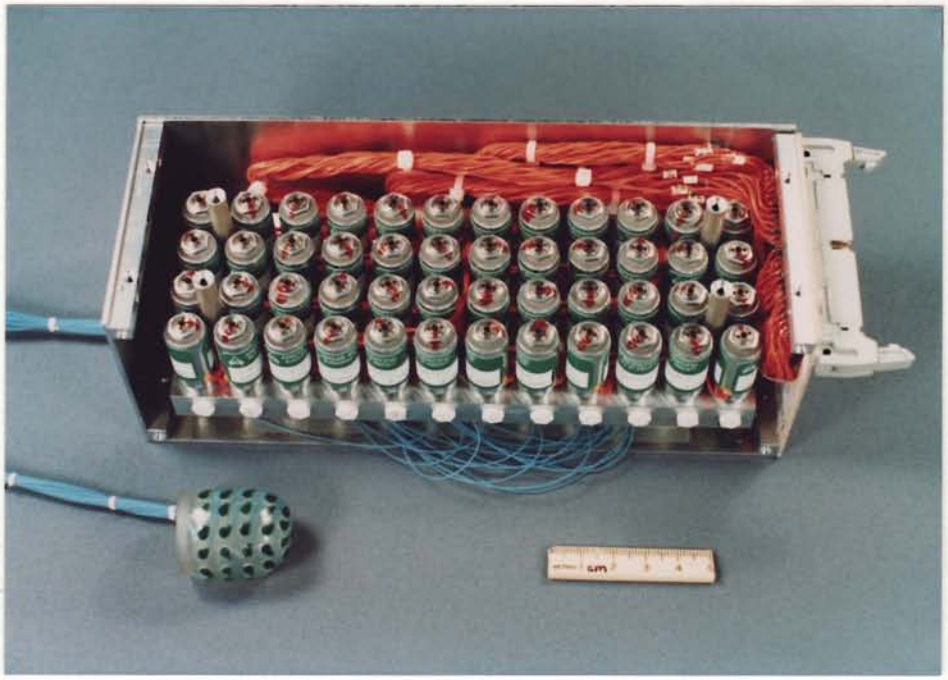


FIGURE 4.3-3: The pneumatic Kynar tubes of an existing 37-element tactile display (Begej [1988b]) were connectorized so as to permit ready attachment or removal of the display head from the display driver.



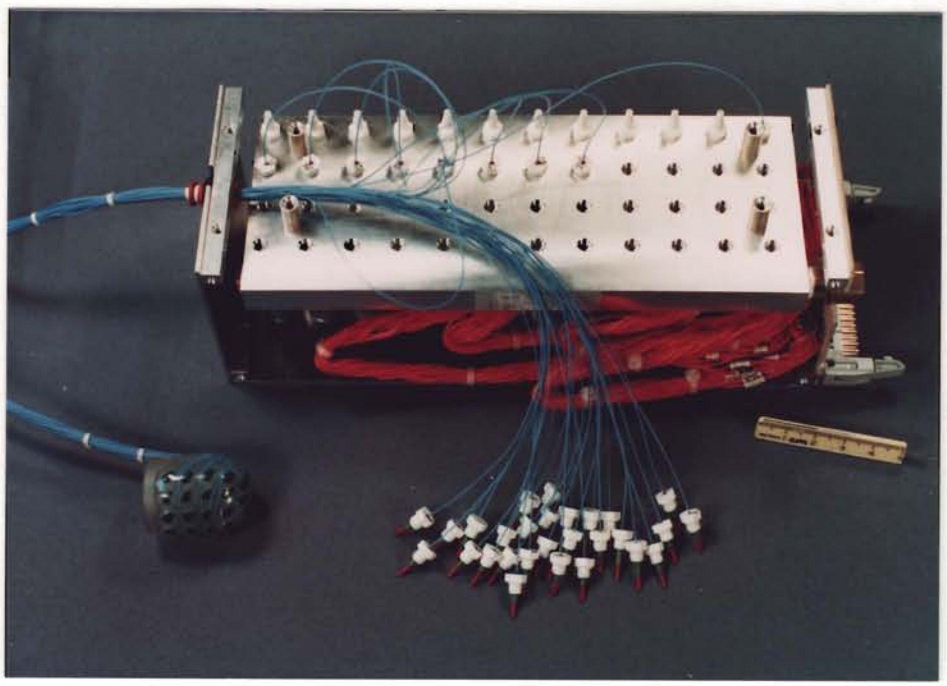


FIGURE 4.3-4: Top and bottom internal views of the tactile display driver. Each valve was driven by a 24 volt PWM signal from the valve driver in the sensor/display interface. The tixel vent ports may be seen on top of the valves.

4.4. Tactile Sensor/Display Interface

The purpose of the Sensor/Display Interface (see Figure 4.1-2) was to serve as a power source and link between the tactile sensor and tactile display. Figure 4.4-1 shows the following components inside the Interface:

- Power supply (3.6 A @ 24 V) for the Tactile Sensor Signal Conditioner, PWM circuits, and valve driver.

- Air filter and regulator set for an output of 250 kPa to the Tactile Display Driver. Additionally, an empty filter container at the output of the regulator served as a accumulator to minimize pressure fluctuations under high flows.

- An oscillator circuit similar to that shown in Figure 3.2-2 was used for the valve driver PWM oscillator, except for the following changes: supply voltage = +24 V; R5 = 2 Mohm; C1 = 0.1 uF; C2 = 0.47 uF; and R10 = 2.2 kohm. The oscillator operated in the frequency range 5 to 100 Hz, and generated a triangle wave with an amplitude of 0 to 10 V. The oscillator frequency was set to 10 Hz.

- PWM valve driving circuitry (48 channels maximum). A circuit diagram for one channel is shown in Figure 4.4-2.

Additionally, an LED Indicator array (see Figure 4.1-2) was provided as a diagnostic tool or familiarization accessory for operators using the tactile display fingertip for the first time. The indicator and channel labeling is shown in Figure 4.4-3. The indicator was connected in parallel with the Tactile Display Driver, and visually displayed the tactile information displayed at the operator's fingertip. The indicator may be placed at any convenient viewing location. The device had a current draw of 178 mA, and consumed 4.3 W (maximum).

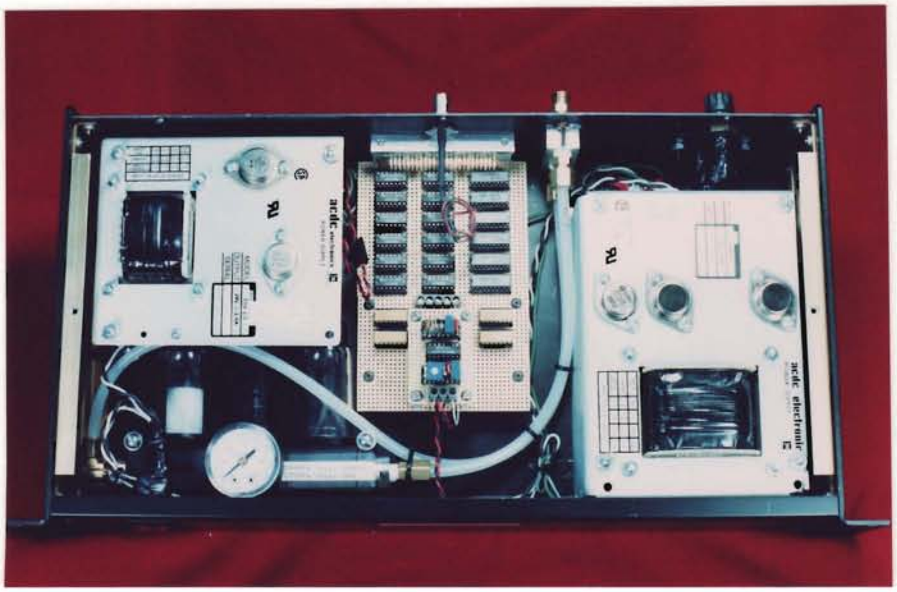


FIGURE 4.4-1: Internal view of the Tactile Sensor/Display Interface showing the power supply for valves (right), pressure regulator, filter, and accumulator (lower left), power supply for tactile sensor signal conditioner and other circuits (top left), board containing PWM oscillator, PWM control, and valve drivers (center).

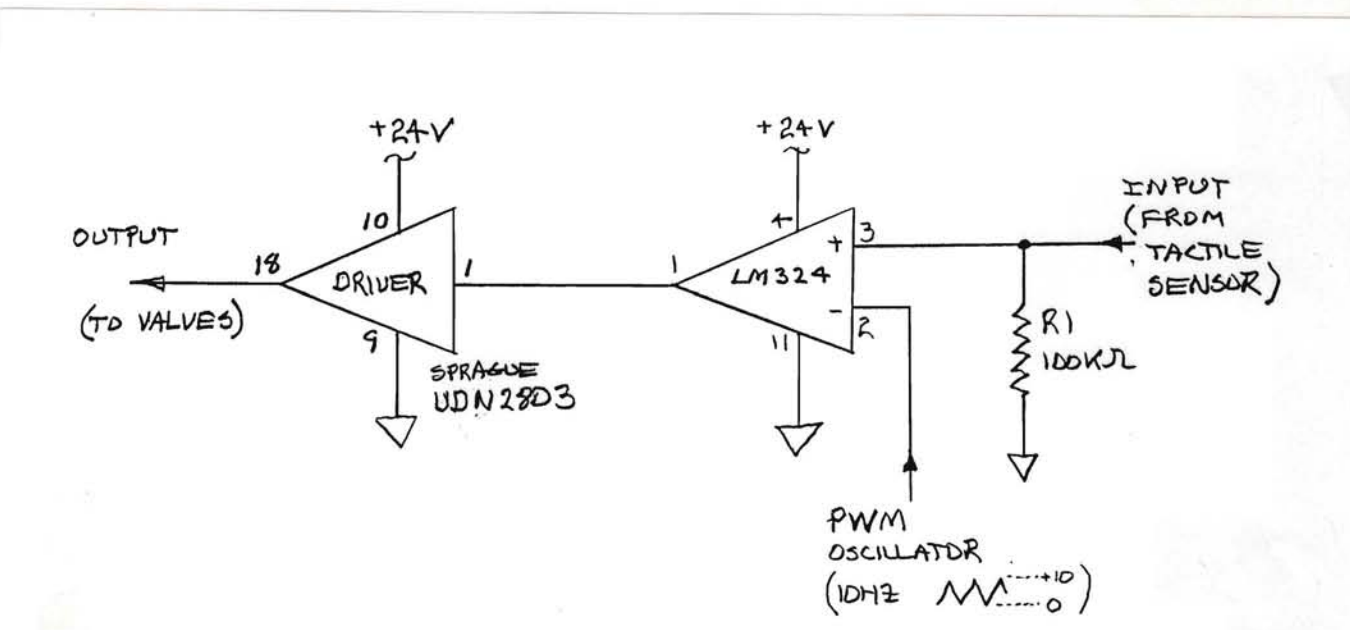
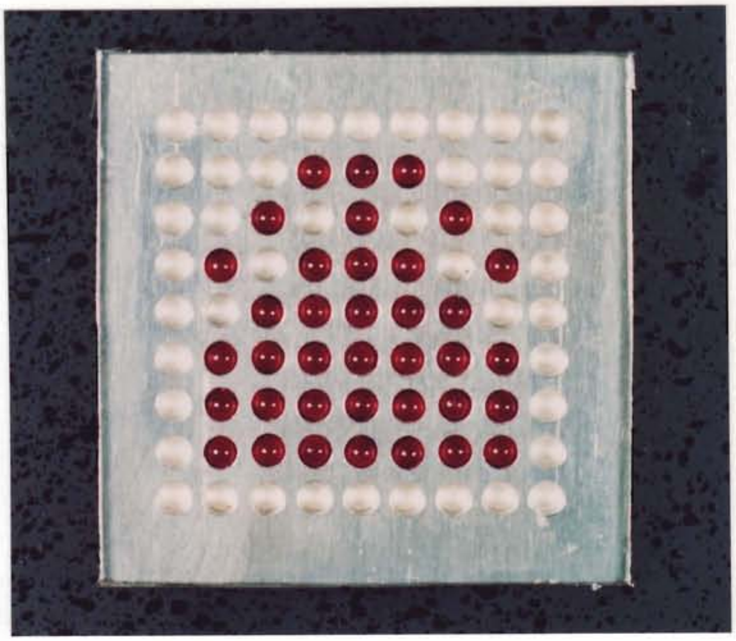
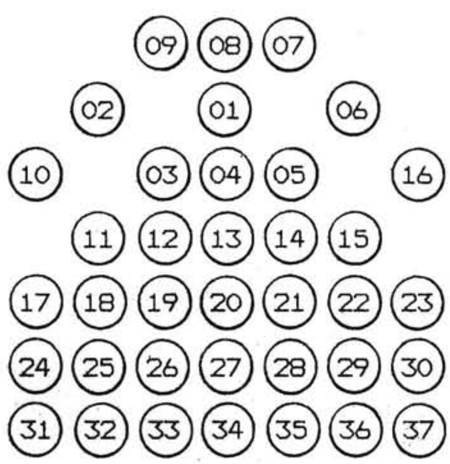


FIGURE 4.4-2: PWM control and valve driver circuit for a single tixel. R1 is a pull-down resistor to insure proper open-circuit operation.





<u>FIGURE 4.4-3:</u> The tactile data presented to the tactile display may also be visually observed on the LED indicator array (top). The correlation between the LEDs and tactile channel numbers (defined in Figure 4.2-2) is shown in the bottom diagram.

4.5. System Calibration

The calibration procedure for the tactile telepresence system was as follows:

- Turn the system ON, attach a clean, dry air supply, and connect the tactile sensor illuminator. Set the illuminator light level at approximately the center of its output range. Firmly clamp the sensor mount in a soft-faced vise to permit probing without danger of tipping. Verify that the oscillator amplitude is 0 to +10 V.

- Remove the side faces from the Tactile Sensor Signal Conditioner cabinet, and turn all gain potentiometers to unity (fully CCW).

- Adjust the coarse offset potentiometers to bring the output to zero. This is conveniently done by watching the LED indicator array, as the LED for the tactile channel under adjustment will just barely flicker at the zero point.

- Using a pressure applicator on the tactile sensor (e.g., a spring-loaded stylus with a soft rubber tip), apply a known pressure to a specific tactile sensor element. Adjust the gain and offset pots so that a full-scale pressure excursion will cause the PWM duty cycle to range from 0 to 100%.

In the course of calibrating the system developed for this program, the tactile sensor was adjusted to respond to pressures ranging from 0 to 100 kPa.

5. EVALUATION of DEXTEROUS TELEOPERATOR SYSTEM

A photograph of the Dexterous Teleoperator System has been shown in Figure 1-2, and reflects the extent of development that was accomplished during this Phase I program. It includes a single finger of a master glove controller, a 37-channel tactile telepresence system for one fingertip, and a master/slave hand control system with associated motor driver and sensor signal conditioner boards for the master finger prototype. Unfortunately, a slave hand or finger was not available as had been originally planned, nor did time permit fabrication of a new force sensor and optical encoder for the pin-hinge joint (see Section 2.1.1) to enable conversion of this device into a simple, one-joint slave finger. Thus, the options for evaluating the entire Dexterous Teleoperator System were somewhat limited, though tests on important components and sub-systems were possible.

One such test was to evaluate the functioning of the single glove joint that was completed and sensorized, and to verify that the actuator, force sensor, joint angle sensor, signal conditioner board, and motor driver were correctly operating. Figure 5-1 through 5-5 illustrate the range of motions that the glove finger was capable of executing. The distal joint was configured to move compliantly in response to finger forces by simply connecting the output of the force sensor directly to the input of the motor driver. The other motors were driven manually with a 6 V battery applied to their terminals.

It was observed that full-swing (62°) of the joint took approximately 1 second when maximally forced. Also, the joint was far less prone to jamming at the extremes of travel when driven in the PWM rather than DC mode. Glove finger tests involving the joint angle sensor were not performed, other than to verify that the sensor signal could be set to vary from 0 to +10 V (or from -10 to +10 V) over the full 62° range of joint travel. Nor was the maximum force of actuation ascertained, as the gears were fabricated of brass for design verification purposes and were not designed or expected to survive full motor torques.

An evaluation was also performed of the fingertip Tactile Telepresence System. It was immediately noticed that the tactile sensations were significantly more perceptible than the older prototype it replaced. This was primarily attributed to the reduction of dead volume and conductance losses associated with 500 to 750 mm of large diameter tubing that was previously used as an interface between the small Kynar tubing leading to the display and the valve manifold.

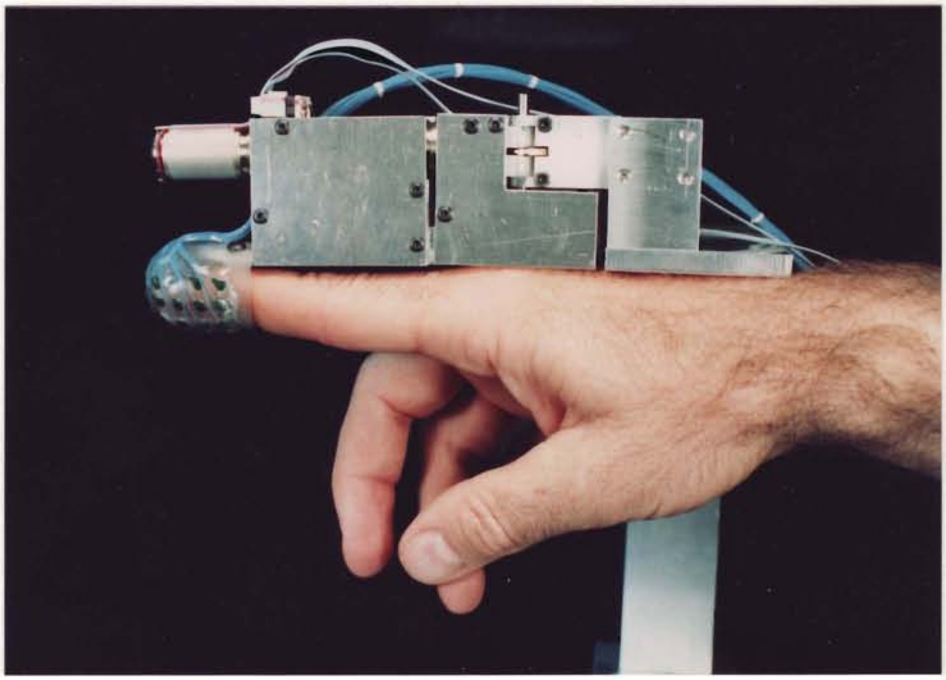


FIGURE 5-1: Prototype of a 3-DOF exoskeletal master glove controller finger developed during Phase I. The distal finger segment was fitted with a 37-channel tactile display.

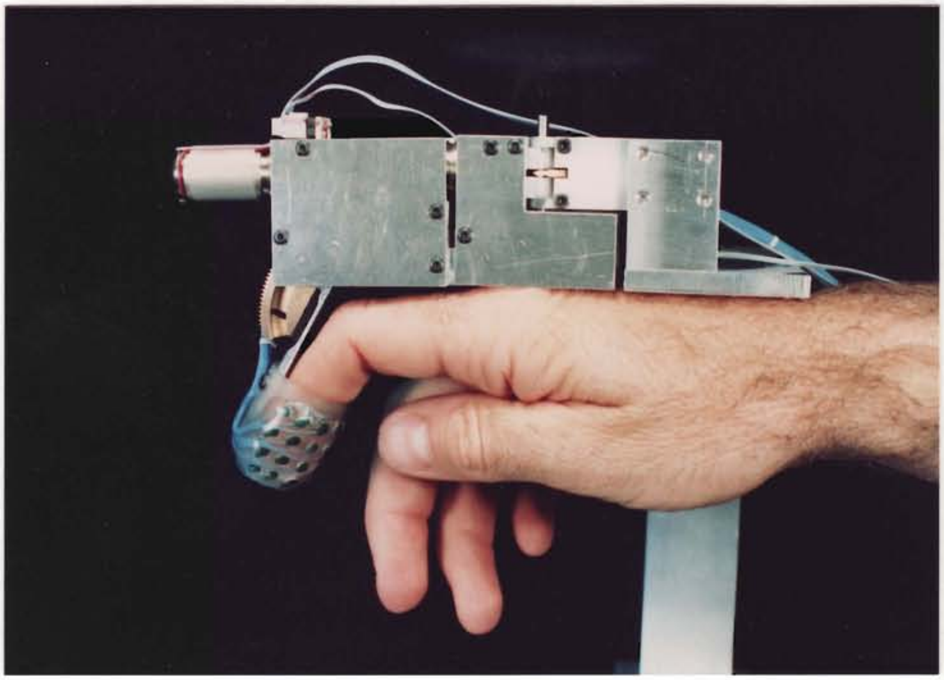


FIGURE 5-2: Master glove controller finger bent at the distal joint. The leads at the top are for motor power, the force sensor, and the joint angle sensor. Only this distal finger segment was fitted with sensors during Phase I.

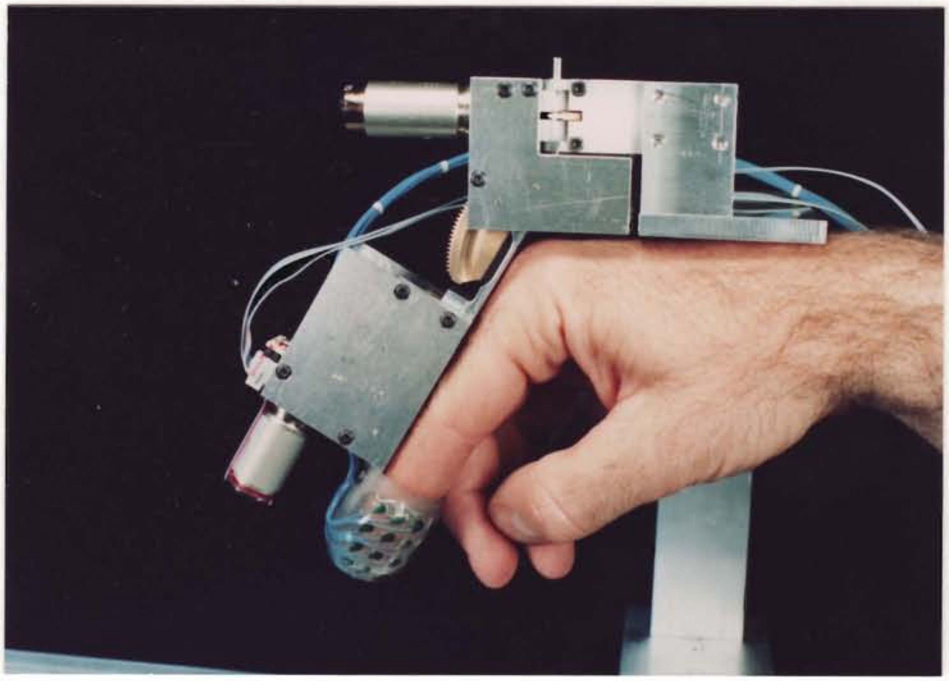


FIGURE 5-3: Glove controller finger fully bent at the main knuckle.

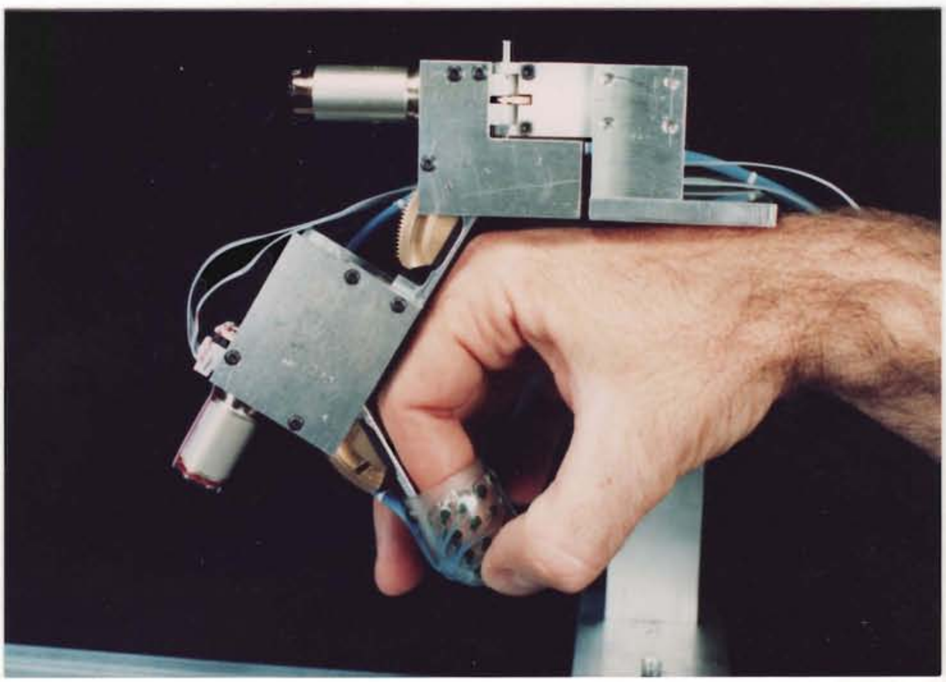


FIGURE 5-4: Both knuckle joints of the finger controller are shown fully bent. Note the lack of shifting between the exoskeletal glove and the operator's finger, thereby maintaining consistent and uniform registry between the tactile display and the skin during finger flexure.

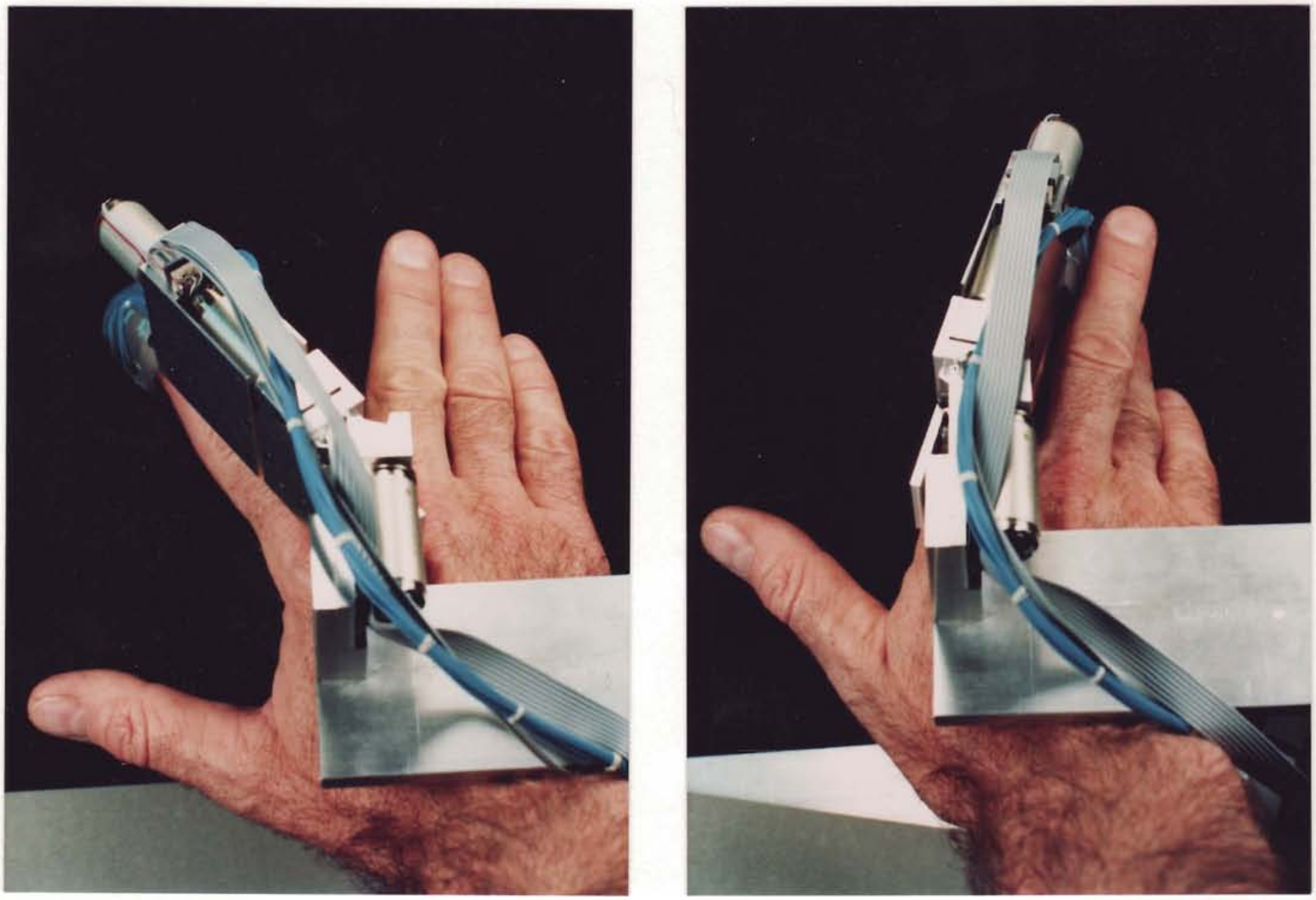


FIGURE 5-5: The main knuckle joint was a 2-DOF spherical hinge that permitted both finger flexure (see Figures 5-3 and 5-4) and lateral finger spreading. Left and right photographs show lateral spreading limits of 35° to the left and 15° to the right, respectively. The actuator motor for the spreading motion is on the right side of the finger structure.

It was also observed that some valves seemed to be permanently in the ON state, even after a significant burn-in period where the display was operated for several hours. As there were no adjustments of the valves to correct this condition, it was concluded that an allowance of approximately 10% must be made on future orders of Angar valves to allow for such defective units.

The LED indicator associated with the tactile display was found to be quite helpful in calibrating the tactile sensor, as it avoided the pervious need to use an oscilloscope or multimeter for this purpose. Also, during use, it was quite fascinating to watch the LED elements activate in response to the applied force pattern.

Unfortunately, as the LED indicator array is driven directly by the valve actuation signals, it did not reveal the previously-mentioned defective valve units that remained continuously ON. Furthermore, during evaluation of the telepresence system, it was noticed that the LED indicator was a significant distraction to the task of concentrating on the tactile signals generated on the tactile display. The reason for this was presumed to be the result of a learned preference for visual displays due to their ubiquitous presence in everyday life, and the obvious lack of experience with tactile displays.

It was concluded that the LED indicator would be best used only for system calibration purposes, but that it should be removed from the operator's sight thereafter as it could become a significant obstacle to acquiring proficiency with the fingertip tactile display.

6. CONCLUSIONS REGARDING TECHNICAL FEASIBILITY

The results of the Phase I work showed that the design and fabrication of an master glove controller utilizing an innovative "virtual hinge" joints is feasible. The feasibility of the concept was further demonstrated by the successful design and fabrication of a 3-DOF glove controller finger that was fully instrumented with regard to force, joint angle, and tactile sensing on the distal finger segment.

7. DIRECTIONS FOR FUTURE WORK

The overall objective of future work should be to design and fabricate an advanced prototype of a three-fingered exoskeletal glove controller featuring force, position, and tactile feedback at each finger. This work should begin with the advancement of the Phase I glove controller finger and single-jointed slave finger to the stage that more detailed performance evaluations may be performed. The general tasks that should be addressed to achieve this are:

- Fabrication and attachment of two force and two analog joint angle sensors to the spherical joint associated with the main knuckle.
- Fabrication and attachment of one force and one analog joint angle sensor to the single-joint slave finger prototype.
- Expansion of the force and joint angle sensor conditioning boards, and fabrication of a twin board for the slave finger element.
- Fabrication of a duplicate motor driver board for the slave finger.
- Implementation (in hardware) of simple master/slave control algorithms.

Initial evaluation of the system would be performed with a bench-test system such as that shown in Figure 8-1, followed by a more exhaustive evaluation of the Dexterous Teleoperator System using a manipulator system with force feedback capabilities. One convenient approach would be to use a mechanical master/slave manipulator (MMSM), such as the horizontally-mounted MMSM (Control Research Laboratory Model-50) at Begej Corporation: see Figures 8-2 and 8-3.

Excluding the 1-DOF represented by the existing gripper motion, the CRL MMSM permits remote manipulation with six degrees of freedom (three translational, and three rotational at the wrist). The existing hand controller (Figure 8-3) and gripper could be replaced with the single-finger glove controller and single-joint slave finger, respectively. Additionally, a simple control console could be built which substitutes a video image for a direct view of the work area. This would permit testing of the glove controller in more realistic conditions, and allow a qualitative evaluation of the effectiveness of force and tactile feedback in simple manipulative operations.

After completion of the evaluation of the Phase I glove controller, an advanced three-fingered controller could be designed and fabricated incorporating some of the following refinements:

- Selection of hardened and/or high strength materials for the virtual hinge and geartrain components to increase the load-carrying capacity and to extend the life of the joint mechanism.

- Standardization of all force-sensing cantilevers so that finger-length customization may be conveniently made from a stock kit of cantilevers. Alternatively, the cantilevers might be made capable of changing their length, thereby making customization of the glove to various operator's hands quick and convenient.

- Possible further miniaturization of the optical force and joint angle sensors.

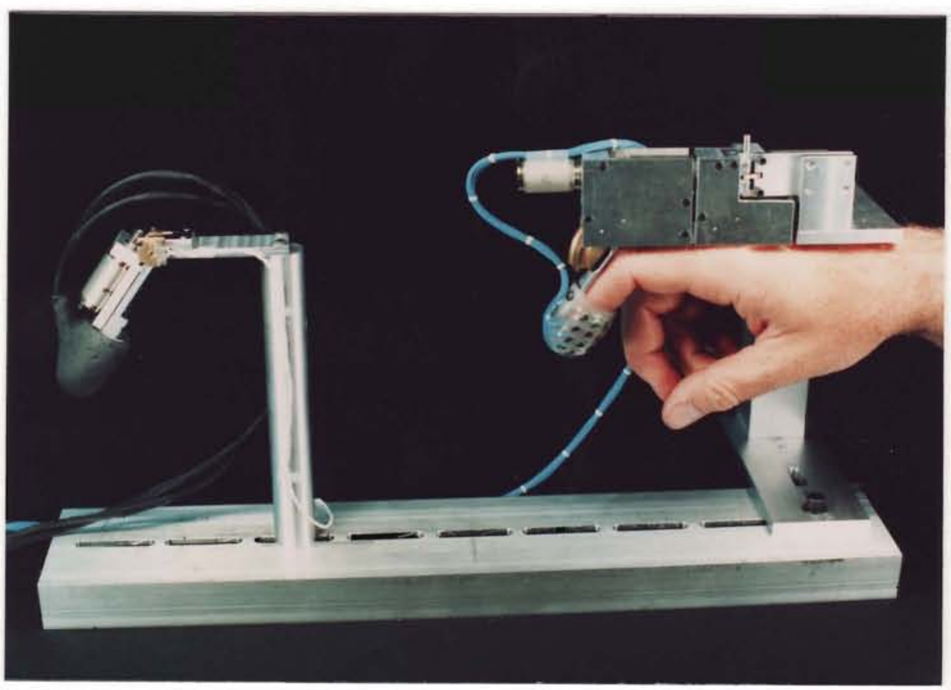
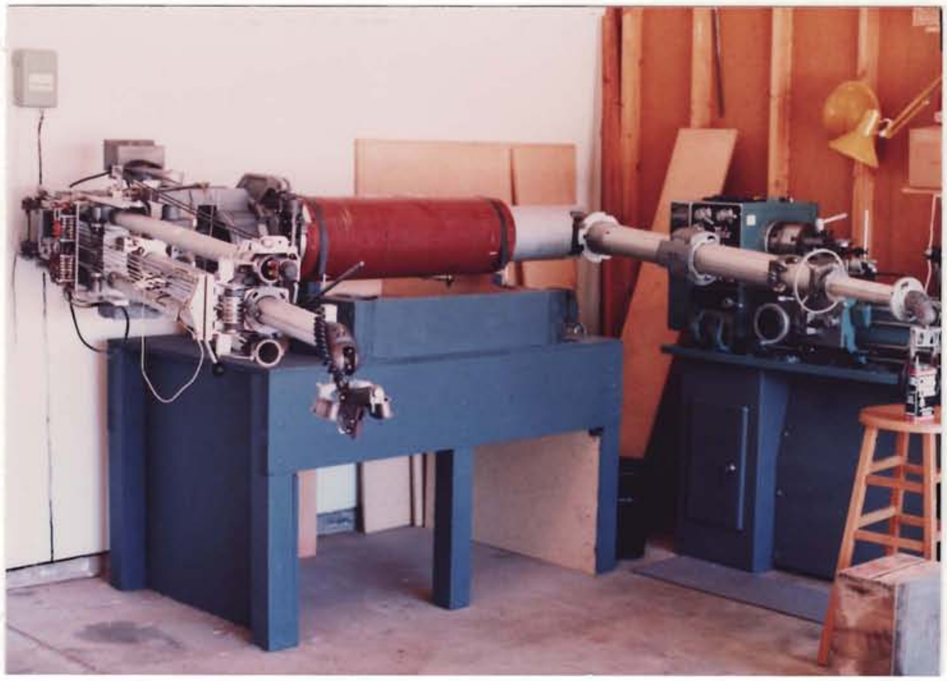


FIGURE 8-1: An initial evaluation of a Phase I glove controller and single-jointed slave finger would be performed on a benchtest arrangement, such as the one pictured here.



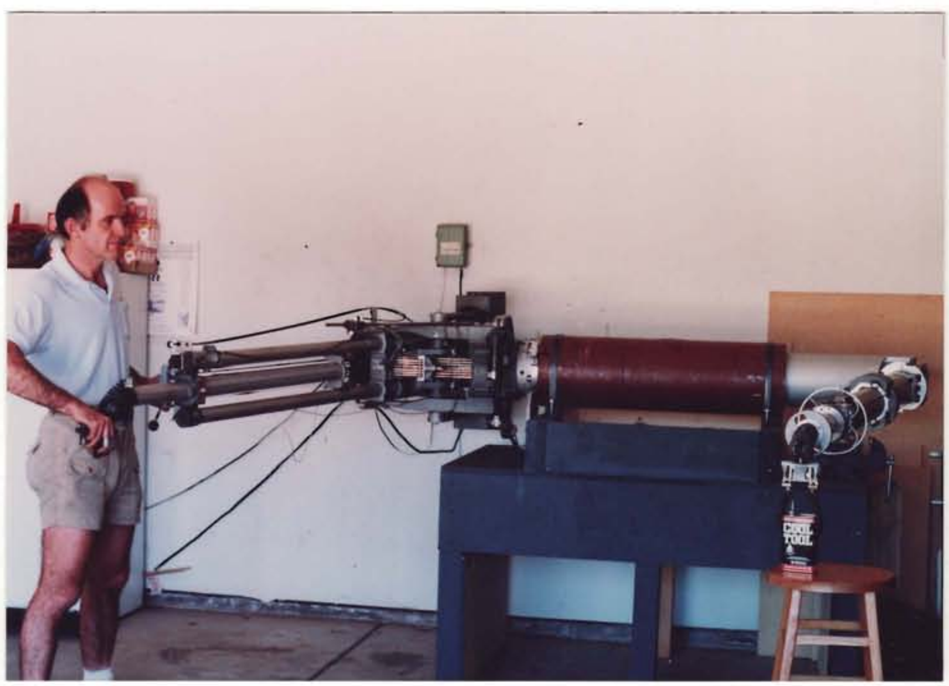
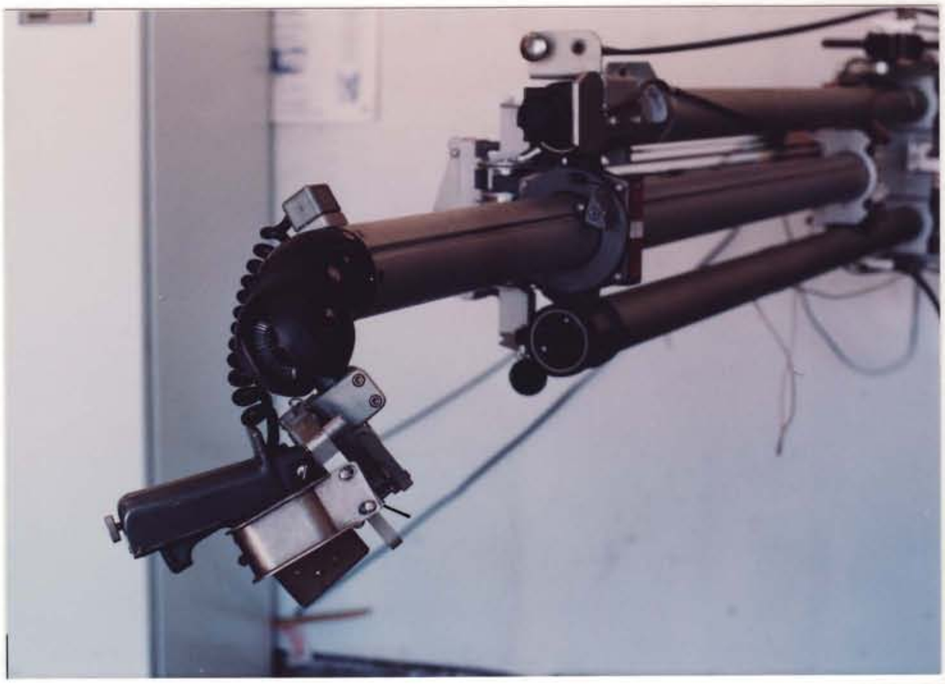


FIGURE 8-2: A horizontally-mounted Control Research Laboratory Model 50 mechanical master/slave manipulator could be modified to permit evaluation of glove controllers and associated system components.



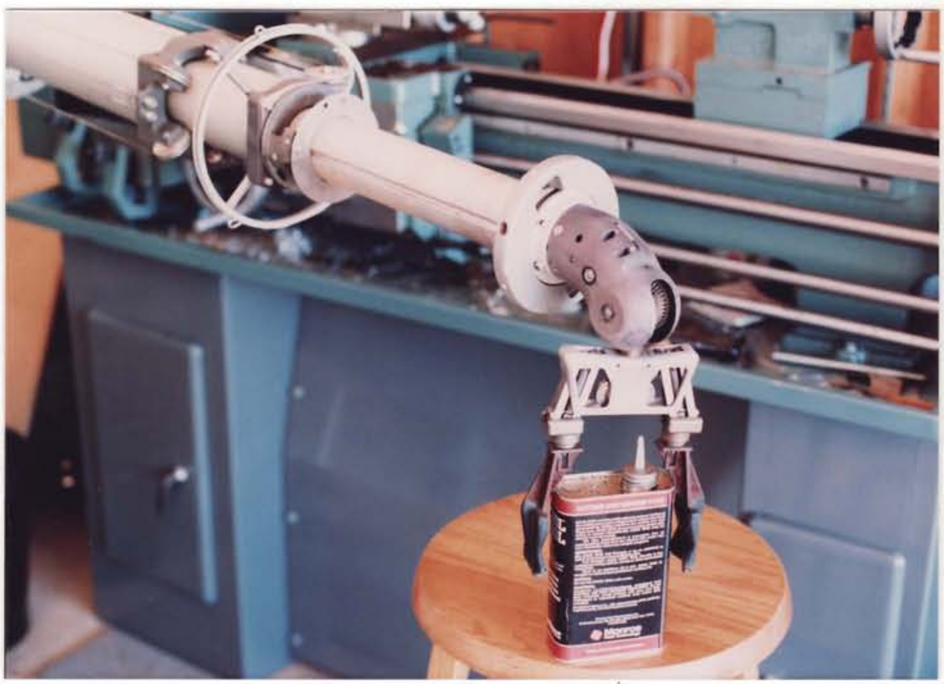


FIGURE 8-3: The existing MMSM gripper controller (top) and gripper (bottom) could be replaced with various Phase I or II glove controllers configured to act either as master or slave devices, respectively. This would permit evaluation of master glove designs under realistic conditions.

- Selection of more appropriate motor drive chips. (The Phase I motor drivers simply employed eight paralleled LM324 op amps to provide bi-polar power to the motors).

- Specification of simple master/slave control algorithms, and design of hardware circuits to implement them.

- Use of shims to adjust the position of the axis or rotation point of the virtual hinge so they more accurately coincide with the finger joint axis or knuckle rotation points.

- Use microcontrollers to linearize and digitize signals from force and joint angle sensors, and to implement a low-level travel-limit detection and control scheme.

- Fabrication of three new tactile telepresence systems featuring: a greater number of channels; more rugged and thinner tactile display; use of printed circuit boards to reduce the size and volume of the tactile sensor signal conditioner and display driver; higher-density packaging of the pneumatic valves (e.g., hexagonal close-packed distribution); and the development of new pneumatic or hydraulic means for rapidly and conveniently calibrating the tactile sensors.

Evaluation of the three-fingered master glove controller could be performed in much the same manner as previously described for the Phase I controller. First, the single-finger Phase I prototype could be converted into a slave finger and (together with the master glove) be placed on a stationary bench test-cell similar to that shown in Figure 8-1. After satisfactory functioning of the system on the bench was demonstrated, the slave finger and glove controller could then be attached to the CRL-50 mechanical master/slave manipulator arm (see Figures 8-2 and 8-3) and evaluated under more realistic circumstances the permitted qualitative characterization of the effectiveness of both force and tactile feedback in dexterous manipulation operations.

7. REFERENCES

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Taylor, H.J. and P.N.P. Ibbotson, "Powered wrist joint," US patent 4,353,677, issued 14 February, 1978.

8. LIST OF SUPPLIERS

Supplier	Product or Service
Angar Scientific Co., Inc. 52 Horsehill Road Cedar Knolls, NJ 07927-2098 Tel: (201) 538-9700 Fax: (201) 538-5937	Miniature pneumatic valves.
Marktech International, Inc 5 Hemlock Street Latham, NY 12110 Tel: (518) 786-6591 Fax: (518) 786-6599	Miniature optical displacement sensors
Micro Mo Electronics, Inc 742 2nd Ave South St. Petersburg, FL 33701 Tel: (813) 822-2529 Fax: (813) 821-6220	Miniature electric motors and gear reducers.
Winfred M. Berg, Inc 499 Ocean Avenue East Rockaway, NY 11518 Tel: (516) 599-5010 Fax: (516) 599-3274	Miniature ball bearings.